INSTRUMENTS FOR MEASUREMENT AND CONTROL

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1. Temperature

When a body is heated, the vibrational speed of its molecules increases rapidly. This has a number of physical effects: in the case of metal, its electrical resistance and dimensions change; in the case of a confined fluid, its pressure increases. In both cases the temperature rises as a result of increased heat. In measuring the temperature, the relative change of the molecular activity is defined by a quantitative expression. An instrument measures temperature because it is sensitive to at least one of the physical effects produced by the increased molecular activity.

One of the effects utilized is *thermoelectricity*. When two wires of different materials, *e.g.*, iron and constantan, are tied together at both ends, they form a closed loop with two junctions of dissimilar materials. If one junction is kept at a higher temperature than the other, a voltage difference is generated which is a function of the temperature difference between the two junctions. By connecting an electric meter to the circuit and keeping one of the junctions at a constant temperature, a measure of the temperature at the other junction is obtained. The measuring junction, representing the temperature-sensitive element, is the thermocouple. The other junction is the reference junction. The latter is usually located within the instrument. In its elementary form, the reference junction is kept at constant temperature; but it will be shown later that limited temperature changes are permissible when suitable compensators are used. The measuring device is either a millivoltmeter or a potentiometer as described in this chapter.

Radiation of a hot body can be measured and the temperature of the body deduced from it. This method has the advantage that no part of the temperature-sensing element comes into direct physical contact with the heated body. Radiation instruments therefore offer a means of determining high temperatures beyond the reach of other instruments. They also find application where rapid response to a change in temperature is essential.

Another effect of heat is the change of *electrical resistance* of a wire. Resistance thermometers utilize this characteristic.

When a fluid is confined its *pressure* increases when the temperature rises. In filled-system thermometers, fluids are confined by hermetically sealed systems and their pressure response is used as a measurement of temperature.

The *expansion* of a liquid or a solid is another effect of heat. The mercury-in-glass thermometer is one example. The principle also applies in bimetallic elements, where two strips of metal of widely different coefficients of expansion are welded together. One may be brass, and the other "Invar," an alloy which has a temperature coefficient approximately 1/20th that of brass. When the strip formed by the two metals is heated, it bends because one metal expands more than the other. The curvature of the bend is a function of the heat applied to the strip. The bimetallic element is widely used in thermostats, in compensators for ambient temperature changes on millivoltmeters, and in industrial thermometers.

Mercury-in-glass and bimetallic thermometers are not described in detail because they are essentially neither remote-reading nor remote-acting.

MILLIVOLTMETERS

Principles

The thermocouple produces a voltage or emf (electromotive force) which is converted into the deflection of a pointer by means of a millivoltmeter. The pointer moves over a scale which is calibrated in degrees of temperature

The moving coil or d'Arsonval type of millivoltmeter, as illustrated in Figure 1-1, combines two magnetic fields. One is produced by a permanent mag-

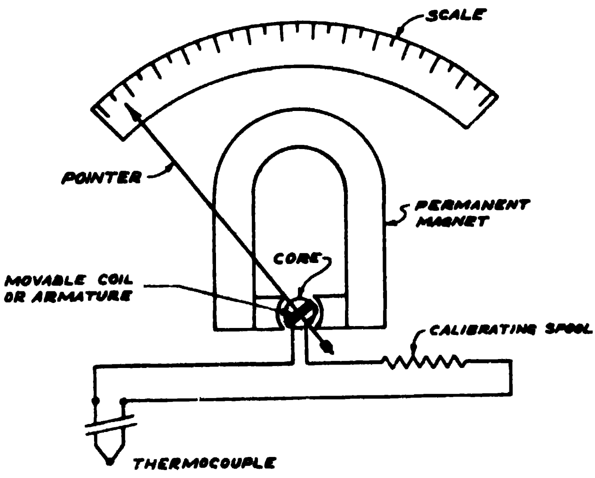


Figure 1-1. Schematic of a millivoltmeter.

net. The other by a current flowing through a movable coil. A torque which is proportional to the current is exerted on the coil by the interaction of the two magnetic fields. The coil is free to rotate against the counter-torque of a spring. The resulting deflection of the coil, as indicated by a pointer mounted on it, is a measure of the current passing through it.

In thus determining the emf as produced by the temperature difference between two junctions of dissimilar metals, one might ask what is really measured—current or voltage. The distinction loses meaning because the meter itself presents the necessary link in completing the circuit. Voltmeters and ammeters are generally accessories to existing equipment In the case of temperature measurements, the meter itself is the equipment. However, an essential difference between ammeter and voltmeter is that the former offers very little resistance to current flow, so that the voltage drop is negligible, whereas with a voltmeter the current through the instrument is limited by resistance to a minimum, so that practically all the voltage drop of the system occurs across the instrument.

In millivoltmeter-type temperature instruments it is advisable to concentrate the bulk of resistance in the instruments. for reasons that will be explained later. Therefore, this form of measurement is rightly called voltage and not current measurement. This is also in line with the expression of thermocouple output in terms of emf, as the only clear definition of its characteristics. The use of millivolts instead of volts is due to the smallness of the values involved.

The millivoltmeter, as described here, is used to measure the electrical potential of thermocouples. The voltages to be measured range approximately between 0 and 50 millivolts. The minimum span of a millivoltmeter is about 12 millivolts.

Figure 1-2 shows a millivoltmeter, made by General Electric Company, as it appears when taken out of its housing. The principal parts of the millivoltmeter are a permanent magnet, which is usually an Alnico magnet, and a movable coil, often called the armature. Other parts are the soft-steel core, which reduces the total air gap between the magnet poles; the pointer, attached to the coil and moving with it; and the scale on which the pointer indicates the magnitude of the quantity measured. Calibrated springs serve the dual function of carrying current to the moving coil and of opposing the torque that results from the current in the coil. The coil may be mounted between two jewel bearings; it may be suspended by means of fine wires that run from the top and bottom of the coil assembly to fixed supports; or it may be suspended from the top, while the lower end rotates in a jeweled bearing.

Certain adjustments are required. Usually a zero adjuster is provided by means of which the tension in the counter-torque-producing springs can be changed. Counterpoises on the coil assembly will balance the system so that it will be accurate in whatever position it is mounted. Furthermore, a calibration spool to allow calibration of deflection of the movable element is generally provided. This is connected in series with the coil and the thermocouple. By in-

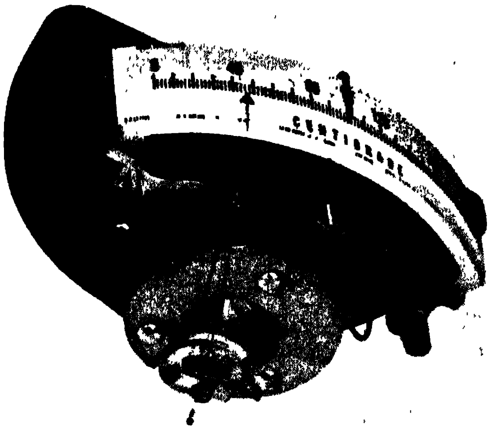


Figure 1-2. Millivoltmeter pyrometer (case removed). (*Courtesy of General Electric Co.*)

creasing or decreasing the total length of wire of the calibration spool, the total resistance is increased or decreased.

The resistance of the millivoltmeter is high, usually around 600 ohms, but it depends somewhat on the range of the instrument. This keeps the current at a minimum and thus decreases the voltage drop in the wires that connect the measuring junction to the instrument. However, the voltage drop is not eliminated altogether. The resistance in the wires to the instrument will affect its calibration. If this is not excessive, correction can be made for it.

The change in the electrical resistance of the wires to the instrument due to changes in ambient temperature is negligible since the lead wire resistance constitutes only a small percentage of the over-all resistance. The calibration spool, which is part of the instrument itself, generally represents more than 90 per cent of the total resistance in the circuit. The effect of temperature changes on the calibration spool would be objectionable if it were not made of "Manganin." This alloy is of very high electrical resistivity and hence little bulk is required; it also has an extremely low temperature coefficient, which leaves the resistance practically constant under all temperature variations to which the instrument can be conceivably exposed.

The copper wire of the galvanometer coil also changes its resistance with temperature. The necessary coil compensation is generally provided by the same bimetallic strip used for reference junction compensation, as described below. In addition, a resistor with a negative temperature coefficient,* a so-called

*A negative temperature coefficient indicates that the resistance decreases with an increase of temperature.

thermistor, is often used in the galvanometer unit to compensate for such coil resistance changes.

The emf measured by the millivoltmeter is the result of the temperature difference between the measuring and the reference junction. The arrangement is usually such that the reference junction is located at the instrument. If the instrument is to indicate the temperature of the measurement junction, either the temperature of the reference junction must be kept constant or suitable compensation must be provided for changes. In millivoltmeters, compensation by means of a bimetallic strip is the preferred method. The strip deflects in response to temperature changes and thus varies the tension in the counter-torque-producing spring, to which it is fastened, in a fashion similar to the zero adjuster.

Sometimes, an additional bimetallic element is used. By means of a pointer attached to it, it indicates the temperature inside the instrument, *i.e.*, the reference junction temperature. This is to facilitate zero setting, since the instrument should read reference junction temperature when the thermocouple is disconnected. For example, at 72°F reference junction temperature, the zero setting is likewise 72°F.

The decisive advantage of the millivoltmeter is its low cost. Its accuracy, while inferior to that of other instruments, is satisfactory for a great many industrial applications. It is usually better than 1 per cent of full-scale reading, disregarding the error caused by the thermocouple.

The millivoltmeter is somewhat sensitive to vibrations. Where vibration is a factor, the potentiometer is generally more suitable than a millivoltmeter.

Millivoltmeters as Recorders

A number of attempts have been made to build the millivoltmeter not only as an indicator but also as a recorder. For example, the moving coil of the Omnicorder made by Thomas A. Edison Industries carries a stylus instead of a pointer. A small synchronous a.c. motor drives a circular chart of 3-inch diameter through suitable gearing and periodically clamps the moving system, pressing the stylus against the underside of the pressure-sensitive chart paper. This makes a small dot appear on the front chart surface. The moving system is then unclamped and is free to move to a new position if the measured temperature has changed. In this manner, and through the rotation of the chart, a series of dots is printed on the chart which appear as a continuous line. The result is a small, low-cost temperature recorder with an accuracy of 2.5 per cent of range.

Another type of millivoltmeter recorder uses an electronic oscillator to detect the position of the pointer, thus avoiding any direct contact with the pointer. The oscillator is essentially an electronic amplifier that feeds back a certain percentage of its output into the input. No other input is provided but this feedback signal. The energy is supplied by a power source in the output circuit. The coupling between output and input is obtained by inductance coils. One inductance coil is connected into the output circuit, another into the input circuit. The magnetic field set up by an alternating current in the coil of the output circuit is intercepted by the coil in the input circuit, generating an a.c. voltage in the latter. Any oscillation of current in the output coil is immediately repeated in the input coil and fed through the amplifier stage from where it passes to the output coil (where it originated) and back again to the input coil. The action results in a self-sustained circle with a frequency of oscillations which is determined by the circuit components. The relation between output and input is destroyed as soon as a metal vane is inserted between the oscillator coils. The vane acts as a shield against the electromagnetic coupling between the two coils. A very minute vane movement, such as 0.004 inch, is enough to produce a signal in the electronic circuit that can be utilized for recording purposes and, as will be shown later, for control purposes as well.

POTENTIOMETERS

Principles

While the electrical engineer frequently considers a potentiometer to be an adjustable voltage divider, the term as used by the instrument engineer refers also to an instrument that measures an emf by the null method, rather than by the deflection method of the millivoltmeter. The unfortunate confusion gets worse when, as later in this text, one has also to refer to potentiometers which are adjustable voltage dividers.

The basic difference between the deflection method of the millivoltmeter and the null method of the potentiometer lies in the fact that the millivoltmeter measures the emf output of the thermocouple directly and indicates its magnitude, while the potentiometer requires a second power source, the output of which is adjusted to balance the output of the thermocouple. The amount of adjustment required to obtain this balance is the quantity which the potentiometer measures.

Figure 1-3 shows a simple potentiometer circuit. A continuous path can be followed from the thermocouple to slide-wire contactor *F*, through part of the slide-wire resistance to *D*, through the galvanometer and the left-hand contact of switch *S*, back to the thermocouple. There is another path that runs from the battery through the standardizing rheostat, through the slide-wire from *D* to *C* and back to the battery. One portion is common to both circuits—the slide-wire resistance between *F* and *D*. Since the contactor, *F*, can take any position along the slide-wire, it is possible to find an adjustment for any emf out-

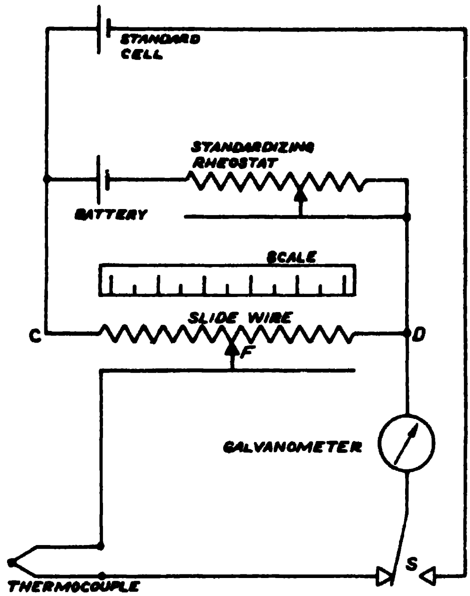


Figure 1-3. Potentiometer circuit.

put of the thermocouple for which the voltage drop between *F* and *D*, as caused by the battery output, balances exactly the thermocouple emf applied to the same two points. In this condition, no current flows through the thermocouple circuit and the galvanometer indicates zero. Provided that the emf output of the battery is constant, there is one and only one balancing position of slide-wire contactor *F* for each emf output of the thermocouple, *i.e.*, for each temperature measured. Hence, the positions of the contactor can be indicated on a scale calibrated in temperature.

It would be difficult to meet the requirement of keeping the emf output of the battery constant. It is possible, however, to make periodic allowance for decrease in emf output by adjusting the resistance of the standardizing rheostat, thereby keeping the voltage drop across the slide-wire resistance constant. The periodic check on the dry cell is made possible by means of the standard cell. The characteristics of these cells are that they cannot support a current discharge of more than fractions of a microampere for any prolonged time; that heavier drains are possible for short intervals, followed by sufficiently long recovery periods; and that within these limitations their emf is practically without change over years.

By transferring switch *S* to its right-hand position, the thermocouple circuit is interrupted and in its stead a circuit from the switch, *S*, through the standard cell, slide-wire resistor, galvanometer and back to switch *S* is closed. To balance the circuit while the standard cell is connected, the standardizing rheostat is adjusted until the battery emf across the slide-wire resistance balances the emf from the standard cell, at which point the galvanometer reads zero.

The advantages of the potentiometer as compared with the millivoltmeter are: (a) the deflection of the galvanometer does not have to be proportional to the emf output of the thermocouple because, whatever the magnitude of the deviation, the zero condition must be reestablished by moving the contactor *F* to obtain a temperature reading; (b) the resistances of the thermocouple, extension wire, and the galvanometer under normal conditions have little effect on the accuracy of the instrument because at balanced conditions no current flows, and hence no voltage drop can occur;* (c) since the span is no longer limited by the deflection of the galvanometer, wider spans are possible, producing better readability of small temperature differences and greater accuracy; (d) the development of an instrument without a galvanometer and the utilization of electronic circuits become possible.

Manual-balance Potentiometers

These potentiometers are often portable instruments such as the MiniMite manual-balance potentiometer made by the Thermo Electric Company which is shown in Figure 1-4.

The instrument has a double temperature scale to accommodate either both millivolt and temperature calibrations or two different thermocouple calibrations or some other combination. The range selector switch permits transfer to either scale.

The thermocouple is connected to the emf terminals in the upper right-hand corner.

The slide-wire, and with it the temperature scale, is manually adjusted by the knurled dial disc below the temperature scales. To measure temperature this disc is manipulated until the deflection of the galvanometer pointer, located above the temperature scales, disappears. Once this position is obtained, the temperature scale which rotates with the knurled dial disc indicates the temperature measured.

The test switch in the lower right corner short-circuits the galvanometer through a damping resistor in its normal position and opens the thermocouple circuits. In order to take a reading, the switch is depressed. It can be locked in position by twisting it one-quarter turn.

*It would not be correct to state that they are without effect, since excessive line resistance would decrease the sensitivity of the measuring device which in turn would affect the accuracy of the instrument.

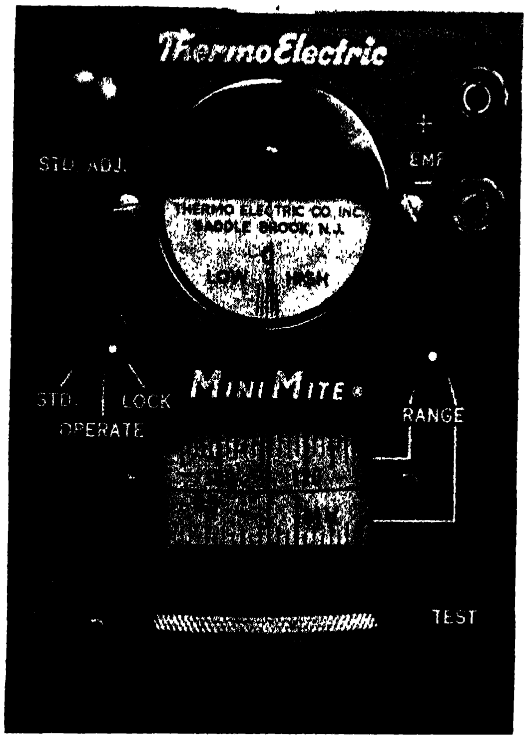


Figure 1-4. Manual-balance potentiometer. (*Courtesy of Thermo Electric Co.*)

The standard cell is connected in place of the thermocouple by switching to *STD.* The galvanometer pointer is then made to read zero by means of the battery adjustment in the upper left-hand corner.

The reference junction is located inside the instrument, but a compensating resistor is provided to maintain accuracy even under normal changes of ambient temperature.

The characteristics of a potentiometer make it an accurately calibrated variable source of emf. It can be used as such to calibrate other potentiometer instruments. The emf terminals then become the outlet terminals, from which wires connect to the thermocouple connections of the potentiometer to be calibrated. The *LOCK* position is used. This short-circuits the galvanometer to prevent motion of its coil which would induce a variable emf in the circuit. When used with a millivolt scale a non-temperature responsive compensating resistor is employed in the circuit. If used with a temperature scale, a temperature compensating resistor is substituted in the circuit.

Self-balancing Potentiometers

The manual-balance potentiometer described in the previous paragraph requires manual adjustment of the slide-wire every time a reading is taken. The self-balancing potentiometer, on the other hand, reads the variable continuously and responds immediately to any changes. Since galvanometers are generally replaced by electronic error detectors, these potentiometers are practically free from the influences of mechanical vibration. Such instruments respond quickly to changes in the measured variable, which is particularly important where the instrument is used for control applications and measurement lags must be kept at a minimum. It is also important in multiple-point recording, where temperatures at a number of points are scanned by a single instrument, and the time that elapses until the instrument returns to a given point must be as short as possible.

Figure 1-5 shows the circuit of a self-balancing potentiometer as used in a number of instruments. The dotted lines in the illustration show the location of

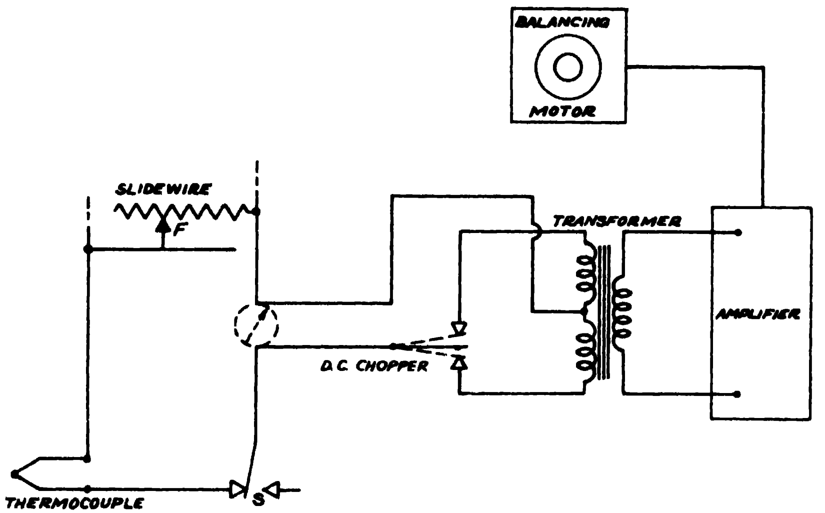


Figure 1-5. Partial schematic of electronic potentiometer circuit.

the galvanometer in Figure 1-3. It is now replaced by a d.c. chopper and its accessories which, though perhaps less durable, are more rugged and powerful during their life. The d.c. chopper, which is essentially a reed swinging rapidly between two contacts, converts the direct current into a pulsating current of rapidly changing polarity. The swinging of the reed is maintained by a magnet arrangement energized at rapid intervals and synchronized with the 60-cycle supply power to which it is connected.

The pulsating current thus produced passes through the windings of the transformer where its voltage is stepped up and fed into an amplifier. The amplifier output controls the balancing motor. This motor, which is also called "servo-motor," has two windings. One of these, the fixed-voltage winding, is energized from the a.c. power supply. The other, the control winding, receives an a.c. signal from the amplifier as long as an unbalanced thermocouple voltage exists. The phase of the control voltage differs from the fixed voltage phase by 90 degrees. The balancing motor will only move when it receives a control signal which is 90 degrees out of phase from the fixed voltage. The direction in which it moves depends on whether the control signal leads the fixed voltage by 90 degrees or lags behind it. In other words, changing the control voltage by 180 degrees reverses the rotational direction of the motor. The amplifier distinguishes between a rising and a decreasing thermocouple signal by a 180-degree phase reversal of its output signal. Thus the rotational direction of the balancing motor depends on whether the thermocouple emf increases or decreases. In rotating, the balancing motor moves the slide-wire contactor to a position where the thermocouple circuit is again balanced. In this condition, the control signal voltage is zero, and the motor stops.

Figure 1-6 shows the somewhat different arrangement of the Bristol Dynamaster. With two vibrating reeds rather than one, a single primary winding can be used in the transformer. This also prevents the possibility of inaccuracies due to production of a thermal emf by the closing contacts of a single-reed d.c. chopper. The two sides of the contacts are made of different materials to

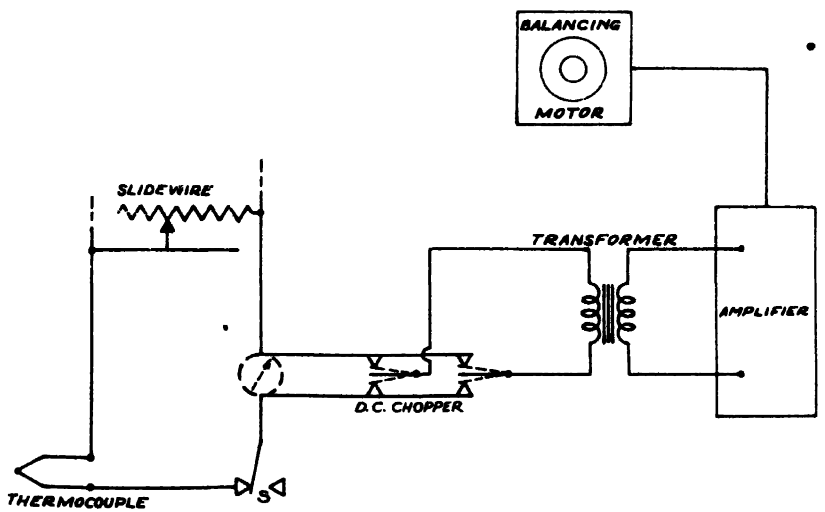


Figure 1-6. Partial schematic of Dynamaster.

prolong their life, and hence may act as additional thermocouples, since heat is developed in making and breaking the contacts. In the two-reed construction any such emf's would be of approximately the same magnitude on each reed and would therefore compensate for each other. This, however, is a rather fine point, at least as far as commercial instruments are concerned.

The Foxboro Dynalog eliminates the battery and the periodic—either automatic or manual—standardizing of the battery voltage by comparing the emf of the thermocouple directly with that of a standard cell. This is made possible by a special circuit which is illustrated in Figure 1-7.

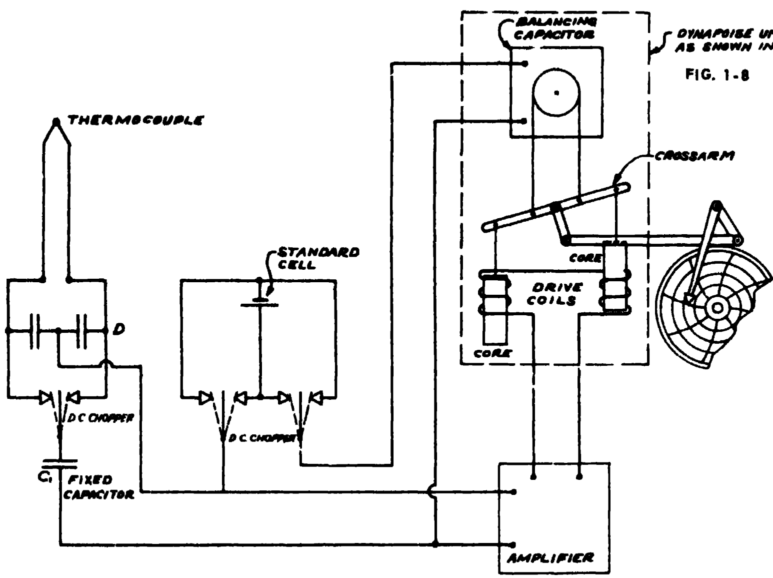


Figure 1-7. Dynalog circuit.

The thermocouple voltage is applied directly to a fixed capacitor C_1. The voltage of the standard cell is applied to the balancing capacitor The balancing capacitor is similar to those used for tuning radios in that it has two stacks of intermeshed plates insulated from each other and its capacity is adjusted by turning one of the stacks (called the rotor) to change the degree of intermeshing.

The two voltages are applied to their respective capacitors, and after the capacitors are charged, they are discharged into each other through the high-speed switching action of the d.c. chopper. The amount of charge of each capacitor is the product of the voltage applied to it and the capacity of the capacitor. The charge on the fixed capacitor varies directly with the thermocouple voltage, but the charge on the balancing capacitor varies only with the value of its capacity, since constant voltage is applied.

Unless the charge on the balancing capacitor is equal to that on the fixed capacitor, an unbalance voltage will exist across the capacitors after they have discharged into each other. This unbalance voltage is fed to the amplifier, which increases its power and applies it to the drive coils of the Dynapoise unit. The electromagnetic field thus produced by the drive coils moves the cores, which through a crossarm adjust the rotor of the balancing capacitor to rebalance the circuit, with the charge on the balancing capacitor equal to the charge on the fixed capacitor. The instrument pen linked to the crossarm registers the temperature signalled by the thermocouple.

Since the only current drawn from the standard cell is the amount needed to charge the balancing capacitor, which is less than 0.1 microampere, it is possible to keep it in the circuit continuously and to dispense with the battery.

The Dynapoise unit which contains the balancing arrangement is shown in Figure 1-8. A slide-wire is no longer needed in this device, nor is it needed in the device described in the following. This eliminates problems of contactor or

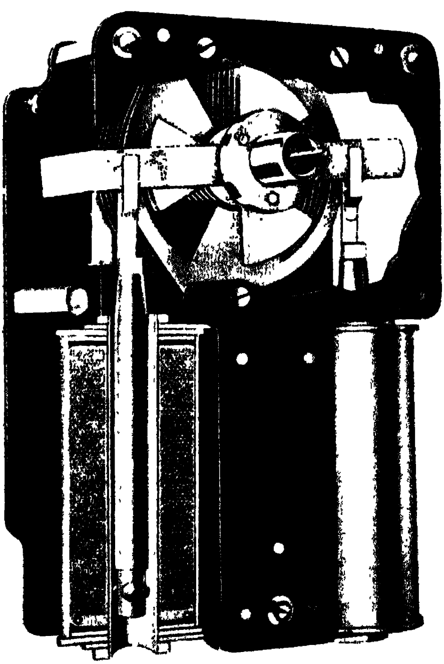


Figure 1-8. Dynapoise unit. (*Courtesy of Foxboro Co.*

slide-wire wear, of bouncing contacts at high pen speeds, and of corrosion effects.

The Electronik 17 potentiometer which is made by the Brown Instruments Division of Minneapolis-Honeywell Regulator Company combines several particular features, amongst them, a transistorized amplifier eliminates vacuum tubes, a Zener diode circuit provides a constant current supply replacing battery and standard cell, and a strain-gage bridge does away with the slide-wire.

Figure 1-9 illustrates the circuit. The four resistances in the Stranducer unit represent four strain-gages connected in a bridge circuit. It is characteristic of

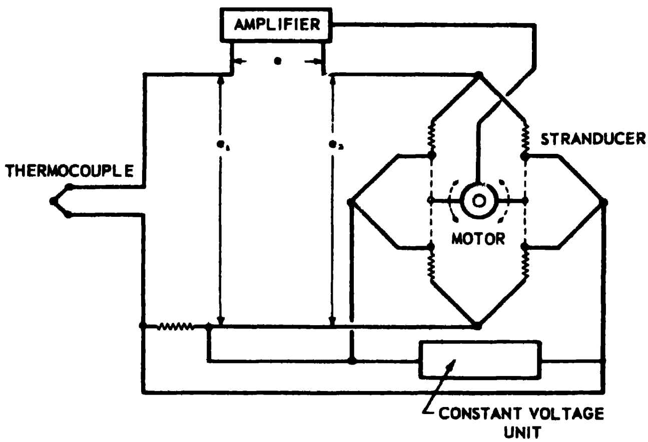


Figure 1-9. Schematic of Electronik 17 potentiometer.

such bridge circuits (or Wheatstone bridges) that, as shown in Figure 1-10, no current flows through resistance *e*, when the relation of the other resistances is $a/b = c/d$. Any change in this relation makes current flow through resistance *e*. In Figure 1-9, the resistance, *e*, is replaced by an amplifier, a thermocouple, and a resistor, all connected in series.

The four wire strands of the Stranducer that form the legs of the Wheatstone bridge are linked mechanically to a balancing motor and electrically to the measuring circuit. As the input signal increases or decreases, it is amplified and drives the balancing motor in one direction or the other. This increases the tension on two of the Stranducer wires and decreases it on the other two, at the same time moving the instrument pen or pointer up or down-scale. The changing tension on the wires changes their electrical resistance.

The circuit is in balance when $e_1 = e_2$. Under this condition, *e* is zero, and the balancing motor stands still. Any temperature change as sensed by the thermocouple results in an unbalanced voltage *e* and renewed action of the balancing motor.

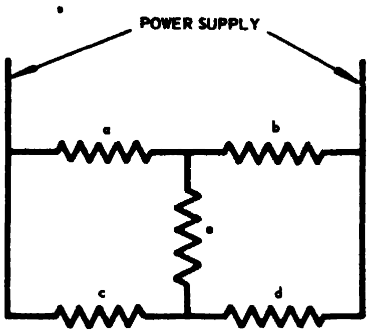


Figure 1-10. Wheatstone bridge.

The Zener diode network replaces battery and standard cell. It connects directly into line voltage and smoothes out all normal line voltage variations. The Zener diode is a transistor-like device, which changes its resistance at a certain voltage from a very high to a very low resistance. This change takes place within about one volt; for example, between 22 and 23 volts. Suppose a Zener diode is connected as in Figure 1-11. Voltage e_1 could be a 115 volt a.c. power supply. Voltage e_2 would be equal to the supply voltage e_1 minus the voltage drop across the resistor, disregarding the effect of the rectifier-capacitor arrangement. If e_2 is above a certain value, the resistance of the Zener diode

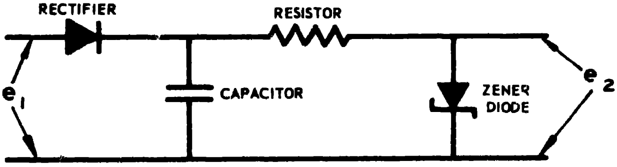


Figure 1-11. Constant voltage supply with Zener diode.

rapidly diminishes and current flows through it. This increases the voltage drop across the resistor, decreasing e_2 and hence again increasing the resistance of the Zener diode. A self-regulating element is thus imposed upon the circuit which maintains the output voltage e_2 within very narrow variations. By means of a cascaded Zener diode network, *i.e.*, e_2 used as the input voltage for a second Zener diode circuit, a further improvement of voltage regulation results. Voltage regulator tubes are sometimes used instead of Zener diodes.

Potentiometer Transmitters

Several transmitters are available which no longer are an integral part of a recorder or indicator but convert the thermocouple emf into some form of standard electrical or pneumatic signal. The potentiometer transmitter made by Taylor Instrument Companies is described as an example. Here again, slidewires as well as batteries and standard cells are eliminated. The circuit is illustrated in Figure 1-12. With the use of cascaded Zener diodes, the voltage is maintained at 87 volts ± 0.1 per cent while the power supply may vary between 90 and 135 volts.

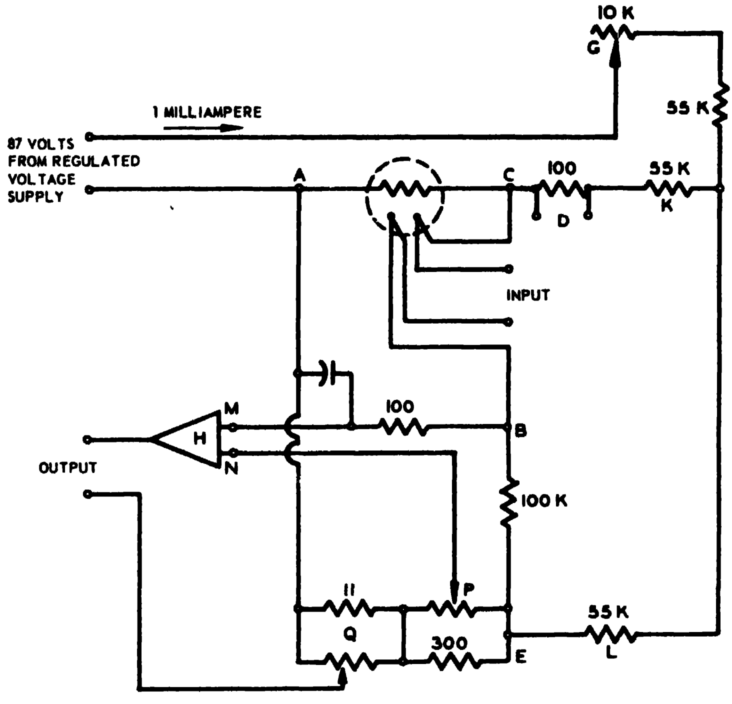


Figure 1-12. Taylor potentiometer transmitter circuit.

A current of one milliampere is drawn by the Wheatstone bridge from the regulated 87-volt supply. This current is split along two nearly equal resistance paths forming the two sides of the bridge. Resistors *K* and *L* are precision resistors of 55 K (= 55 thousand) ohms each. Since these resistors are much larger than the resistors which are in series with them. *i.e.*, the resistors between *A* and *C*, and between *A* and *E*, as well as resistor *D*, the current through each side of the bridge remains essentially constant—regardless of resistance changes in all other resistors. The currents through each side of the bridge are set at exactly 0.5 milliamperes by measuring the voltage across the very precise 100-ohm resistor, *D*, and adjusting the 10-K ohm rheostat, *G*, until the voltage across *D* reads exactly 50 millivolts.

The output signal from amplifier *H* is also the feedback. The current flows through the load connected to the output, such as a milliammeter, an electropneumatic transducer, a recorder or a final control element, and then back into the network through potentiometer *Q*. The output current is independent of any load resistance up to 20,000 ohms.

The thermocouple is connected to the input terminals. For zero amplifier output, terminals *M* and *N* must be at the same potential. This is initially accomplished by adjusting potentiometer *P*. If the thermocouple emf changes so that *M* becomes more positive than *N*, the amplifier output current rises. An adjustable portion of this current flows through the 11 ohm precision feedback resistor *Q* and raises the potential of *N* so that it can follow the potential of *M*.

The resistor between *A* and *C* is temperature sensitive. Embedded in close proximity to the resistor is the reference junction of the thermocouple. Since there is a fixed current of 0.5 milliamperes through this resistor, the size of the resistor can be chosen so that its voltage change with temperature matches the voltage generated by the reference junction of the thermocouple. Thus the voltage between points *M* and *N* will be independent of ambient temperature changes at the reference junction.

If the thermocouple should burn out or break, the 100 K resistor between *B* and *E* will cause the output of the transmitter to drift to full scale. The purpose of such thermocouple burnout features is described further down in this text.

Circular Charts and Strip Charts

There are two classes of recorders: circular charts and strip charts. The nominal diameters of circular charts are usually 10 and 12 inches, and the larger size is most frequently used. The actual calibrated radius is generally 3 1/2 to 4 3/4 inches. The conventional strip chart, as used with self-balancing potentiometers, gives a calibrated width of 2 to 3 times more.

In connection with potentiometers and other transmitters, miniature recorders as shown in Figure 1-13 are available. The calibrated chart width of such recorders is generally 3 to 4 inches which is slightly less than circular charts. The required panel space of such a recorder is, however, considerably less than standard circular chart recorders.

Where ease of *indicator* reading is of importance, the circular chart instrument is preferable because the circumferential pointer scale is 28 inches long, as compared with the 11 inches of straight scale in the strip-chart potentiometer recorder, and 3 or 4 inches in the miniature recorder. One of the exceptions to the chart dimensions as given here is the Brown Electronik 17 potentiometer. The chart on the circular chart recorder is 7 1/2 inches in diameter

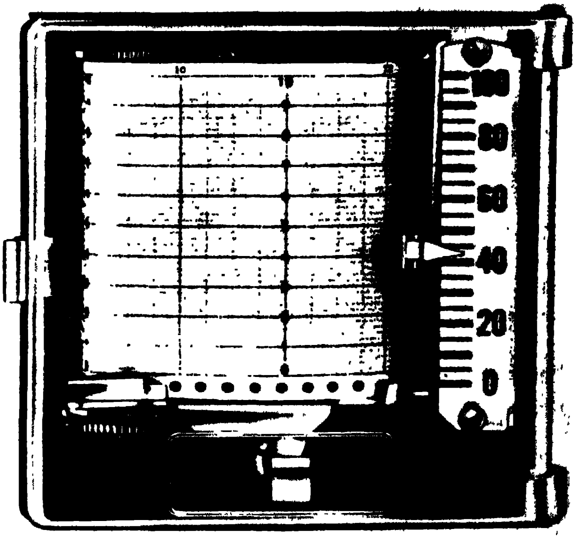


Figure 1-13. Miniature recorder (*Courtesy of Bristol Co.*)

and has a calibrated width of 3 1/4 inches. The concentric indicating scale is 20 1/4 inches long. The strip chart recorder has a calibrated width of 6 inches.

The most frequent speeds for circular chart recorders are 24 hours per revolution and 7 days per revolution. The driving power is provided by an electric clock. A spring-driven clock, as used in other types of instruments, has no practical advantage for an instrument which requires electric power for its measuring function. In the strip chart recorder, the chart drive motor is geared to the chart drive drums. The gear set is usually interchangeable so that a number of speeds can be chosen, and it is easy to change from one speed to another in the field. In the Weston Recording Potentiometer, for example, it is only necessary to loosen a screw, change to another leverage in the transmission, and fasten the screw again in order to obtain a different speed. This flexibility is an advantage of the strip chart as compared with the circular chart. It is true that it is also easy to change the chart drive for a circular chart, but generally this means that chart drives must be kept in stock for each speed desired. Interchangeable turrets are available to facilitate changing of speed for circular charts. They are described on page 47.

In a circular chart recorder, the closer the pen moves to the center of the chart, the shorter is the graph line for a given time. If the pen moves on a linear scale at about 2/3 of the chart range, *i.e.,* nearer to the edge of the chart than to the center, the length of the graph on a 24-hour, 12-inch chart will be about 24 inches a day, or 1 inch an hour.

Strip-chart potentiometer recorders usually have standard chart speeds of 1, 2, 6, 10 or 60 inches per hour. The faster speeds give better legibility of the graph, cost more in chart paper, and need more frequent replacement. Since chart rolls for these potentiometers usually come in lengths of 120 feet, a speed of 60 inches per hour means a new roll every 24 hours. The more conventional speed of 1 inch means a bi-monthly chart roll replacement.

The standard speeds with miniature recorder are 3/4, 7/8 or 1 inch per hour. Chart roll lengths are usually such that a monthly. replacement is specified.

Referring to a certain day on a strip chart is usually more cumbersome than looking for the particular circular chart. Also, where the chart record is to be passed on daily to some other party, it is better to use a circular chart than to cut off a daily record from the strip chart.

The strip chart is usually of sufficiently transparent material to make Ozalid or blueprint copies possible, while the circular chart material may be too dense. Furthermore, the choice of print colors should depend in this case on the ease with which they duplicate.

Multiple-point Instruments

Any pyrometer can be manually switched to a number of thermocouples, and consecutive readings can be taken. Suitable switches with terminals for all the thermocouples to be connected are available.

To obtain a continuous record on one chart from a number of thermocouples, one of several instruments can be used. The Bailey electronic-type recorder, for example, can be furnished for 1, 2, 3, or 4 continuous line records on the same circular chart. A separate amplifier and motor-driven slide-wire is used for each recording pen so that no switching devices are necessary. The amplifiers in this case are mounted on the rear of the recorder housing. The advantage of such an arrangement is that it eliminates all switching and consequent time differences between measurement of the different points. The pens are entirely independent and traverse the full width of the chart without interfering with each other. The graphs obtained are thus continuous and simultaneous measurements of the different variables. Some correction for time differences is, however, required on all those multiple-pen instruments which allow two or more pens to pass each other. This feature requires that one pen arm be slightly shorter than the other, and the consequence is that the graph of one pen will always be slightly ahead of the other. This time difference has to be considered when reading the chart, although it may become negligible as, for example, in the Bailey recorder, where the pens trace on arcs only 0.042 inch apart.

The so-called duplex recorders are furnished by a number of manufacturers. These recorders have strip charts and two independent measuring systems.

Each measuring system operates either over a separate 50 per cent of the chart width or in common over the full width of the chart.

The Foxboro Dynalog records up to twelve measurements on one circular chart, in as many as six different colors. Figure 1-14 illustrates the arrangement. A device called a pen cage is provided to which the pen arm moves to pick up one pen after another. The motion is caused by a cam driven from an electric motor. Every six seconds, the pen arm returns to the pen cage. Each time the cage shaft moves to the next position. The pen which is being returned is wiped off the arm, and a new pen is delivered to it. A small magnet on the end of the pen arm holds this pen until it is returned to the pen cage. Each pen is keyed to a characteristic color by a series of ink pads which are mounted on a drum and move in synchronism with the printing mechanism. While one pen moves into position to be picked up by the pen arm, the next pen is being inked by passing it over the corresponding ink pad.

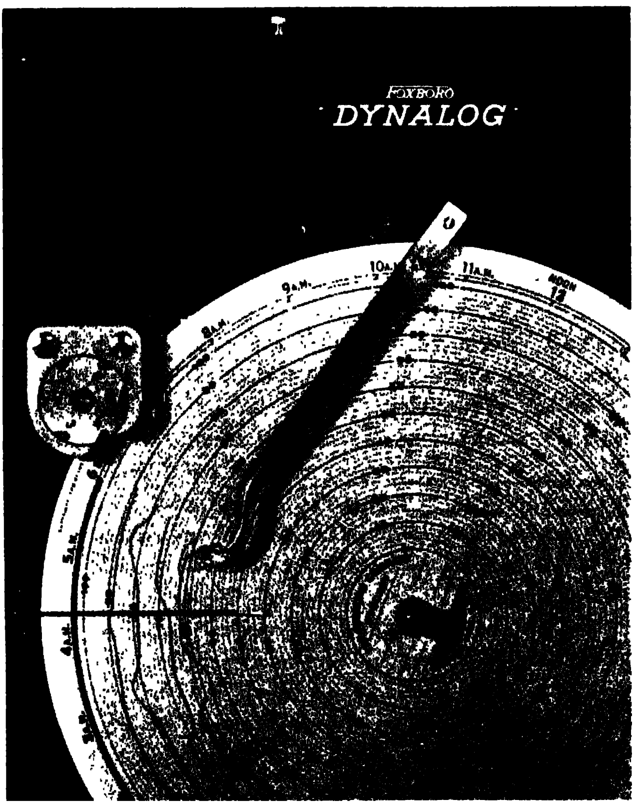


Figure 1-14. Printing mechanism of Dynalog. (*Courtesy of Foxboro Co.*)

As the pen cage turns, the commutator switch also turns and a new thermocouple is connected. The pen arm, which returns from the pen cage in a plane horizontal to the chart, is stopped at the measured value and now moves in a vertical direction toward the chart. As the pen touches the chart, it leaves a dot of ink at that point. In this fashion successive dots are printed so close together that a solid-appearing line record results.

The Brown Electronik multiple-record potentiometer, made by the Minneapolis-Honeywell Regulator Company, is typical of a number of similar instruments by different manufacturers. Up to 24 thermocouples can be connected and distinctly recorded on a single instrument. Special arrangements provide for even larger numbers of thermocouples but are rarely used for recording of temperatures of industrial processes. The print wheel carriage (Figure 1-15) moves along a shaft and is positioned by a balancing motor for the tempera-

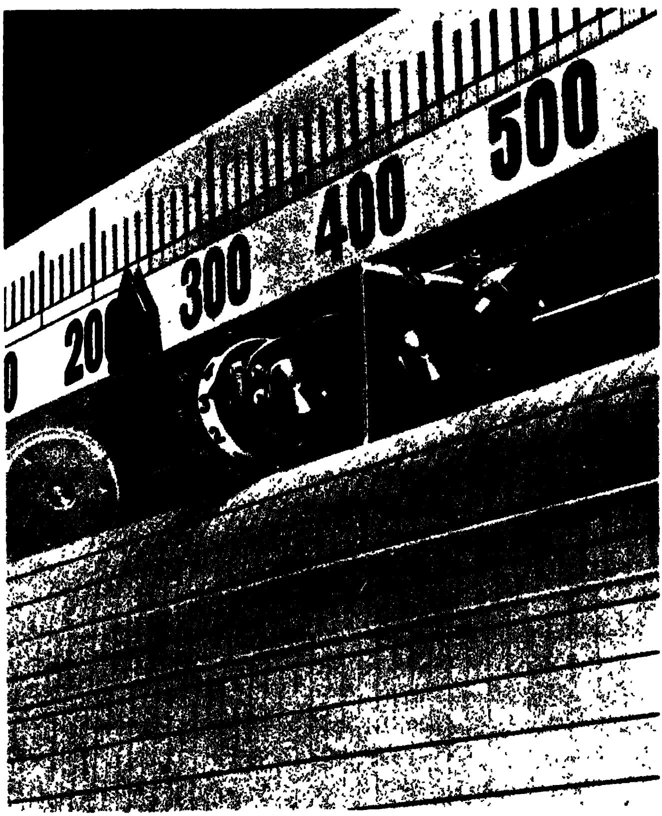


Figure 1-15. Print wheel of Brown Electronik. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

ture corresponding to the emf of the thermocouple connected. A continuously rotating motor-driven switch working in synchronism with the carriage connects one thermocouple after the other to the measuring mechanism. The carriage has a print wheel, ink pad wheel, moving pawl, actuating ratchet and gears. The whole assembly is mounted to a bar which is free to move up and down.

The so-called print bar channel, which extends parallel to the chart-drive drum, is periodically moved up and down by a gear train driven by the same motor that drives the chart. Each time the print bar channel goes through its cycle it lifts up the bar to which the printing wheel is fastened, thus bringing the print wheel into contact with the chart and printing the record. An over-travel spring permits the driving mechanism to continue its motion after the print wheel has contacted the chart. Thus the record is printed by the pressure this over-travel spring exerts on the print wheel. As the print wheel is moved back again, it is advanced to the next reading by a pawl and ratchet mechanism. At the same time, the thermocouple switch actuated from the same gear is advanced to the next thermocouple.

After each temperature reading up to 23, other thermocouples are scanned until the first temperature is picked up again. High speed in positioning the printing wheel and actuating it becomes necessary. Obviously, high speeds will wear down mechanical components faster and thus shorten the life. Typical available speeds are 1, 2, 4½, 12 and 24 seconds for full-scale travel. Even with a 1-second speed and a 12-point recorder, twelve seconds elapse between two successive readings from the same thermocouple.

To obtain maximum speed in printing, the fixed interval which allows for a possible full-scale travel of the print wheel becomes a hindrance, and a much shorter interval would suffice where two successive prints are close together. Therefore, on very fast instruments the printing intervals are no longer fixed. In the Brown synchroprinting arrangement each point is printed as soon as the instrument comes into balance. To accomplish this the balancing motor co-ordinates the positioning motion of the print wheel carriage, while the printing motion is caused by the gear train connected to the chart drive motor. As soon as the balancing motor stops, the printing mechanism is released to operate without delay.

Records of multiple-point instruments distinguish between the different points by several methods—most frequently by printing different numbers with each point or else by using different colors.

The possibility of printing one record on top of another must be considered in selecting the chart speed for multiple-record instruments. Too slow a chart speed will produce illegible records due to overlapping of successive printings. These overlappings may be either successive prints of the records of a single point or records of two (or more) points which approximately coincide at the same place on the chart. To alleviate this situation, Bristol and others prefer multicolored dot printings (at least up to 6 points) to number printing. It is easier to distinguish between different colors than to read correctly overlapping numbers printed in a single color.

Where single-colored numbers are used, the slowest non-overlapping chart speed should be calculated. Knowing the space that each numbered printing requires, the number of points, and the printing interval, it is possible to obtain the chart speed. For example, in a Bristol Dynamaster, the chart space required for each printing is 1/16 inch. To determine the chart speed for a 4-point recorder with 30-second printing intervals, without having the four records crowded together on the chart, the following calculation is made:

$$\text{Minimum chart speed} = \frac{1/16 \times 3600}{4 \times 30} = 1.875 \text{ in./hr.}$$

The multiplier 3600 is used to convert from seconds to hours.

Bristol's Dynamaster multiple-bank recorder will record up to 200 separate variables on a 12-inch strip chart. For each bank of 20 points, the recorder prints a bank-identification number in the left-hand margin of the chart. A selector switch is provided for "indicate only," "print continuously" or "print only on alarm condition."

Special Recorders

The conventional recorder or indicator is provided with only one temperature range. However, it is occasionally a requirement that a small part can be switched to a narrower span, making it possible to use the equivalent of an enlarging glass for one fixed portion of the range. The dual-range switch makes this possible by permitting coverage of a normal span of temperatures for ordinary operation, but permitting a switch to a narrow span when close observation becomes necessary. An instrument with a dual-range switch also can be used for two altogether different ranges. In this case, one range is used for one thermocouple, and the switch permits changing over to a second thermocouple with a different range of measurement. This method can be expanded to multiple-range switches with 4 to 15 narrow steps, allowing extremely close readings throughout the total range. The steps may be overlapping or may be widely separated, and need not be of the same width.

Two-speed chart drives automatically increase the chart speed when the measured variable passes some predetermined set point. When the variable returns, the chart speed is reduced to its original value. In one specific Brown model, the speed is multiplied by a factor of 30 or 60.

Another special recorder, the function plotter, may be mentioned. A *standard*, conventional strip chart is in effect a graph of temperature versus time. The chart drive motor furnishes the time variable, the balancing motor the temperature variable. In some cases, however, what is desired is a graph showing the relation between two temperatures—illustrating how one changes in relation to the other—rather than a time-temperature graph. The complication is that the increments of *time* which a *standard* instrument takes into consideration are equal and additive throughout. If time is replaced by a *temperature* variable, this condition is no longer fulfilled. However, the function plotter permits such a graph of two variables: the linear *time* variable is replaced by an arbitrary second *temperature* variable. The chart drive motor is no longer unidirectional but is controlled by the second variable, just as the balancing motor is controlled by the first variable. The chart will move up or down in response to the signal from the second variable. The pen thus represents the magnitude X in a rectangular coordinate system. The chart position corresponds to Y, and the net result from the simultaneous operation of both systems is a continuous plot of Y as a function of X.

The same principle is used in plotting polar coordinates on a round chart.

Reference Junction Compensation

Theoretically, the temperature of the reference junction in a thermocouple instrument must be constant if the instrument is to indicate the correct temperature of a thermocouple. However, since the reference junction is usually located in the instrument case, the temperature of the reference junction will be subject to minor changes. Several methods for compensation of such temperature changes are available.

One method is to use a temperature-sensitive compensating resistor in the measuring circuit. This resistor is located close to the reference junction so that both are equally affected by any change in ambient temperature. An example was illustrated in Figure 1-12. When the emf output of the thermocouple drops because of an increase in the temperature of the reference junction, the resistance of the compensating resistor rises. The circuit is arranged so that the increased value of the resistor compensates for the decrease of the thermocouple output.

In multiple-point instruments, it is necessary to place the different reference junctions as close together as possible and provide thermal masses in close contact with them so that all will be equally affected by temperature changes, and so the compensating action of the resistor may be of equal effect on each point being measured.

Another method of reference junction compensation is to keep the reference junction at a constant temperature by locating it in either an ice bath or a kind of miniature oven which is heated and kept at a constant temperature. In the latter case, the heat is supplied by an electrical heater resistor which is part of the electronic circuit, and the current through this resistor is modulated by means of a resistance thermometer, with the temperature-sensitive element surrounding the oven heater resistor.

In the Foxboro Dynalog, reference junction compensation is obtained by adjusting a small voltage in series with the standard cell by means of a temperature-sensitive resistance bridge.

Scope of Potentiometer Application

The electronic potentiometer was developed in connection with thermocouple applications, but today it has far surpassed this limitation. It is a highly accurate, extremely sensitive, and surprisingly powerful and rugged instrument for measuring small electrical potentials; these frequently lie far below the thermocouple outputs, but can be fed into electronic potentiometers either directly or through a preamplifier. It is perhaps the first instrument to have been developed for industrial applications and later used in laboratory work—the reverse of the normal procedure.

THERMOCOUPLES

The following list shows the most common metals and their combinations together with symbols as used in commercially available thermocouples:

Thermocouple			Thermocouple Systems		
Combination	Positive Wire	Negative Wire	Combination	Positive	Negative
Iron-constantan (type J)	Iron	Constantan	J	JP	JN
Chromel-Alumel	Chromel	Alumel	K	KP	KN
Platinum/10% rhodium-platinum	Pt., 10% Rh	Platinum	S	SP	SN
Platinum/13% rhodium-platinum	Pt., 13% Rh.	Platinum	R	RP	RN
Copper-constantan	Copper	Constantan	T	TP	TN

Calibration standards for these thermocouples have been published by the National Bureau of Standards. The standards refer to the emf output versus the temperature difference between measurement and reference junction. These characteristics depend on the metallurgical composition of the thermocouple wires. Therefore, to obtain an output according to such calibration, matched wires are required; any iron wire cannot be combined with any constantan wire; but rather a particular combination is required to furnish the correct calibration. The same holds true for any thermocouple combination.

Constantan is an alloy of approximately 55 per cent copper and 45 per cent nickel. Chromel* is an alloy of approximately 90 per cent nickel and 10 per cent chromium. Alumel† is an alloy of approximately 95 per cent nickel, 5 per cent aluminum, manganese, and silicon. Thermocouples containing platinum are called noble-metal thermocouples, and all the others are known as base-metal thermocouples.

Figure 1-16 shows the emf output versus the temperature of five of the thermocouples listed in the above table. These curves are not entirely linear and the instrument scales have to be calibrated accordingly. Consequently, the instrument should always correspond to the type of thermocouple with which it is used.

The choice of a thermocouple depends mostly on the temperature for which it is used. Figure 1-16 shows the approximate temperature ranges. Tempera-

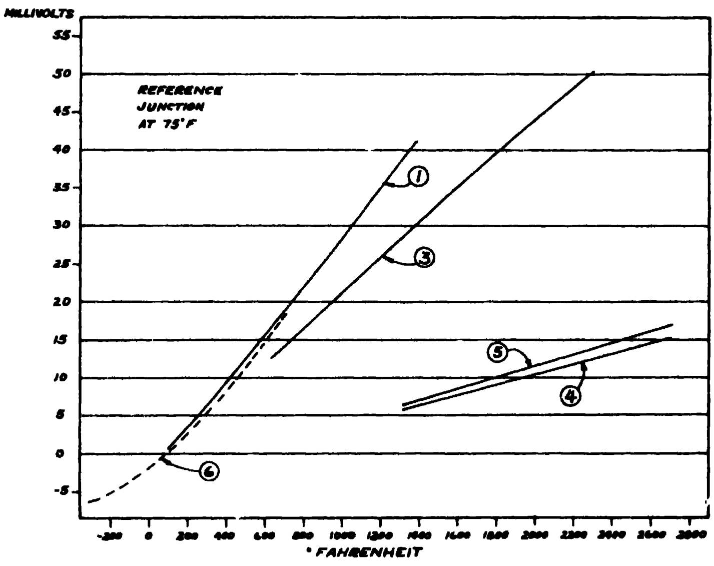


Figure 1-16. E.m.f. output of thermocouples *versus* temperature.

ture limits are determined not only by the material, but also by wire gauge, whether there is intermittent or continuous use at maximum temperature, and whether the bare thermocouple or a protection tube or well is provided. The maximum temperature should be applied only to thermocouples of the heaviest wire (on wire thicknesses see further below) and for use with protecting tubes.

If the thermocouple is used without protection (which should be avoided

*Trade name, Haskins Manufacturing Co.
†Trade name, Haskins Manufacturing Co.

whenever possible), or if the protection is not gas-tight, the chemical reaction of the thermocouple must be considered. In clean oxidizing atmospheres, Chromel-Alumel should be used; in reducing atmospheres, iron-constantan. Copper-constantan, which is the favorite in low temperatures (to −300°F) can be used for slightly oxidizing and reducing atmospheres.

Chromel-Alumel thermocouples are very sensitive to sulfur in the atmosphere. This condition exists with some types of fuels and adequate protection must be provided. Care should be taken that neither the protection itself nor the wire insulation contains any reducing agents which might be liberated at high temperature and contaminate the thermocouple. When such thermocouples are used in oxidizing atmospheres, it is advisable to use vented tubes to prolong their life.

Noble-metal thermocouples cannot be used without a ceramic protection tube if Chromel-Alumel is the only base metal that can be used in this range (but not above 2300°F), though a heavy No. 8 AWG wire is required in this case. Noble-metal thermocouples cannot be used without a ceramic protection tube if reasonable life and accuracy are expected. In a reducing atmosphere the tube must be absolutely gas-tight and should not contain silica. The precautions taken with a noble-metal thermocouple are all the more convincing when it is considered that a single bare couple 24 inches long costs 15 to 20 times as much as a base-metal couple of equal size.

For measurement of temperatures above 2700°F and up to 4000°F, a number of special thermocouples are available. They include iridium-iridium/rhodium, iridium-tungsten, rhenium-molybdenum, rhenium-tungsten and other combinations. The major problems of these thermocouples are rapid deterioration and adequate insulation and protection tubes that can withstand the high temperatures.

Wire sizes as recommended by the Instrument Society of America are:

For iron-constantan and Chromel-Alumel. Nos. 8, 14, 20, 24, and 28 AWG, in inches of diameter, 0.1285", 0.06408", 0.03196", 0.0201", and 0.01264"

For copper-constantan. Nos. 14, 20, 24, and 28 AWG.

For platinum/rhodium-platinum. No. 24 AWG only.

Where maximum responsiveness is required, a very fine wire should be used. If longer life is wanted, particularly when the thermocouple works toward its upper temperature limit, the heavier gauge is recommended.

The accuracy of the actual thermocouple reading is affected by a number of factors. Since the thermocouple indicates its own tip temperature, a difference may exist between this temperature and the one it is to measure. This difference is most frequently caused by either one or both of two different conditions. One is that the thermocouple wire itself is a good thermal conductor and has therefore a continuous cooling effect on the thermocouple tip. This effect and the consequent error increases with wire size; the heavier the wire the more heat it will conduct away from the thermocouple tip. To reduce this error finer wire and deeper immersion in the measured fluid or solid is required. Insulators should be kept a reasonable distance from the thermocouple tip to prevent heat being carried away by them.

Radiation is the other condition that causes a difference between the thermocouple tip temperature and the measured temperature. For example, radiation may pass from the thermocouple to the furnace walls, which are at a lower temperature, and thus make the thermocouple read low; or radiation may be absorbed by the thermocouple, as from luminous flames, and cause the thermocouple to signal a temperature above the correct value. The answer to this condition is adequate shielding of the thermocouple.

The shortcomings of the thermocouple so far mentioned are those which occur in its application. Assuming that these can be eliminated, there remain errors that are inherent in the thermocouple itself. According to the Recommended Practices on Thermocouples of the Instrument Society of America, measurement inaccuracies should be limited in *new* thermocouples to the following values:

Type of Thermocouple	Temp Range (°F)	Limit of Error	
		Standard	Special
Iron-constantan	0 to 530	± 4°F	± 2°F
	530 to 1400	± 3/4%	± 3/8%
Chromel-Alumel	0 to 530	± 4°F	
	530 to 2300	± 3/4%	
Platinum/rhodium platinum	0 to 1000	± 5°F	
	1000 to 2700	± 1/2%	
Copper-constantan	− 300 to − 150	—	± 1%
	− 150 to − 75	± 2%	± 1%
	− 75 to +200	± 1 1/2°F	± 3/4°F
	200 to 700	± 3/4%	± 3/8%

The accuracy of any thermocouple depends on the homogeneity of the material. Any mechanical working, bending, twisting, or hammering will cause calibration changes. Repeated heating or cooling, or even short exposures to temperatures beyond the operating limits, will have the same effect. Excessive vibration also has adverse effects.

It is always preferable to protect a thermocouple (although the responsiveness is decreased) in order to reduce the possibilities of mechanical damage and contamination. Protecting tubes and wells are used for this purpose. A protecting tube is defined by the Instrument Society of America as "a closed-end tube adapted to receive the measuring junction of a thermocouple, designed for attachment to a connection head and not primarily designed for pressure-tight attachment to a vessel." A well is defined as "a pressure-tight receptacle adapted to receive a temperature-sensitive element, provided with external threads or other means for pressure-tight attachment to a vessel." Wells are used in pressure vessels and pipe lines.

Protecting tubes are either metallic or ceramic; wells are generally metallic. A large number of materials is available, the choice generally being determined by the atmospheric conditions to which it is exposed. Noble-metal thermocouples require special consideration because they are sensitive to metallic vapors which can be produced inside a metallic well or protecting tube and require therefore the use of ceramic tubes. Since ceramic tubes are fragile, they are frequently used with a second protecting tube made of metal.

Protecting tubes and wells introduce a considerable lag in temperature measurement. The thermal resistance of the material is generally a very small proportion of the over-all resistance. The more serious contribution is due to the gaseous film on the outside and inside of the tube, and to the air cushion between thermocouple tip and tube wall. The errors due to radiation and conduction of heat are also considerably greater, since area and mass are increased.

To obtain thermocouples of quicker response without giving up their mechanical protection, various methods were developed. Figure 1-17 illustrates

Figure 1-17 Bristol's Armorox thermocouple.

Bristol's Armorox thermocouple with grounded junction. This is a metal-sheathed ceramic-insulated construction. The standard sheath materials are type 304 stainless steel and "Inconel." While this gives the desired mechanical protection, it does little to impair the speed of response since there is no air space between measuring junction and protection tubes. Furthermore, by imbedding the thermocouple in reactor grade magnesia with a maximum impurity of 10 parts per million, the use of very small gauge wires becomes possible even at high temperature without detriment to the life expectancy. Any of the standard thermocouples, can be used and the diameters of the sheaths range from .025 to .312 inch.

Another approach to quicker response of thermocouples with protection tubes is the pipe or pencil-type thermocouple. The Foxboro Pyod couple is of this kind (Figure 1-18). It is an iron-constantan thermocouple where the iron element is tubular in form and 9/16 inch in outside diameter, the constantan element being heavily insulated and fully enclosed. In this way, the iron element serves as a protector for the constantan element (the weaker of the two). At the

Figure 1-18. Foxboro's Pyod thermocouple.

same time, the heavy iron tubular element, with walls approximately as thick as the diameter of a No. 8 gauge wire, is exposed to oxidation only on the outside. The inner walls of the tube remain pure, uncontaminated and accurate throughout the working life of the couple. In addition, mechanical strength is greater. Pyod couples can be used without protection in temperatures up to 1050°F. This means faster response to temperature changes.

The thermocouple is connected to the instrument itself by means of extension wires which have thermoelectric characteristics similar to those of the respective thermocouple wires. The head of a thermocouple assembly contains a rather heavy ceramic terminal block with large terminals, in which are inserted the thermocouple wires from one side and the extension leads from the other. This construction reduces the possibility of temperature differences at the two connections as much as possible. This is necessary because otherwise thermocouple characteristics may be introduced at the terminals and produce errors in reading. The terminals are also designed to provide a solid contact between wires, since the introduction of resistance would provide another error source.

Thermocouple Burnout Feature

The emf which a thermocouple generates decreases with decreasing temperature. In a controller, the response to a decreasing emf signal is to increase heat input to the process. In the case of a burned-out thermocouple, no emf is put out; the pointer of the instrument goes down-scale and the danger exists that a maximum heat input to the process takes place because the thermocouple is out of order.

In most controllers which receive their signal from a thermocouple, some method similar to the general principle illustrated in the diagram of Figure 1-19 is used.

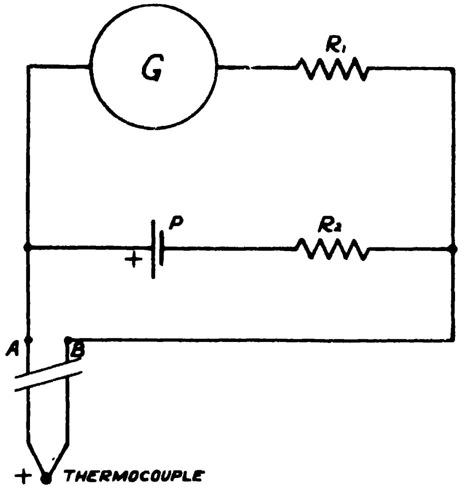


Figure 1-19. Schematic of thermocouple burnout feature.

The magnitudes of the resistors, etc. as used in the following are not necessarily actual, but serve for illustration. Let the combined resistance of the galvanometer G and the calibrating spool R_1 be 500 ohms. Let the resistor R_2 be 5000 ohms and the power source P be 1 volt. The resistance of the thermocouple, together with its connecting wires to A and B, is assumed to be 1 ohm and is called R. The voltage drop across the thermocouple plus the lead wires connecting to terminals A and B due to current from P is equal to $[P/(R_2 + R_3)]R_3$ which is equal to approximately 0.0002 volt or 0.2 millivolt. It requires about 7°F temperature difference to obtain enough emf output from the thermocouple to cancel this voltage, and the instrument can readily be calibrated to compensate for this linear shift. Under this condition no emf due to P is indicated in the galvanometer G.

In case the thermocouple wire opens, the bucking effect to the output from P disappears, and the result is that a current flows through R_1 and the galvanometer. The voltage drop caused by this current across the galvanometer and the calibrating spool is then $[P(R_2 + R_1)]R_1$ or 0.091 volt, *i.e.,* 91 millivolt.

This is higher than normally can be obtained from a thermocouple. The galvanometer consequently will read high and controls will shut down the heat.

The G.E. pyrometer thermocouple burnout feature is illustrated in Figure 1-20. It shows one of the variations of the principle described above. The secondary winding of a transformer with an output of 6.3 volts is connected in series with a rectifier. This produces a pulsating d.c. voltage which is applied

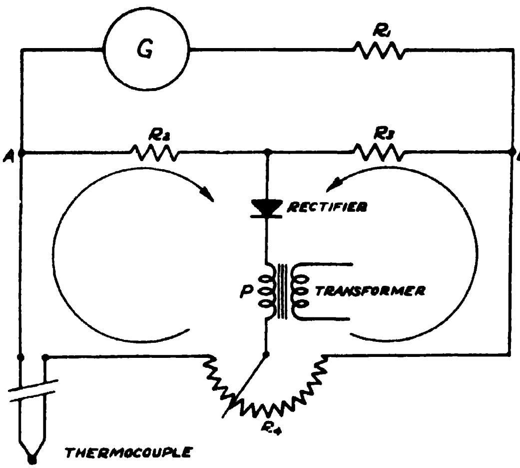


Figure 1-20. Schematic of G.E. thermocouple burnout feature.

to a Wheatstone bridge formed by resistors R_2 and R_3 and resistor R_4, which is divided into two parts by a sliding contact or wiper. The thermocouple is part of this bridge circuit. Circular currents as indicated by arrows in the illustration will flow due to the power source P. The variable resistor, R_4, can be adjusted so that no voltage differential exists between A and B for the lower limit of the temperature indicating instrument. Under these conditions no current will flow through G and R_1. A change of emf output from the thermocouple, however, will produce a corresponding voltage differential between A and B, which is measured by the galvanometer G. If the thermocouple opens, the left-hand circular path for current from P no longer exists, the balance is destroyed, and current from P flows through G, driving the pointer to the high side and actuating the controls accordingly.

RADIATION PYROMETERS

The thermocouple as described above is in direct physical contact with the hot substance the temperature of which is to be determined. In the ideal case it obtains all the heat it measures by conduction. The instrument reads the temperature of the thermocouple. Since this means that the thermocouple must become as hot as the measured material, there are limits of temperature beyond which the thermocouple cannot be applied. Furthermore, conduction is a slow process, especially when the thermocouple is equipped with a protection well, as it usually is. Rapid measurement is almost always desirable and sometimes essential.

By measuring radiation, instead of conduction, a considerable increase of speed in measurement can frequently be obtained. Furthermore, it is no longer necessary to expose the sensing element directly, since it can view the hot body from a distance and convert the effect of radiation into temperature; hence higher temperatures can be measured.

Radiation here refers to energy emitted from a hot body through a wide spectrum of wavelengths that covers the ultraviolet, visible, and infrared regions from about 1/100 to 100 microns (1 micron = 10^{-4} cm). A radiation pyrometer can be sensitive to the whole spectrum or to only a part of it. In the latter case it is called an optical pyrometer. Although, strictly speaking, both radiation and optical pyrometers measure radiation, one over a more limited spectral band than the other, common terminology refers to a radiation pyrometer, and means either the whole class, including the optical pyrometer, or the radiation pyrometer in particular as distinguished from the optical pyrometer. The monochromatic optical pyrometer uses a rather dense red filter which eliminates all wavelengths but that pertaining to one color. What remains is monochromatic light, the intensity of which is expressed in brightness.

The monochromatic optical pyrometer measures the temperature of a hot body from a determination of the brightness of the surface under measurement. It has wide application as a portable instrument. Its operation consists in manually matching the intensity of two light sources viewed in the pyrometer. One source is the hot body, the other an electric lamp bulb in the measuring device. The brightness of the lamp bulb can be adjusted by manipulating an electrical resistance in series with it. The amount of adjustment required to match the intensity of the two light sources is a measure of the temperature. The use of monochromatic light eliminates the factor of individual differences in color judgment or color sensation.

The two-color pyrometer is an optical pyrometer which differs from the monochromatic type in using two different wavelengths from the same radiation source. The Pyro-Eye made by the Instrument Development Laboratories is such a two-color pyrometer. Its schematic is illustrated in Figure 1-21. The object at which the Pyro-Eye is directed to measure its temperature is called the target. Radiation from the target enters through the objective lens and passes through another lens to the partially transparent mirror, *A*. This mirror re-

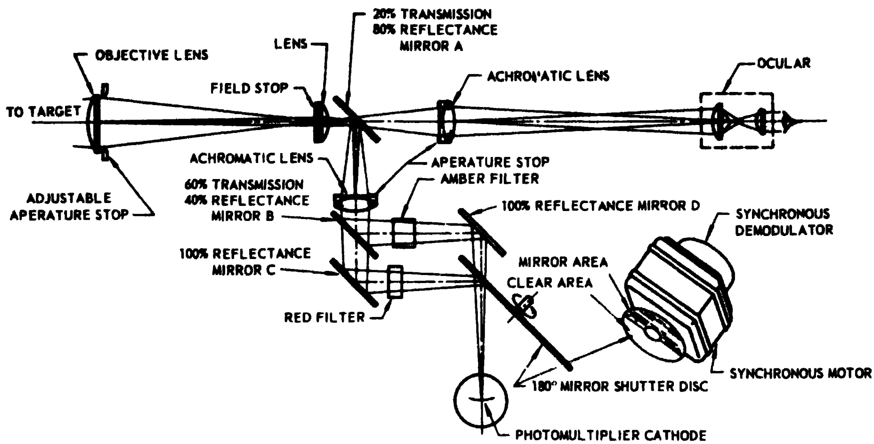


Figure 1-21. Optical schematic of Pyro-Eye.

flects 80 per cent of the radiation. The remaining 20 per cent continues horizontally through an achromatic lens to an eye-piece, a so-called ocular. The operator can observe the target through the ocular and thus aim the instrument properly. Once in position the instrument is locked and the ocular is no longer needed except for checking.

The 80 per cent reflected radiation passes from mirror *A* through another achromatic lens to mirror *B*. The latter distributes 60 per cent to mirror *C* and 40 per cent to mirror *D*. Hence, mirror *B* breaks up the radiation signal into two components—one for mirror *C*, the other for mirror *D*. One component passes through an amber filter, the other through a red filter. Thus, two signals of different wavelengths are obtained, both being proportional to the temperature of the target.

The synchronous motor rotates a shutter disc. Half of this disc is translucent; the other 180 degrees have a mirror surface. Hence, while this disc rotates it lets radiation pass from mirror *D* to the photomultiplier cathode during half of its revolution, and reflects radiation from mirror *C* to the photomultiplier cathode during the other half of its revolution.

The photomultiplier cathode is part of a photomultiplier tube from which an electrical signal is obtained that is proportional to the incident radiation. The photomultiplier tube has some drift, which means that for the same incident radiation, different electrical signals may be obtained at different times. One of the main reasons for having two filters, one amber and one red, is to make the drift effect negligible. Due to these filters the radiation to which the photomultiplier tube is exposed is limited to two narrow bands of different wavelengths. Alternately, it is exposed to one or the other band. It is thus made to measure essentially the ratio of the target radiation between two wavelengths rather than the radiation of a single source. Drift of the photomultiplier tube thus becomes of negligible effect for the measurement. Another important reason for this method is to reduce the errors caused by target emissivity which is discussed further below.

The radiation pyrometer is sensitive to the total energy emission of the hot body. Figure 1-22 shows the Leeds & Northrup Rayotube—an example of a

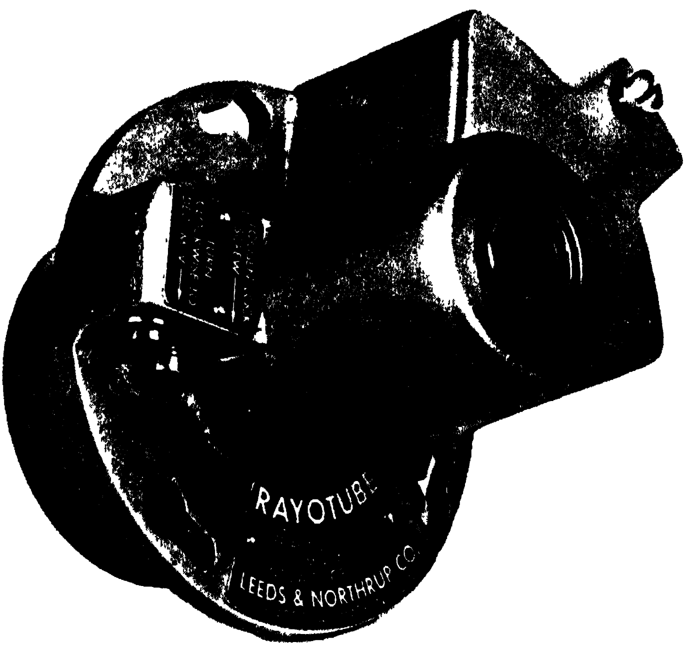


Figure 1-22. Rayotube. (*Courtesy of Leeds & Northrup Co.*)

typical measuring unit. The radiation pyrometer is basically a thermocouple instrument, but instead of bringing the sensing element into the greatest possible physical contact with the hot body, separated only by a protecting tube or well, the measuring element of the radiation pyrometer is contained in a tube which is "sighted" on the body from a distance, thereby receiving what is commonly known as radiant heat. The amount of radiant heat absorbed by the thermocouple must be sufficiently large to yield an emf which is measurable by either a millivoltmeter or potentiometer of the types previously described.

Two methods are used for this purpose. One is to multiply the response by connecting several thermocouples in series. Such an arrangement of thermocouples is called a thermopile. Since to each measuring junction of a thermocouple there is a corresponding reference junction, it would be cumbersome to extend all these wire connections to the instrument. Instead they are mounted in the sighting tube, but are not within reach of the radiation. As long as no radiation is received, both measuring junctions and reference junctions are at the same temperature. When they are exposed to radiation, the temperature of the measuring junctions will rise by an amount determined by the temperature of the hot body. The emf generated is therefore relatively independent of the temperature at the reference junctions.

However, errors can be produced. They are due mainly to two conditions. One is related to the fact that the emf output of a thermocouple is not a *linear* function of the temperature difference between measuring junction and reference junction. In a radiation pyrometer, measuring junction and reference junction are exposed to the same ambient temperature. In addition to this the measuring junction receives the radiation from the hot object of which the temperature is measured. The increase of emf per degree of change of measured temperature is different at an ambient temperature of 300°F than it is at an ambient temperature of 60°F. Hence, if reference and measuring junction are both exposed to the same ambient temperature, it is the level of this temperature that determines how the instrument is to be calibrated to convert into accurate temperature readings the emf produced by radiant heat striking the measuring junction. In view of this condition the sighting tube must be kept within certain ambient temperature limits. Water- and air-cooling can be used for this purpose.

The other error source is due to temperature gradients that may exist within the sighting tube and result in an emf between measuring and reference junction. This is particularly likely to occur when low temperatures are measured. The temperature increase at the measuring junction produced by the radiant heat is in this case extremely small, and a temperature gradient can cause a considerable error. Therefore, many radiation pyrometers employ reference junction compensators of the kind previously described. In low-temperature applications (125 to 700°F) a temperature control unit is used. This is done, for example, in the low-range Radiamatic made by Minneapolis-Honeywell Regulator Company. The shell that surrounds the measuring element is electrically heated. A resistance thermometer monitors the temperature that is maintained within ± 1°F for a pre-selected value.

The lead wires that connect a thermopile to the instrument are ordinary copper wires, since the reference junctions are not extended to the instrument.

Another method of intensifying the emf output is the use of a lens which focuses the radiant heat on the measuring junctions. Practically all sighting tubes contain such a lens. The intensification with a lens of short focal length might be sufficient to allow the use of a single thermocouple instead of a thermopile. This is the case in the Bristol Pyrovisor which has a single Chromel-Alumel thermocouple. The measuring junction is an extremely thin foil strip 2 mm wide and 9 mm long, and is mounted in an evacuated glass bulb. Because this thermocouple junction is sealed in a vacuum, loss of accuracy due to oxidation or contamination is eliminated and the permanence of calibration of the unit is assured. The reference junction in this case is located in the measuring instrument.

The end of the sighting tube is either open or closed. In the latter case, the radiant heat from the closed end is measured as an indirect expression of the temperature to be determined. The open-end tube is sighted directly on the hot object; for this purpose a sighting hole is provided in back of the tube, as visible in Figure 1-22, to permit observation of the hot object as it is focused by the tube. A large number of accessories are available, including air- and water-cooling jackets and safety shutters which protect the open-end tube against flame impingement. The latter has a fusible link that normally keeps the shutter open. Under excessive temperature the link melts and the shutter snaps into its closed position.

Any radiation pyrometer, including the optical pyrometer, is accurate only under blackbody conditions, *i.e.*, where the radiation of the hot body is completely absorbed by another body which encloses it. Such a body is a perfect radiator of energy and is said to have an emissivity of 1.0. The emissivity is used as a factor to express the relative amount of radiation that is emitted by any body as compared to the ideal blackbody. For example, copper at 1110°F has an emissivity of about 0.57; gray oxidized lead, about 0.28. A number of bodies closely approach 1.0, and for practical purposes can be considered as blackbodies. This is true for the insides of furnaces and kilns, the sides of which are heated.

The radiation pyrometer can well be used for non-blackbody conditions by means of either correction factors for the reduced emissivity or by reading temperatures rather for comparison than for their absolute value.

The advantages of a radiation pyrometer are mainly the high temperature range for which they can be used and the high speed of response which is characteristic for them. The Honeywell high-speed Radiamatic, for example, responds to 98 per cent of a temperature change within 0.5 second. Further reasons for choosing a radiation pyrometer include its ability to measure the actual surface temperature of an object in a furnace, rather than the atmospheric temperature of the furnace, as well as the possibility of measuring temperatures of moving objects and at points which cannot be reached with a conventional thermocouple.

RESISTANCE THERMOMETERS

The electrical circuit of a resistance thermometer, as illustrated in Figure 1-23, is a Wheatstone bridge. A change of resistance in any one of the four legs will be indicated by a current flow through the detector. Since the resistance of an electrical conductor changes with temperature and since small changes of resistance can be positively detected by the Wheatstone bridge, only the combination of these two phenomena is needed to produce a temperature-measuring instrument.

The resistance thermometer bulb, corresponding to resistor *B* in Figure 1-23, is made of a material with a high temperature coefficient, which means that it changes its electrical resistance by a relatively large amount with a given change in temperature. Resistances *a*, *b*, and *C* are made of material whose resistance is practically constant under normal temperature changes. Resistor *B* is therefore the only variable, and its variations are a function of temperature change. Thus the instrument can be made to indicate the temperature that exists at resistor *B*.

If no precautions were taken, the change of resistance in the connecting wires with changes in ambient temperature would unduly influence the reading. Figure 1-23 shows one arrangement for reducing such errors to a minimum, by

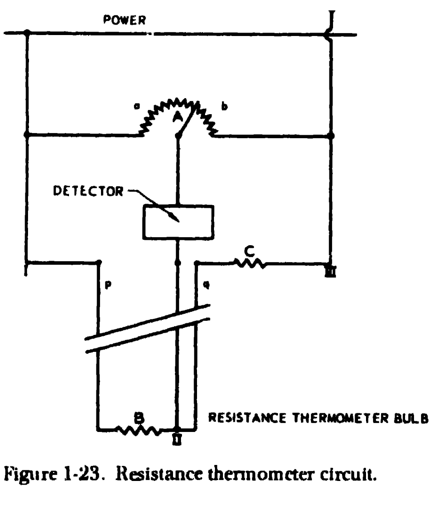


Figure 1-23. Resistance thermometer circuit.

providing three connecting wires rather than two. I, II corresponds to one leg of the bridge and II, III to the other, while *p* and *q* are the respective connecting wires between resistance thermometer bulb and instrument. Any change in *p* because of ambient temperature changes will correspond to an equal change in *q*, provided that both wires are of the same size, material, and length, and are run close together. The ratio of p to q will thus be always the same and will not affect the reading. The ratio of B to C, however, will change and determine the unbalance of the bridge.

Strictly speaking, the foregoing is not quite correct. The balance of the bridge depends on the ratio of the total resistance in the two legs, and this ratio is expressed by $(p + B)/(q + C)$. If B and C are unequal, and p and q increase by an equal amount, the ratio changes, and is not stable as assumed above. This change, however, will be smaller than if only p changed. Furthermore, p and q are small compared with B and C, and the error becomes negligible.

Minor changes of the resistance in the middle wire, connecting the resistance thermometer bulb and the instrument detector are of no consequence for the following reasons: the small emf that appears across the instrument detector with an unbalance in the Wheatstone bridge as caused by the temperature response of the resistance thermometer bulb can be measured by any millivoltmeter or potentiometer. If a millivoltmeter is used, the resistor, A, is only for the initial adjustment. With a potentiometer the balancing motor will adjust A for each unbalance and thus rebalance the circuit. As long as the deflection method of the millivoltmeter is used, the high resistance of the instrument makes negligible the small changes of resistance in the connecting wire which might be caused by changing ambient temperature. When a potentiometer is used, the balancing action always reduces the current in the connecting wire to zero, which again leaves the resistance change without effect.

The double slide-wire arrangement used by Leeds & Northrup (Figure 1-24) in connection with a potentiometer eliminates the effect of resistance changes in connecting wires completely. The two slide-wires, A and D, are mechanically linked and the automatic balancing action of the potentiometer consists in adjusting the slide-wires simultaneously. The linkage between the slide-wires is such that in any position the sum of resistances b, g, and d is equal to the sum of resistances C and e or, in other words, the ratio of these two sums is always equal to 1. For the bridge balance it is required that $B/(f + a) = (C + e)/(b + g + d)$ or, in this particular case, that $B/(f + a) = 1$. Hence, the two legs to which connecting wires p and q belong will always be equal to each other under balanced conditions. Resistances p and q may change their value under the influence of atmospheric temperatures. As long as they are equally affected this will not change the reading of the instrument.

The resistance thermometer bulb is usually made of platinum or nickel wire, and sometimes of copper. Any material selected for this purpose must have a reasonable high temperature coefficient which will remain constant during the life of the bulb. Its change of electrical resistance as a function of temperature should follow a curve which is easily reproducible in the manufacture of the bulb. A certain amount of nonuniformity in this relationship can be overcome by calibration, as described below for the Foxboro Dynatherm bulb. Choice of

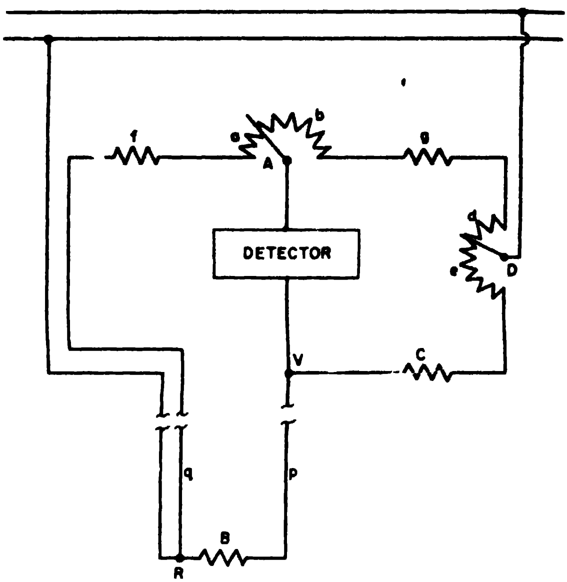


Figure 1-24. Double slide-wire bridge.

a particular metal depends to a certain extent on the temperature range within which the resistance thermometer bulb is to be used; the Leeds & Northrup Thermohm, for example, uses copper and nickel up to 250°F, and platinum up to 1000°F.

Resistance thermometer bulbs are either tip-sensitive or stem-sensitive. Figure 1-25 is a cutaway view of the stem of a stem-sensitive detector made by

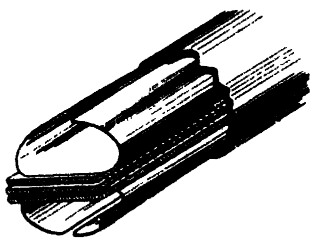


Figure 1-25. Resistance thermometer bulb. (*Courtesy of Thomas A. Edison, Inc.*)

Thomas A. Edison, Inc., which makes both types. The spring provides a resilient cushion against vibration as well as close thermal contact with the shell on one side and with the sensitive winding through the mica insulation on the other.

Potentiometers used with resistance thermometer bulbs are somewhat modified as compared to those used with a thermocouple. The thermocouple produces its own emf which is balanced by a known emf in the potentiometer. The resistance thermometer is a bridge arrangement where the potentiometer adjusts for any urbalance; hence no standard cell and standardization or equivalent equipment are required. The detection of the unbalance and the methods for reestablishing the balance are identical however; and basically the same instruments apply to resistance thermometers as to thermocouples.

Figure 1-26 shows a schematic diagram of a Foxboro Dynalog connected to a Foxboro Dynatherm, a detail of which is illustrated in Figure 1-27. The

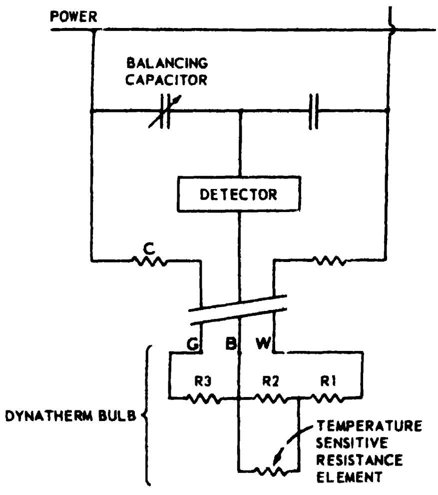


Figure 1-26. Measuring circuit with Dynatherm element.

principle of the Wheatstone bridge allows the replacement of resistances by inductances or capacitances. Thus, in the Foxboro Dynalog, where balance is obtained by a balancing capacitor, two legs of the bridge are formed by two capacitors, one of them the balancing capacitor in the Dynapoise unit as illustrated in Figure 1-8.

The Dynatherm resistance thermometer bulb is only about 3 inches long. The capsule at the lower end of the extension bulb contains the resistance element, Figure 1-27 shows the metal foil in the bottom which assists the heat transfer from the end of the well to the solid silver tip and core. Silver has a very high heat-transfer coefficient, which means that in this case the heat is rapidly distributed and transferred to the resistance winding.

The connection head of the thermometer bulb, which is not shown, contains resistors R_1, R_2, and R_3 of Figure 1-26. They are needed for calibrating the

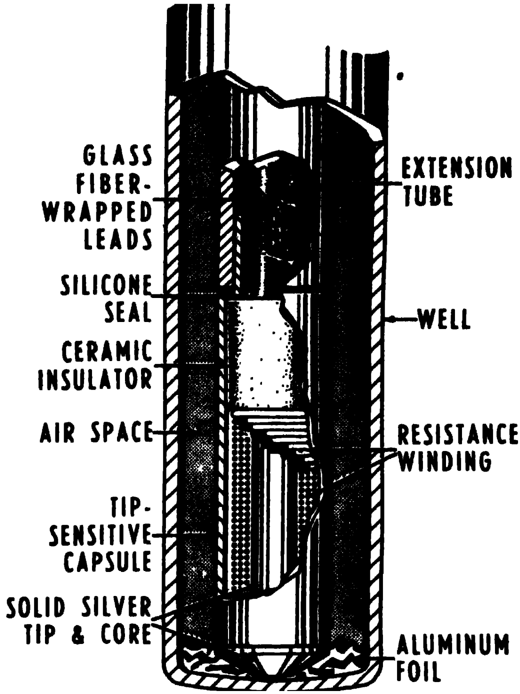


Figure 1-27. Detail of Dynatherm bulb (*Courtesy of Foxboro Co.*)

Dynatherm bulb. Resistors R_1 and R_2 are required to bring the bulb resistance to a desired point on the calibration curve, and the third resistor, R_3, consists of a portion of the bridge resistor C removed to the end of the lead lines. This provides approximately equal resistances between the $G-B$ terminals and the $W-B$ terminals, thus giving a symmetric distribution of resistances (and hence of capacitances) between the connecting wires.

Resistance thermometer bulbs are more accurate than thermocouples. They are usually rated at ± 0.5°F. Accuracies of thermocouples were listed in the discussion of thermocouples. In addition, the thermocouple always offers a slight possibility of inaccuracy due to changes in reference junction temperature because of insufficient compensation. Errors caused by this condition may amount to as much as 2°F or more, depending on the amount and speed of ambient temperature changes. Errors of this magnitude are unimportant—in fact are not readable on instruments with wide temperature ranges; but in narrower ranges, they may become a serious percentage of the total scale reading.

Resistance thermometer bulbs have the advantage of greater sensitivity because the change of resistance per °F in a bulb is easier to measure than the change of voltage per °F in a thermocouple. This makes spans as narrow as 5°F, which are spread over the whole range of the instrument, readily available for resistance thermometers.

The resistance thermometer bulb was formerly considered to be slower in response than the thermocouple. With modern high-speed detectors like those previously described, this is no longer necessarily true. Response speed is about the same as that of a thermocouple with a well.

Thermocouples usually require somewhat more frequent replacement than resistance thermometer bulbs. Since the initial cost of the latter is higher, the final cost of either arrangement is about the same. The inconvenience caused by replacing thermocouples might throw the balance in favor of the resistance thermometer bulb, although the latter has some drawbacks.

In general, the resistance thermometer bulb is used in preference to the thermocouple wherever possible. The principal limitation is temperature. Copper resistance bulbs are generally limited to 250°F maximum, nickel bulbs are 600°F maximum, and platinum bulbs to 1000°F with occasional uses up to 1600°F. The flexibility of the resistance thermometer bulb has made it useful in a number of special-purpose detectors, some of which are described in the following.

The Foxboro roll-surface temperature head, employing a special resistance thermometer bulb, makes it possible to measure and control the temperature of practically any moving surface to a high degree of accuracy. The surface may be moving at speeds up to approximately 2000 ft per minute and may be flat or curved to about any radius of 8 inches or over. The measuring element is of flat, rectangular shape, is supported by a free-floating spring-suspended faceplate, and bears on the measured surface with only feather-weight pressure.

In another device, the surface temperature detector is a paper-thin element approximately the size of a postage stamp. It is cemented to the surface whose temperature is to be measured. It can be used on any surface, flat or curved. Its characteristics are a very low mass with comparatively large area, high accuracy, rapid response, stability, and low cost. The lack of adequate protection, however, makes it sensitive to humidity and mechanical damage.

Thermistors have the characteristic of decreasing their resistance with an increase of temperature. This permits their use as resistance thermometer bulbs. Their response is, however, very nonlinear, which presents particular problems. The Hagan PowrMag temperature detector solves these problems by a circuit which is illustrated in Figure 1-28. The four legs of the Wheatstone bridge consist of two fixed resistors, R_1 and R_2, and two silicon-type resistors which form the resistance thermometer bulb. The power supply is so designed that by means of Zener diodes it maintains a constant d.c. output voltage across bridge terminals 1 and 6 for a.c. supply voltage changes between 105

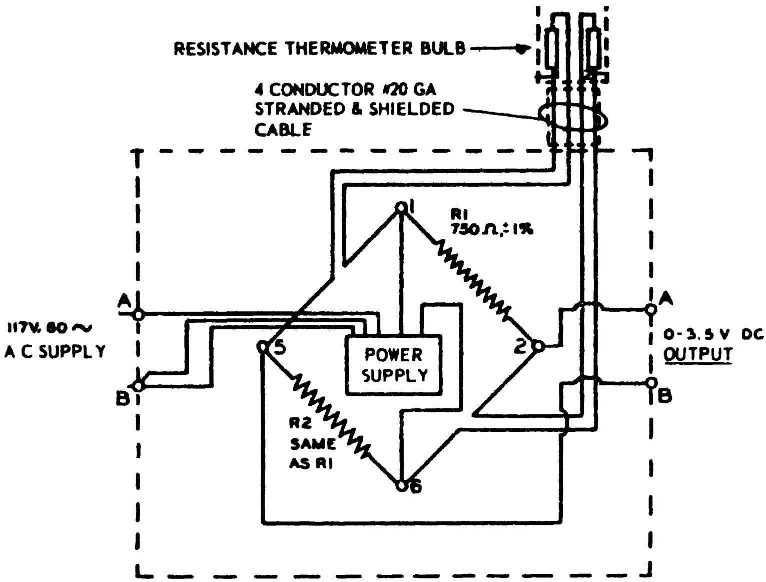


Figure 1-28. Circuit of Hagan PowrMag temperature detector.

to 125 volts—provided that the load is constant. The load consists of the bridge resistances. The power supply is load-sensitive. When the silicon-type resistors change their resistance in response to a change in temperature, the power supply changes its d.c. output voltage correspondingly. The degree and sense of the voltage change compensates exactly for the nonlinear temperature-resistance relationship. The bridge output across terminals 2 and 5 thus becomes a linear expression of the measured temperature.

Weston has developed an averaging resistance thermometer to measure the average temperatures in storage tanks, grain bins, long drying and baking ovens, blending operations and wherever the average temperature of a mass of material such as solids, gases, or liquids is to be determined. The resistance temperature detector consists of a number of resistance units varying in length with the height of the tank and mounted in a single flexible tubing. Figure 1-29 is a schematic diagram showing the arrangement of the resistance units. A level selector switch located at the instrument panel permits switching to the position that corresponds to the height of the level in the tank; thus one of the nine resistance units is switched into the circuit which best averages the temperature from the top level to the bottom of the tank. When the level changes, the level selector switch is used again to change over to another resistance unit corresponding to the new level.

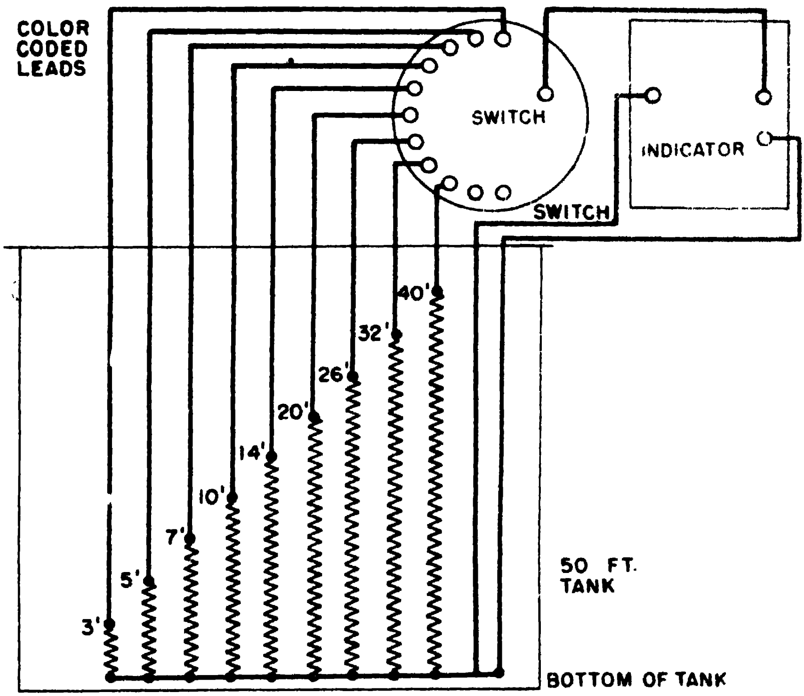


Figure 1-29. Schematic of averaging resistance thermometers. (*Courtesy of Weston Instruments*)

FILLED-SYSTEM THERMOMETERS

The Instrument

There is one very decisive difference between all the instruments previously described and the filled-system thermometer. So far, the effect of heat as expressed in temperature has been converted into an electrical signal, which in turn was measured by the instrument. Now, the temperature is converted into a mechanical motion caused by pressure or expansion, and this motion is measured. This requires an entirely different instrument, and as a matter of fact a much simpler one. Basically, the filled-system temperature recorder corresponds to a straight pressure recorder. Figure 1-30 shows Taylor Instrument Companies' filled-system recorder. In this case, only the fact that the Bourdon spiral is connected by a capillary to the thermometer bulb—instead of being tied into some bottom connection for the pressure signal—would indicate that it is used for temperature and not for pressure measurement. This particular instrument is a two-pen recorder with one actuating element on the left, and the other on the right. This permits measurement of two different temperatures ap-

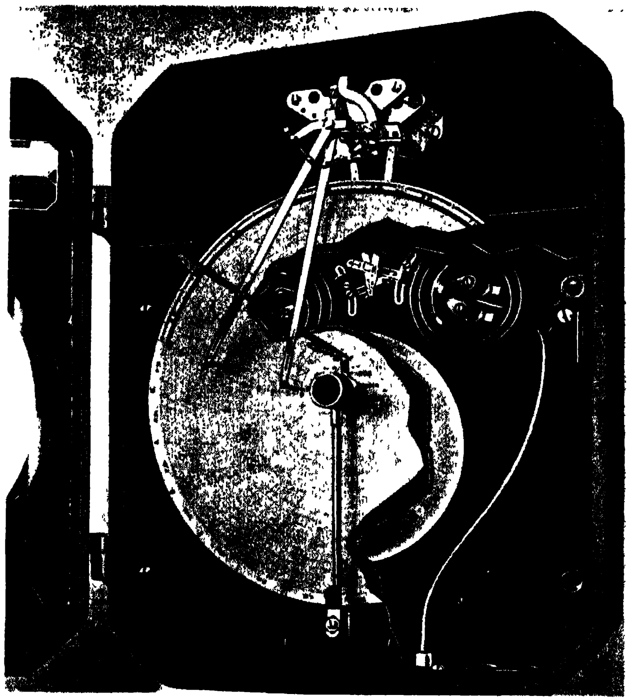


Figure 1-30. Filled-system recorder. (*Courtesy of Taylor Instrument Cos.*)

plied to two independent measuring systems. The temperature signal is converted into a dilating movement of the Bourdon spiral. This movement is transmitted to the pen by a link-and-lever mechanism. By changing the leverage, the angle through which the pen moves for a given movement of the Bourdon spiral can be calibrated. Also, by adjusting the screw on top of the pen arm the zero position of the instrument can be corrected.

The Chart Drive

The circular chart is driven by a motor. This can be a spring-driven clock or an electric motor. Pneumatic drives are also available, but since they require air connection, they become a typical accessory of pneumatic controls, which are treated in a later chapter. The spring-driven clock has the advantage of being entirely self-contained and of not requiring electric connections. Since the filled-system thermometer itself is a mechanical and not an electrical instrument, it is inherently explosion-proof—a condition that can be best maintained by using a spring-driven clock. However, electric clocks are also available in explosion-proof housings, although the relatively high initial cost of the clock and the electrical installation justifies its use only in specific cases.

Spring-driven clocks are generally used with speeds of 24 hours or 7 days per revolution. Some manufacturers offer spring-wound clocks that can be switched from one speed to another by means of a small lever, *e.g.,* from 24 hours to 7 days per revolution. Rockwell Manufacturing Company makes a chart drive that can be adapted for eleven different rotation cycles by interchangeable turrets. The turrets consist of small gear trains and the hub to which the chart is fastened in the usual way. The turret required for a given speed is slipped over the shaft of the spring-wound clock and locks onto it by meshing gears. The Bristol Company makes available a duplex chart drive to be used where an electric clock is preferred. Provision is made for an unbroken chart record if power failure occurs. This is done by means of a synchronous electric chart-drive unit in combination with a spring-driven clock, which takes over automatically during a power failure.*

A disadvantage of the circular charts is that, as compared with strip charts, they require relatively frequent replacement. For filled-system thermometers, strip chart recorders are almost unavailable. However, the Barton Instrument Corporation developed an automatic chart changer which changes circular recording charts at an exact time each day (or each revolution of the chart drive). It is possible to use 24-hour charts and leave the instrument unattended for 16 days.

Figures 1-31 and 1-32 show the Barton automatic chart changer. Special charts are required which are slit along their time arcs as illustrated. The chart plate can be loaded with up to 16 charts. The scroll is then mounted on top of the charts. The chart drive moves the chart around until a small tab on the special chart is picked up by the scroll. As the chart plate continues to rotate—the scroll is always kept in place—the chart is peeled off the chart plate automatically; and as all charts are slit along identical time arcs, the pens will move to the next chart at the moment the preceding chart has been completed. The completed chart moves forward onto the chart drive shaft where it is stored. The scroll design prevents it from interfering with the next chart or the operation of the pens.

The Thermal Systems

The thermal system of a filled-system thermometer comprises the thermometer bulb, an expansion element, such as a Bourdon tube, diaphragm, capsule or bellows, and a capillary tube connecting the bulb and the expansion element.

*A similar arrangement is available with some potentiometers such as those made by De Var Systems, Inc. A battery is provided in these instruments which supplies power during emergencies. The batteries are kept charged, and automatically take over on supply power failure.

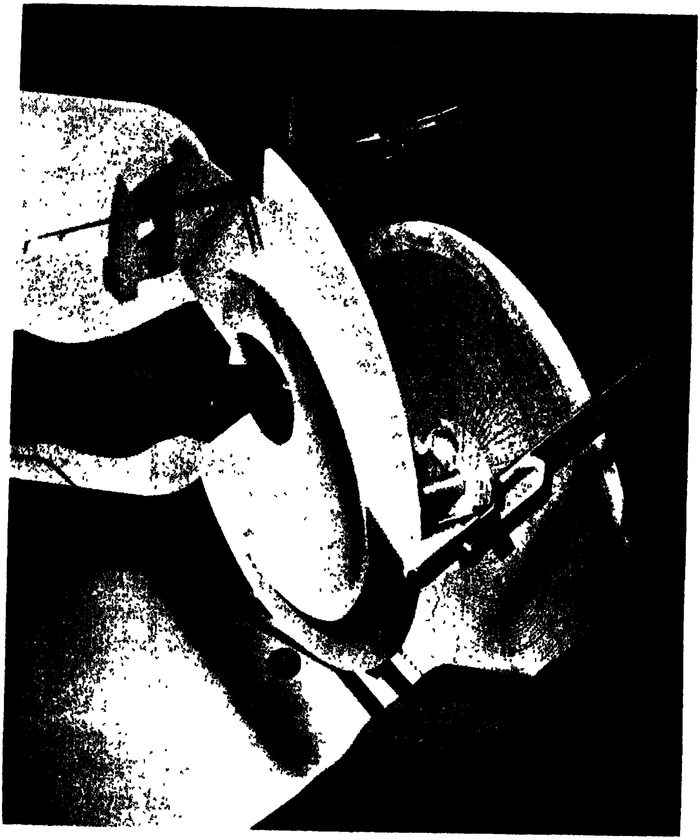


Figure 1-31. Loading the automatic chart changer. (*Courtesy of Barton Instrument Corp.*)

The Scientific Apparatus Manufacturers' Association has issued standard classifications which are used by practically all manufacturers. They divide filled-system thermometers into four basic classes:

Class I — The thermal system is completely filled with a nonmetallic liquid and operates on the principle of liquid expansion.

Class II — The thermal system is partially filled with a volatile liquid and operates on the principle of vapor pressure.

Class III— The thermal system is filled with a gas and operates on the principle of pressure change with temperature.

Class V — The thermal system is completely filled with mercury or mercury-thallium eutectic amalgam and operates on the principle of liquid expansion.

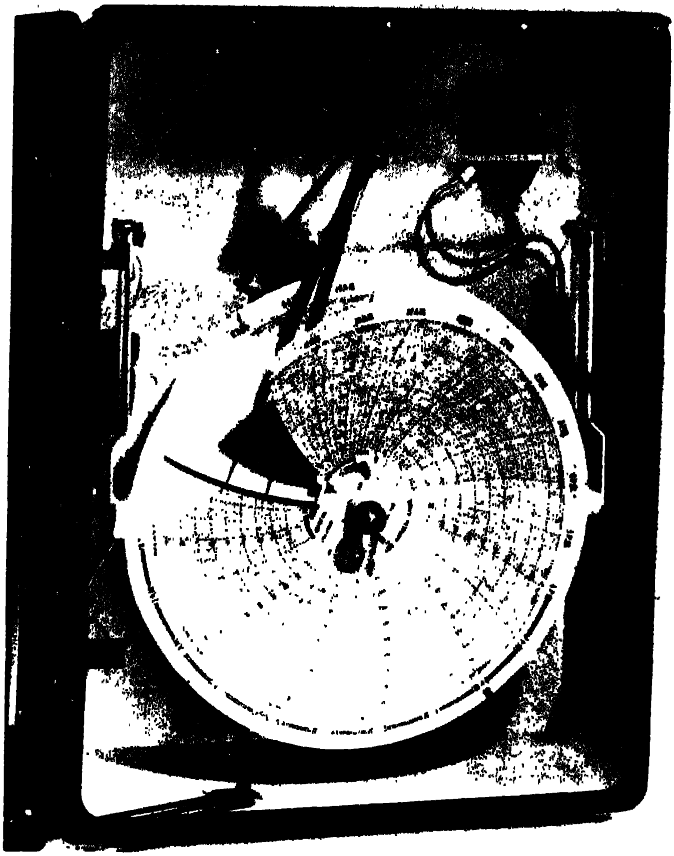


Figure 1-32. Operation of automatic chart changer. (*Courtesy of Barton Instrument Corp.*)

The filling fluid in the *entire* thermal system is normally temperature-sensitive. This can produce errors because of ambient temperature changes along the capillary tubing and the expansion element. Methods of compensation are described, together with the different thermal systems, in the following sections.

Mercury-filled (Class V) Systems. Temperature range of these systems is generally between -40 to +800°F. Use of some mercury alloys permits a lower limit of -65°F. The upper limit may be expanded to 1000 and even to 1200°F, but this would generally entail periodic recalibration of the instrument.

The mercury requires a stainless-steel thermal system. Where process conditions do not allow the use of stainless steel, some other class must be chosen. Class V systems are sometimes undesirable because in case of leakage of the thermal system, the mercury could contaminate or otherwise endanger the process.

To compensate for changes in ambient temperature, two methods are used: (1) case compensation, which counteracts ambient temperature effects at the instrument case only, and (2) full compensation, which includes the capillary also called the measuring tubing.

Figure 1-33 shows both compensation systems as used with Minneapolis-Honeywell thermometers. The same principles are utilized by other manufacturers. Illustration *A* shows the case compensation. The measuring spiral is fastened to a bimetallic strip, which in turn is fastened to the case support. When the temperature inside the case rises, the measuring spiral dilates in proportion to the change and tends to move the pen upward; simultaneously, however, the bimetallic strip moves the spiral in the opposite direction and the resulting net movement transferred from the spring to the pen is zero.

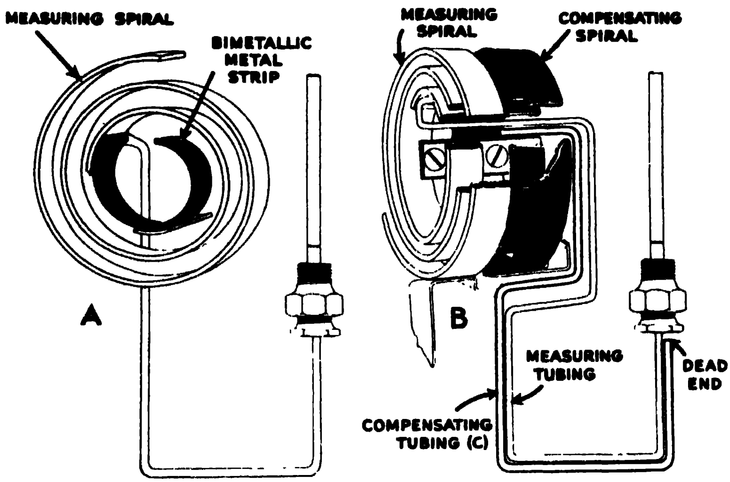


Figure 1-33. Case compensation (A) and full compensation (B). (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

The fully compensated system is illustrated in *B* of Figure 1-33. Two tubings and two spirals are used—two thermal systems in fact, filled with the same temperature-sensitive fluid and having the same dimensions. Only one tubing, however, is interconnected with the bulb. The other, *C*, is a compensating tubing and is dead-ended at the bulb entrance. The consequent effect is that both tubings react to the ambient temperature, but only one responds to the additional bulb effect. The two spirals are so mounted that they are coupled together, but they move in opposite directions. The resulting net effect, then, is due only to the bulb temperature, and complete compensation of ambient temperature influences on measuring spiral and capillary tube is obtained.

Figure 1-34 illustrates an ambient temperature compensation offered by Taylor, called the Accuratus Mercury-actuated Tube System. The system consists of bulb *A*, mercury *B*, 18-8 (type 347) stainless-steel Accuratus tubing *D*, filler wire *E*, and the measuring spiral. The filler wire extends throughout the bore of the tubing. This wire is made of invar metal which has a very low temperature coefficient. It decreases the volume of mercury in the capillary to the point

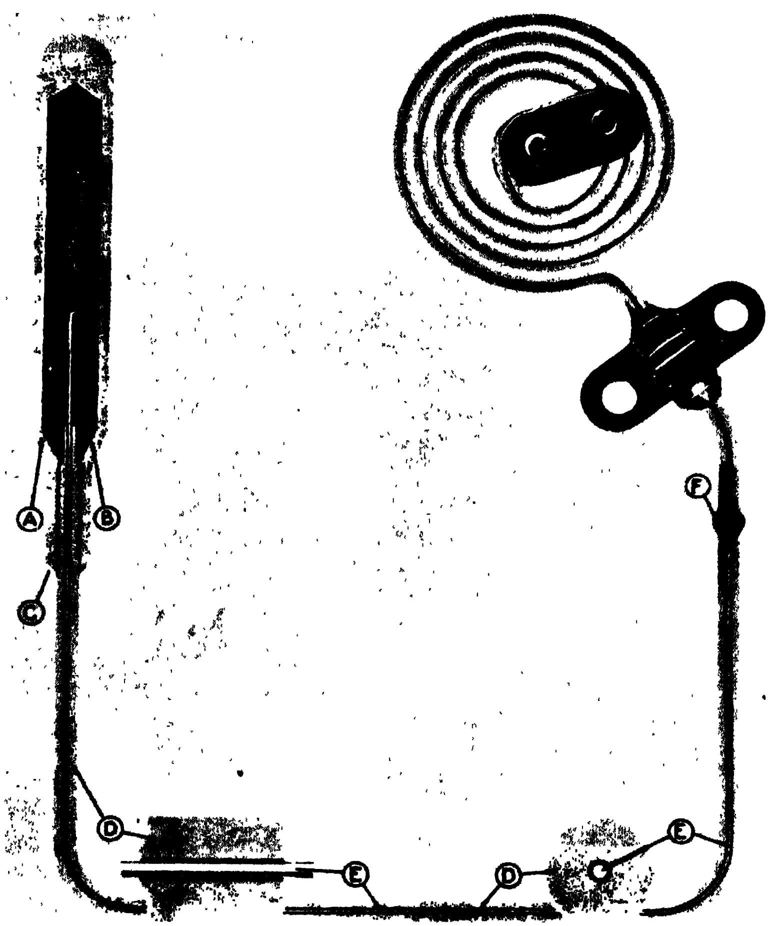


Figure 1-34. Accuratus system. (*Courtesy of Taylor Instrument Cos.*)

where the volumetric expansion of the mercury with a given increase of ambient temperature will exactly equal the increase in volume of the metal capillary due to the same ambient temperature increase.

Full compensation should always be used with capillaries of more than 15 feet, unless very stable ambient temperature conditions exist.

Vapor-filled (Class II) Systems. The temperature range of these systems is generally between −40 and +600°F, although low limits of -300°F are available. However, in these low ranges, Class III systems will generally be preferred. Class II systems are probably the most widely used thermal systems, being the fastest in response and the lowest in cost. The thermal system is filled with a volatile liquid and its vapor. Various kinds of liquids like propane, sulfur dioxide, ethyl ether, methyl chloride, and toluene are used, depending on the range of the instrument. The bulb is partly filled with the liquid, the rest of the thermal system being filled with the same material in its vapor state. The whole assembly can be compared with a miniature pressure boiler where, by well-known relations, the vapor pressure is a function of the temperature of the liquid. Under operating temperature conditions, with the bulb at a higher temperature than the capillary tube, the capillary and the spiral are filled with some of the liquid. Conversely, when the bulb is at a lower temperature than the instrument, all the liquid is in the bulb, and the capillary and measuring spiral are filled with vapor.

The accuracy of a Class II instrument is not affected by changes in ambient temperature, as long as these changes do not oscillate around the process temperature which the instrument is to measure. Suppose the process temperature is between 60 and 65°F and the ambient temperature around the capillary and the spiral fluctuates between 50 and 75°F. Such conditions are called cross-ambient temperatures. When the ambient temperature cuts above or below the process temperature, a temporary unbalance will occur. If, for example, a rapid increase of the ambient temperature from 50 to 75°F takes place, the liquid in the capillary and spiral will expand and the internal pressure will increase. This causes the pen to move up-scale, although the process temperature has not changed. However, liquid will be discharged into the bulb until a state of equilibrium exists and the pen returns to the correct reading as determined by the temperature of the liquid in the bulb.

Another factor which affects the instrument under cross-ambient temperatures is the head effect. At 50°F, in the above example, the capillary tube and spiral are filled with liquid; at 75°F they are filled with vapor. The liquid weighs more than the vapor, and if the bulb is mounted above the instrument, the measuring spiral will respond to the difference in weight by a corresponding inaccuracy in temperature reading. If the fluid in the capillary and spiral is *always* in the vapor phase or *always* in the liquid phase, the calibration of the thermometer takes care of the head effect. However, changes from liquid into vapor and vice versa, as caused by cross-ambient effects, will cause errors.

A similar condition exists when the bulb is located below the level of the instrument; then the head pressure of the liquid will shift the boiling pressure and hence the instrument response.

The situation is similar when the process temperature oscillates around the ambient temperature. Let the ambient temperature be constant at 63°F and the process temperature increase from 60 to 65°F. Before the instrument can read the correct temperature, it will be necessary that the fluid in the capillary and spiral change from vapor to liquid. This causes an undesirable time lag.

The shortcomings of Class II systems under cross-ambient temperatures can be circumvented. For example, in the Bristol Dual-filled Vapor Pressure Thermometer system, illustrated in Figure 1-35 the bulb is only partially filled with a volatile liquid and its vapor, and a nonvolatile liquid takes the remainder of

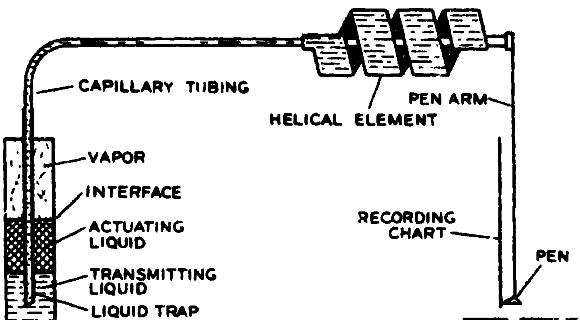


Figure 1-35. Dual-filled vapor-pressure thermal system. (*Courtesy of Bristol Co.*)

the space. As the temperature at the bulb increases, the vapor pressure of the volatile liquid rises. This change in vapor pressure is transmitted to the helical element through the nonvolatile liquid. Since the nonvolatile liquid remains in the liquid phase even at the highest ambient temperatures that ordinarily exist along the connecting tubing, there is no range of indefinite accuracy when ambient temperatures along the tubing and the instrument approximate the measured temperature.

The relationship between pressure and temperature in Class II is not a linear one. The result is an instrument scale with spacings that gradually increase with temperature. They are rather close together in the lower part of the chart. A vapor-actuated thermometer should therefore be selected to record all essential data in the upper third of its scale. Figure 1-36 shows two sections of Foxboro charts. One has the linear graduations of Class I, III and V, the other

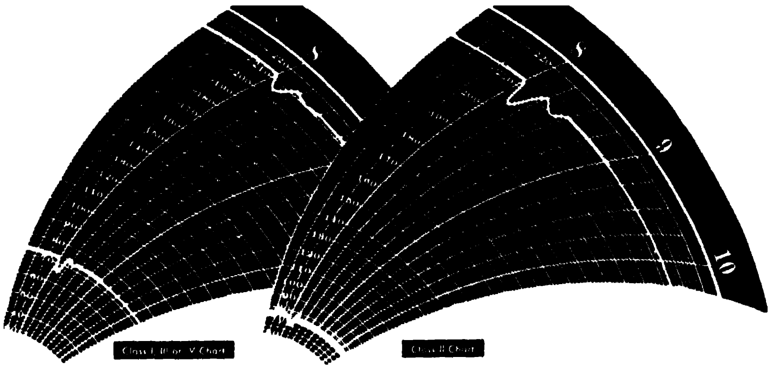


Figure 1-36. Comparative chart readings. (*Courtesy of Foxboro Co.*)

the nonlinear of Class II. It can be seen that this characteristic facilitates the reading in the upper third of the Class II scale and impairs it for low values. In many cases, this expansion in the upper regions is an advantage.

Bristol Company developed a linkage between measuring spiral and pen that converts the nonlinear response of the spiral into a linear pen movement, which allows the use of evenly graduated charts.

Liquid-filled (Class I) Non-mercury Systems. The maximum temperatures which can be measured with these systems are generally 600°F, the same as with Class II systems. Lower limits may go to -125°F or even to -300°F. For small spans, below 100°F, the bulb required with a Class I system may be smaller than with any other system. Its response is linear and the corresponding charts are therefore evenly graduated. The problems of ambient temperature conditions are the same as those described for Class V, and compensating systems similar to those illustrated in Figure 1-33 will be used.

Gas-filled (Class III) Systems. Together with Class V thermometers, these can be used for relatively high temperatures, *i.e.*, up to 1000°F, and also with lower temperatures than any other instrument. They are generally used for wide measuring spans because the change of pressure per degree change in temperature is extremely small. This characteristic also results in a limitation of actuating power available. Consequently, full compensation can hardly be applied as the compensating action of two spirals (see Figure 1-33B) further decreases the net power needed to position the pointer or pen of the instrument. Thus, these systems are generally supplied with case compensation only. They also use relatively large bulbs to obtain a high ratio between thermal system and capillary, to reduce the relative effects of ambient temperature upon the tubing. The relatively large bulb is a disadvantage as it reduces responsiveness to temperature changes. In normal application, Class III is therefore the slowest system. In other applications, however, like the temperature transmitter described below, the length of the capillary tube becomes negligible, and the bulb size can be correspondingly reduced. Under these conditions, Class III is of very fast response.

Bulbs, Wells, and Tubing

Bulbs may continue directly into the capillary, or a flexible extension may be provided between bulb and capillary. The latter method is used especially where the bulb is inserted in a vessel that does not allow the bulb to project at right angles to the wall, or where it is necessary to extend the bulb for a considerable distance into the vessel to obtain average temperature.

Figure 1-37 illustrates typical Foxboro bulbs and methods of installation in kettles and pipes. All these bulbs have bendable extensions, except bulb *F*,

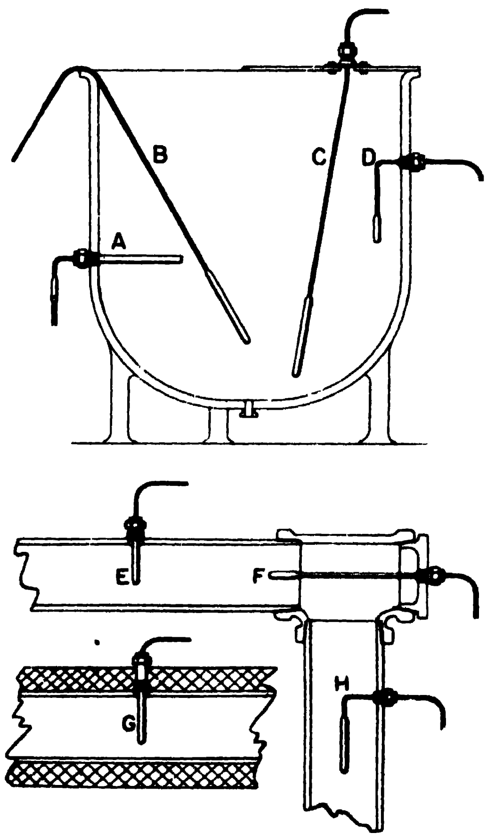


Figure 1-37. Typical bulb installations. (*Courtesy of Foxboro Co.*)

which may be either bendable or rigid. Bulbs *A*, *E*, and *G* are provided with unions which are slipped over the capillary tube by the manufacturer before the capillary is welded to the measuring spiral. These three bulbs are inserted into wells. In case *A* the well is threaded into the side wall of the vessel, in cases *E* and *G* it is screwed into a half-coupling welded to the wall of the pipe. In case *G* the well is provided with a lagging extension. The extension of bulb *B* is bent to hang on the edge of the kettle, and bulb *C* is provided with a union in order to install it through a threaded flange in the cover of the kettle. Bulb *D* is also provided with a union and is installed through a threaded hole in the side wall. The union-rigid or union-bendable type, *F*, is installed in a tee through a reducing bushing, and *H* is a union bendable-type bulb installed through the pipe wall and bent. This last method permits the use of a longer bulb than that used in *E*.

The response of filled-system thermometers to changes in temperature is relatively slow. One of the main causes is usually the gaseous film on the outer surface of the bulb. To improve the condition, particularly in spaces where the

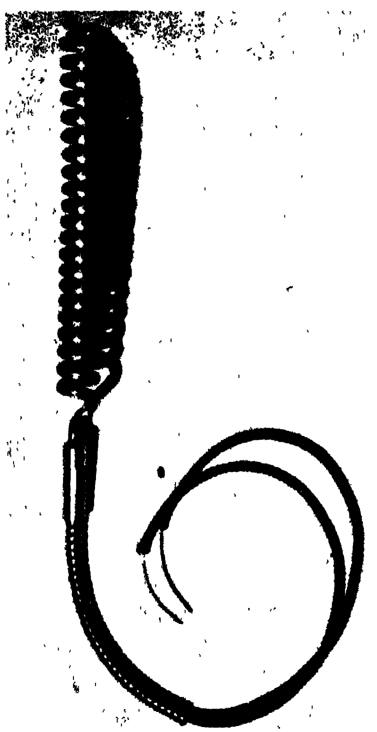


Figure 1-38. Coiled air-temperature bulb. (*Courtesy of Electric Auto-Lite Co.*)

circulation about the bulb is poor, bulbs are designed that have a relatively large surface. Figure 1-38 shows a coiled air-temperature bulb made by the Electric Auto-Lite Company, as used for the measurement of air temperatures. Their over-all length usually ranges between 6 and 20 inches.

A well (bulbs *A*, *E* and *G* of Figure 1-37) is used where it is necessary to protect the bulb from pressure, erosion, corrosion, or abrasion, or where a pressure-tight connection is required, together with the ease in removing the bulb without service interruption. When used with a well, the bulb is specified with a bushing for union connection. Where the well is screwed into a lagged vessel, an extension neck for the lagging should be provided on the well.

The well considerably retards the response of the bulb to temperature changes. To minimize this, it should fit the bulb tightly. Any space between bulb and well should be filled either with an inert liquid or with a metal foil that makes good thermal contact with the inside of the well and the outside of the bulb.

The capillary tube may be used bare, without added mechanical protection. In the case of Class V systems, it usually is done this way, since the mercury requires a stainless steel tubing of sufficient mechanical strength. However, an additional spirally wound armor is available for all tubings. The armor may be of stainless steel or of plastic-covered bronze, or a plain lead sheathing. In Classes I, II, and III, the capillary is generally either stainless steel or copper. In the latter case either of the aforementioned protections or spirally wound bronze and smooth copper armors are used.

Temperature Transmitters

The length of capillary tubing between bulb and measuring spiral is limited to about 200 feet. This limitation is overcome by a transmitter which converts the pressure signal from a thermal system into an air-pressure signal which can be transmitted for longer distances.

Figure 1-39 shows a Moore Nullmatic temperature transmitter. This unit transmits air pressures which have a direct linear relation to the temperatures measured by the bulb. A standard pneumatic indicator, recorder or controller is used as a receiver. The thermal system is of the Class III variety and its gas pressure, which is a function of the controlled temperature, exerts a force on the balance bellows of the transmitting unit. Any increase or decrease in this force, resulting from a change in bulb temperature, is detected by the nozzle, and is balanced by the pressure of the air within the balance bellows. This balance pressure is obtained through the operation of the pilot valve.

The supply air flows through a restriction to the top of the diaphragm, and out of this chamber through the nozzle. Supply air also flows through the pilot valve to the under side of the diaphragm which connects with the inside

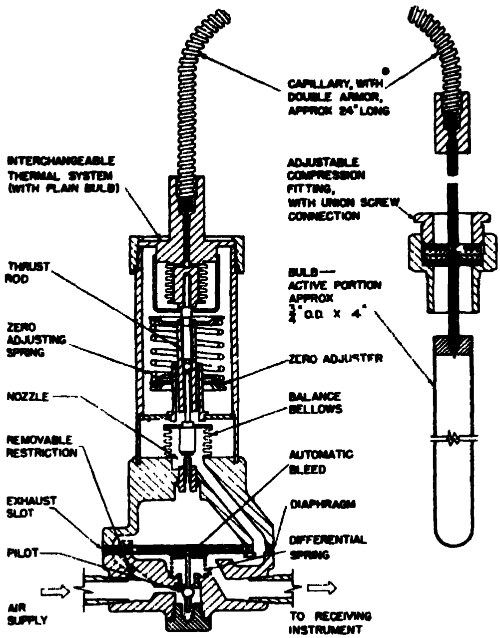


Figure 1-39. Nullmatic temperature transmitter. (*Courtesy of Moore Products Co.*)

of the balance bellows and with the receiving instrument. The slightest change of the pressure in the thermal system tends to move the bellows and the nozzle seat either to or away from the nozzle. Such a change, therefore, causes an increase or decrease of pressure on top of the diaphragm, which operates either to admit more air through the pilot or to exhaust air through the automatic bleed, and thus to re-balance the system. The exhausted air escapes to the atmosphere through the porous fabric center layer of the diaphragm.

It is interesting to note that in balanced conditions the pressure drop across the nozzle is always the same, regardless of the pressure within the balance bellows. The pressure drop is determined only by the force of the loading spring under the diaphragm. Nonlinear nozzle and bellows characteristics are thus eliminated. The significance of the constant-pressure drop becomes obvious in the discussion on *Basic Mechanisms* in chapter 12.

The Taylor Transaire Transmitter is illustrated in Figure 1-40. The actuation of the diaphragm through the thermal system is the same as that of the bellows through the thermal system of the transmitter in Figure 1-39. The diaphragm is connected to the motion lever, to which it transmits its movement. This causes the baffle to move away from the nozzle, producing a decrease in air pressure between orifice and nozzle. This pressure is also applied to the re-

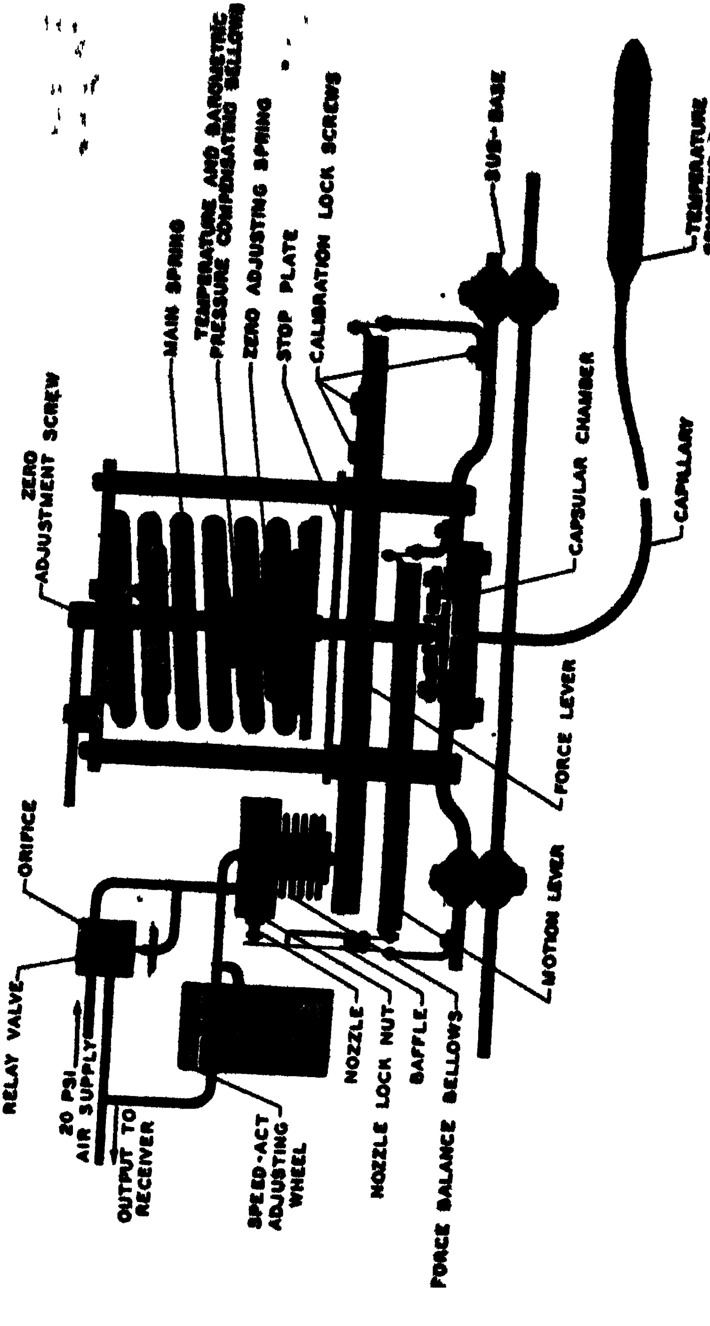


Figure 1-40 Transaire temperature transmitter (Courtesy of Taylor Instrument Cos.)

lay valve where it deflects a small diaphragm, which in turn moves the valve stem. This will increase the output air pressure and cause an increased downward force to be exerted by the force of the balance bellows, which counterbalances the force due to the temperature change and brings the system into equilibrium. The new output pressure is a measure of the new temperature and is transmitted to the remotely located receiver.

The thermal system is the gas-actuated Class III. Since the capillary is short, the bulb can be small. Standard sizes are 3/8 by 3 inches and 1/2 by 7/16 inches. There is also a coiled bulb available, where the bulb is a pre-formed extension of the capillary. Since the relative surface area of the latter bulb is much larger than that of the other two types, it gives a response about four times faster. Its over-all dimensions are $1\,{}^3/_8$ by $2\,{}^1/_2$ inches.

The Transaire transmitter allows compensation of inherent lag of bulb response to a noticeable degree. This is done by the Speed-Act adjustment of Figure 1-40. As described above, the output air pressure is applied to the force-balance bellows. The Speed-Act adjustment is inserted in the connecting line and offers an adjustable restriction between the force-balance bellows and the output air. This delays the action of the bellows, and therefore the balancing of the system. The greater the rate of response of the temperature-sensitive bulb, and the faster the resulting change of output air pressure, the greater is the relative lag in the action of the force-balance bellows. The result is an acceleration in the change of output air pressure. The magnitude of this acceleration is a function of the rate of response of the temperature-sensitive bulb. The desired purpose, *i.e.*, acceleration of the bulb's lagging response, is thus obtained.

When a temperature change takes place, the temperature difference between process and bulb is at first at its maximum and then gradually decreases until at last a new thermal balance is established. The response of the bulb becomes increasingly slower as the temperature difference diminishes. Consequently, the change in air output to the receiver decelerates, and the lag in the action of the force-balance bellows becomes smaller. The result is a self-regulating feature that reduces overshooting of the air output.

Overshooting is an indication of sensitivity. Sensitivity is desirable, but overshooting is not. A compromise in the Speed-Act adjustment is therefore necessary which allows overshooting within permissible limits and accepts the sensitivity obtainable under these conditions.

The Transaire transmitter compensates for both ambient temperature and barometric pressure conditions. This is obtained by the compensating bellows shown in Figure 1-40 which, together with the springs, determines the pressure on the top of the diaphragm in the capsular chamber, while the gas pressure in the thermal system is applied to the lower side of this diaphragm.

2. Humidity and Moisture

The differentiation between humidity and moisture is made here because a distinction is desirable between the humidity existing as water vapor in a gas, and moisture as a liquid adsorbed or absorbed by a solid. The instrumentation approach is so different that such a distinction is of advantage.

HUMIDITY

Measuring humidity as discussed here, means determining the amount of water vapor in a gas. The gas under consideration is usually air; although this discussion takes air as the most practical example, all principles can be applied equally well to other gases.

The water vapor content in a given atmosphere can be expressed in weight of water vapor per unit weight of gas, *e.g.,* 0.01 pound of water vapor per pound of dry air. In many applications, the information regarding the water vapor content is insufficient for the following reasons. The ability of a gas to hold water vapor depends on its temperature. The physiological sensation of humidity in atmospheric air, for example, is a response to the relation between water vapor present in the air and the maximum amount of water vapor that could be carried in the air at the existing temperature. This relationship is equivalent to relative humidity. It is this condition of relative humidity which it is important to measure and control in many industries.

The Hygrometer

Air saturated with water vapor, *i.e.,* of 100 per cent relative humidity, at a temperature of 58°F would contain 0.01 pound of water vapor per pound of dry air. The same amount of water vapor at 77°F would correspond to a relative humidity of only 50 per cent. On the other hand, a hygroscopic material like human hair or nylon, as it is used in many hygrometers, will absorb more moisture at 58°F than at 77°F. Consequently, the instrument using such an element would respond not to the amount of water vapor present but to the relative humidity. Instruments utilizing this absorption effect are called hygrometers. They are either of the mechanical or the electrical type. The most general form of the mechanical type uses the above mentioned human-hair and nylon elements. The element will contract when the humidity decreases and expend when it increases. The great advantage of the mechanical type is the extreme simplicity of its operation. It does require, however, frequent calibration as these elements change their characteristics over a period of time.

Bristol's direct-reading, relative humidity instruments use a sensitive wood element. As illustrated in Figure 2-1, it consists of a thin strip of specially

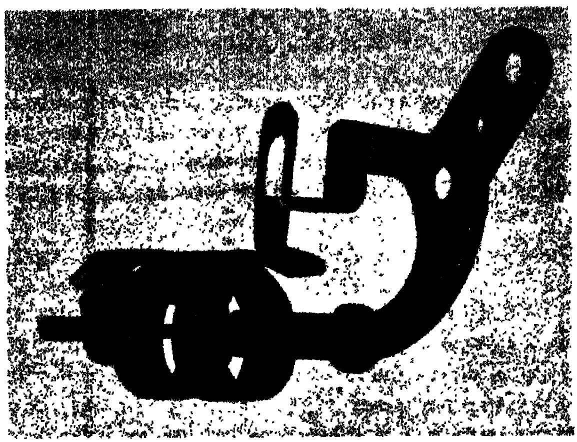


Figure 2-1. Hygroscopic element. (*Courtesy of Bristol Co.*)

treated wood cemented to a strip of metal and wound into a helix. The hygroscopic wood expands and contracts with changes in relative humidity. This causes the element to deflect through an angle, thus producing the same type of a motion as the measuring spiral of a filled-system thermometer. Similar to hair elements, these devices require relatively frequent re-calibration. Their low cost is, however, an advantage over more elaborate and accurate devices.

The Taylor relative humidity transmitter uses nylon fibres as sensing elements. Two such fibre elements are connected in series so that they produce a dimensional change that is the equivalent of one element of twice the length. The change in fibre length caused by a change in relative humidity acts on a pneumatic nozzle-baffle system to produce a change in nozzle back pressure which is also the transmitter output signal. This output pressure change is applied to a Bourdon tube. Its resulting movement serves to reposition the baffle with respect to the nozzle and to maintain an essentially constant tension of the nylon fibres throughout the working range.

The electric hygrometer was originally developed by the U. S. Bureau of Standards. The sensing element in its usual form consists of a cylindrical core made of insulating material, around which two precious metal wires are wound side by side. The two wires are connected to an a.c. power source so that a voltage differential is maintained between them. The distances between the windings are exactly equal. A coating of hygroscopic material, such as lithium chloride in solution, is applied over the whole. The electrical conductivity of the hygroscopic material changes in proportion to the amount of moisture it absorbs, *i.e.,* in proportion to the relative humidity of its surrounding atmosphere. A small electric current flows over the hygroscopic layer from one wire to the other. The amount of current flow depends upon the amount of moisture absorbed by the hygroscopic material.

The humidity sensing element, made by Hygrodynamics Inc., is a commercial unit that operates in the following manner. The wire is wrapped around a polystyrene cylinder, and the over-all dimensions of the element are 2 inches long by 3/4 inch in diameter. For purposes of measurement, the unit is connected with a Wheatstone bridge. The changing electrical conductivity of the hygroscopic layer caused by changes in relative humidity results in an unbalance of the bridge, the amount of which is indicated by the instrument in terms of per cent relative humidity.

The element will respond to changes of as small as 0.15 per cent relative humidity. The range of relative humidity which one element will cover is limited. These elements are available in staggered, overlapping ranges, and it is possible to cover relative humidity from 6 to 99 per cent by means of 8 elements.

In the Honeywell humidity element the same principle is applied; a flat plastic form is used upon which two gold leaf grids are stamped, with the voltage between the grids. The over-all form is covered with a lithium-chloride salt solution. The operation is the same as in the previous example.

The Wet-and-dry-bulb Thermometer

It is obviously impossible to dry a wet object when the surrounding air is saturated; the lower the relative humidity in the surrounding atmosphere, the better are the drying conditions. It is also well known that drying, being a process of evaporation, absorbs heat from its immediate surroundings, *i.e.,* produces cooling. The cooling thus becomes an effect of the relative humidity, and it is measured in the wet-and-dry-bulb thermometer. The dry bulb measures the air temperature. The wet bulb, however, is surrounded by a porous material, which is kept moist and across which an air stream is circulated. The air stream must have a speed of 15 feet per second or more to obtain maximum evaporation. The bulb, either a pressure-actuated temperature element or a resistance temperature detector, is cooled by evaporation to a point which is called the wet-bulb temperature. This temperature in itself is not indicative; it is significant only as an expression of the amount of cooling, *i.e.,* as the difference between the air temperature and the wet-bulb temperature. Once wet-bulb and dry-bulb temperatures are known, relative humidity can be determined by tables, special slide rules, or psychrometric charts. Direct reading of relative humidity is possible in a Leeds & Northrup instrument which measures wet-bulb and dry-bulb temperatures by means of resistance temperature detectors. The unbalances of the respective Wheatstone bridges are combined and the result is recorded in terms of relative humidity.

Two methods of wetting the wet-bulb surface are commonly used; in one a wick is used and in the other a porous ceramic sleeve that fits over the bulb. In both cases a continuous water supply must be provided from a trough or a pipe, or directly from the water line. Care should be taken that the water itself is at the wet-bulb temperature. The wick is wrapped around the bulb and dips into the water. Thus it is kept wet continuously and keeps the bulb adequately moistened. When a ceramic sleeve is used, one end is usually connected to a water supply and evaporation through its pores produces the wet-bulb temperature.

When the bulbs are installed in air ducts, the velocity in the duct is usually high enough to provide adequate evaporation. In still air, however, a fan must be used to provide the required air movement.

Dew Point Measurement

The psychrometric chart informs about the most essential physical characteristics of the air, once two of the characteristics contained in the chart are given. The dew point of the air under some given conditions is one of those characteristics that can be read from the psychrometric chart. The dew point is the temperature to which a given atmosphere can be cooled without condensing any of its water vapor. Using the previous example, air at 77°F with 50 per cent relative humidity could be cooled to 58°F, at which point its relative humidity would increase to 100 per cent. Any further cooling would produce condensation. In other words, 58°F is the dew point of air under these particular conditions. The dew-point methods consist of determining the temperature at which condensation begins.

Where low moisture contents must be determined, and especially where an absolute humidity measurement independent of temperature is desired, hygrometers and wet-and-dry-bulb thermometers are not so well suited as are some of the dew-point methods. The General Electric dew-point measuring equipment uses a mirror surface which is cooled to a temperature at which a layer of dew first forms. The temperature at which this occurs is recorded, and corresponds to the dew-point temperature. The operation of the equipment is shown in Figure 2-2. The equipment consists of four components: (1) a two-stage refrigerating system with compressors; (2) a gas chamber with a dual photoelectric system; (3) an electronic power unit and amplifier; and (4) a temperature recorder calibrated in dew point.

The two-stage refrigerating system can maintain a temperature of −90°F or

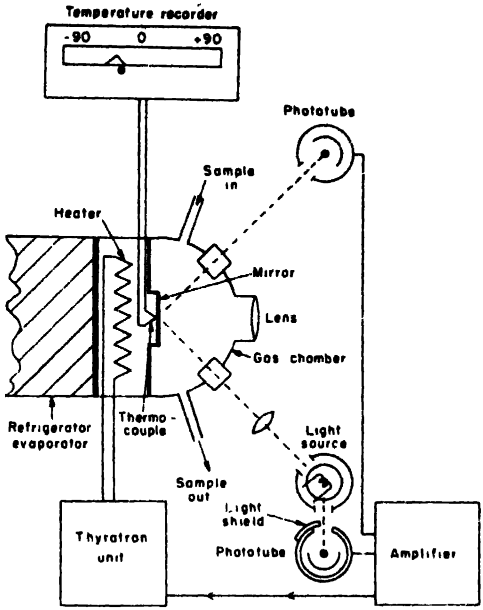


Figure 2-2 Schematic of G. E. dew-point recorder. (*Courtesy of General Electric Co.*)

lower in the space behind the mirror. While the cooling rate remains constant, it is possible to raise the temperature in the space behind the mirror by means of a heater. The heater-mirror assembly has a low heat capacity, and hence a low thermal inertia; it gives fast response, and reduces the load on the cooling system.

A gas flow of 0.05 to 0.10 cu ft per minute is continuously passed through the gas chamber to provide for the formation of a dew spot on the mirror, which is detected by the phototube viewing system. Two ports at an angle to the mirror surface allow a beam of light from the small light source to enter and leave the chamber. The entering beam reflects from the mirror surface and leaves the chamber, to be measured by a phototube. The presence of dew on the mirror reduces the intensity of the reflected light by an amount proportional to the size of the dew spot.

If the dew spot tends to grow, the reflected light intensity drops and the electronic circuit supplies more power to the heater, preventing this growth by raising the temperature of the mirror. If the dew spot tends to diminish in size, the reflected light is increased and less power is supplied to the heater.

A thermocouple is mounted directly on the mirror and the temperature—the dew-point temperature—is read by a temperature recorder.

Another method of dew-point measurement is based on the fact that dew point and vapor pressure are closely related. For example, saturated air at 58°F contains 0.01 pound water vapor per pound of dry air. If this amount of water vapor should decrease as a result of atmospheric changes, the remaining water vapor would expand and consequently lower the vapor pressure. It is true that relative humidity is equivalent to the ratio of the water vapor pressure in the air to the maximum amount of water vapor that could exist in the air at a given temperature. But it can also be defined as the relation between the existing water vapor pressure and the water vapor pressure of saturated air at the same temperature. The latter, in fact, is the usually accepted definition.

Suppose a hygroscopic material would be exposed to a given atmosphere. It would absorb a certain amount of moisture. It would then be attempted to dry this material by the application of heat. The amount of heat to be applied would depend in the first place on the quantity of moisture absorbed and in the second place on the water vapor pressure of the surrounding air. Once the material is dried the minimum amount of heat applied to keep it in this state depends solely on the vapor pressure. This vapor-pressure method is applied in the Foxboro Dewcel.

The Dewcel construction is similar to an electric hygrometer. A thin-walled metal tube is covered with a woven glass tape impregnated with lithium chloride solution. The assembly is wound with a pair of silver wires over the tape and covered with a perforated metal guard. The element differs in operation from the electric hygrometer in that it carries a current large enough to heat the hygroscopic material to a point where the absorbed water tends to escape to the atmosphere. As the hygroscopic material dries, the current decreases because the conductivity of the hygroscopic material diminishes. An equilibrium point is reached where just the right amount of current is passed to provide a temperature at which the escaping tendency of the water is equal to the tendency of the hygroscopic material to take on water from the atmosphere.

The center of the Dewcel is either a Class I thermometer bulb or a resistance thermometer bulb. Either element serves to measure the temperature of the equilibrium point of the Dewcel. This temperature, which is an indication of the water vapor pressure, corresponds to the dew point temperature.

Heat of Adsorption

The Mine Safety Appliances Company together with the Esso Research and Engineering Company developed a water vapor recorder for continuous recording of low concentrations of water vapor in air or gas streams. The principle of operation is to measure the heat energy exchanged when a gas is adsorbed on or desorbed from the surface of a solid adsorbent. Figure 2-3 illustrates the method. A continuously flowing sample of gas is split into two

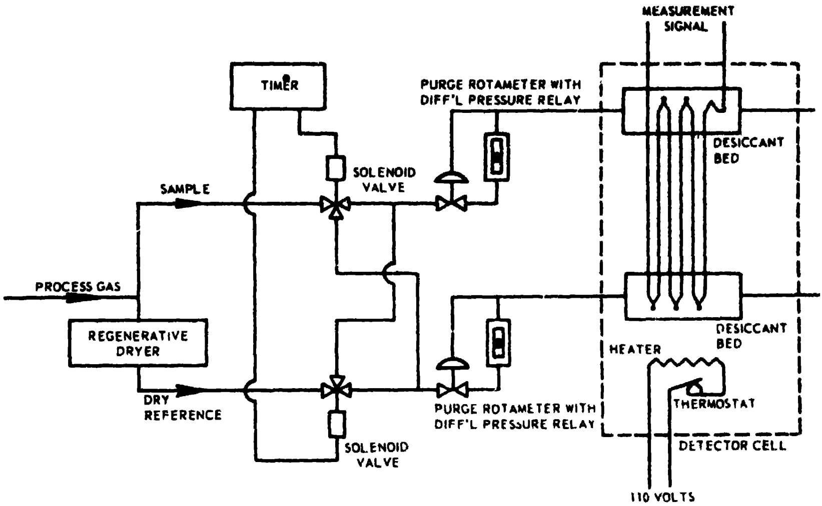


Figure 2-3. Simplified diagram of M-S-A continuous water vapor recorder.

equal streams, one of which is dried completely by the regenerative dryer. The two streams are then directed through two automatically timed and operated three-way solenoid valves. The timer alternately opens and closes the two valves. After passing through the solenoid valves and two purge rotameters with differential-pressure relays (*cf.* Figure 5-3), the samples enter the detector cell. Two desiccant beds in the detector cell either adsorb the moisture from the moist gas or moisture is desorbed from them by the dry gas. The result is an exchange of heat between desiccant and gas and a consequent change in temperature. Thermopiles measure the temperature in the two desiccant beds.

The timer switches the solenoid valves every two minutes and thus exposes the desiccant in each bed alternately to each stream—the moist and the dry. Since adsorption and desorption occur simultaneously in the respective desiccant beds, the total emf developed by the two thermopiles is proportional to the sum of the gain of heat in one bed, and loss of heat in the other. During each 2-minute cycle the temperature differential between the two desiccant beds rises rapidly, passes through a maximum, and then diminishes slowly. In the next 2-minute cycle, the desiccant bed which had lost heat in the previous cycle gains heat, and vice versa. The emf generated is equal to that of the preceding cycle but of opposite polarity. The result is an alternating signal which would be difficult to interpret. To convert this swinging signal to an easily interpreted recording and to use it in automatic control systems, the thermopile signal is fed into a peak-to-peak voltmeter. As a result the swinging signal from the thermopile is converted into a deviation from a fixed zero.

To eliminate errors due to temperature variations in the sample flow, the sample is heated to a temperature which is a few degrees above the highest ambient temperature anticipated. The detector cell and the heat exchanger are housed in a stainless steel Dewar flask for thermal insulation. The heat exchanger consists of coiled copper tubes surrounding the cell. The proper temperature is maintained by an electric heater and thermostat control.

The instrument comes in ranges from 0 to 10 ppm (parts per million)* to 0 to 5000 ppm. Its accuracy is within one per cent of full scale.

Electrolysis

The Beckman Electrolytic Hygrometer operates as follows. A sample of the process gas is continuously passed through the instrument. The rate of flow is held constant by a flow control system. The flow-regulated sample enters the analysis cell. There, moisture is absorbed by a thin film of phosphoric acid held between platinum electrodes. A direct current potential applied between the electrodes dissociates or electrolyzes the absorbed water into hydrogen and oxygen. The process of dissociation produces a current that is directly proportional to the concentration of water in the sample. This current becomes the linear signal which drives the indicating meter.

This instrument comes in ranges from 0 to 10 ppm to 0 to 1000 ppm. Its accuracy is within 5 per cent of full scale.

MOISTURE

At the beginning of the chapter, a distinction between humidity and moisture was made for the purposes of this discussion. The term *moisture* was applied to water adsorbed or absorbed by solids. Moisture measurements in continuous processes occur frequently in the paper and textile industries, where the moisture content of the material must be kept constant during fabrication.

Some effect of the moisture content is measured. The usual methods consist of determining either the electrical conductance or the capacitance of the material under consideration. Both these electrical characteristics are functions of moisture content.

Electrical Conductance

Figure 2-4 shows a schematic diagram of Honeywell's Moist-O-Graph system. In this case, the material, the moisture content of which is to be measured, passes over the machine roll of a dryer which is electrically grounded.

**parts per million* expresses the concentration of H_2O in the gas by volume. For example, 100 ppm means that the volume ratio of H_2O to the gas is 100:1,000,000, or 1:10,000.

The detector roll rides on the material at a constant pressure. A minute electric current passes from the detector roll through the material to the grounded machine roll. The material is equivalent to an electric resistor, the value of which changes with the moisture content. The circuit forms part of a Wheatstone bridge. One leg of the bridge is formed by the material. When the moisture content changes, the bridge becomes unbalanced. The unbalance is detected by a potentiometer, which rebalances the bridge by the methods described for potentiometers as applied to resistance thermometers. The amount of slide-wire or strain-gage adjustment required is indicated by the instrument, and since this is a function of the moisture content, it can be calibrated accordingly.

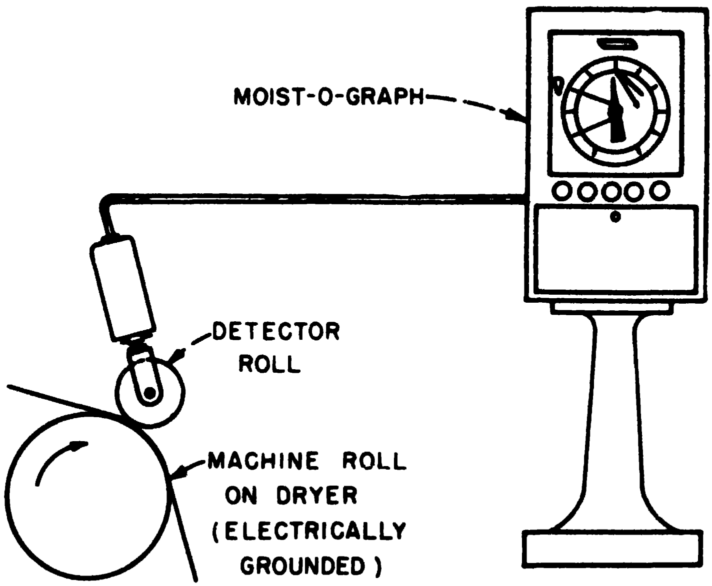


Figure 2-4. Schematic of Moist-O-Graph system. (*Courtesy of Minneapolis-Honeywell Regulator o.*)

Electrical Capacitance

The Foxboro moisture control system was developed primarily for the paper industry. It measures the moisture content of the paper web during manufacture at speeds of up to 3000 feet per minute. It also provides control by adjusting the dryer temperature in response to moisture changes.

The measuring head is an electrical capacitor which uses the paper web itself as part of the measuring circuit, as illustrated in Figure 2-5. Electrical capacitance is directly proportional to the dielectric constant of the material in the

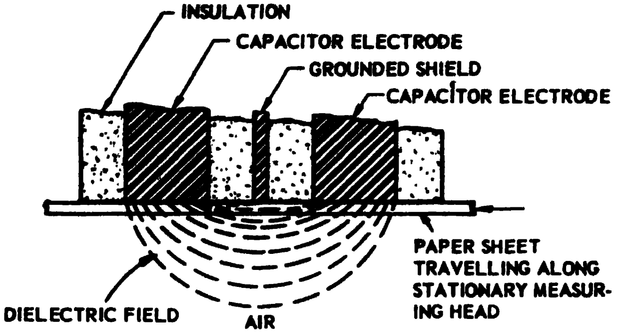


Figure 2-5. Schematic of measuring head of Foxboro's moisture control system.

electric field of the capacitor. In this case, the material in the electric field is the paper whose moisture is measured.

The dielectric constant of dry paper is about 3; of water about 80. Hence, the effective dielectric value of moist paper varies widely, depending on its percentage of water.

3. Pressure

When pressure is measured, it is usually desired to read it in terms of either gauge pressure, absolute pressure, vacuum, or pressure differential. Gauge pressure is the difference between the measured and the atmospheric pressure. Zero gauge pressure is equal to atmospheric pressure—about 14.7 psia, *i.e.*, pounds per square inch of absolute pressure. at sea level. An instrument that reads gauge pressure will change its reading with changes in atmospheric pressure. With instruments that read absolute pressure, the design problem is to eliminate the influence of changes in atmospheric pressure. The concept of vacuum covers the absolute pressure range from 0 to atmospheric. Since the total range of pressures in industrial applications extends today to about 100,000 psi, it is obvious that vacuum measurements refer to an extremely small part of the entire range. This fact is accentuated in very high vacua. For example, the Pirani gauge, described below, responds to pressures from 10^{-3} to 1 mm mercury column. which corresponds to 0.000 0193 to 0.0193 psia, *i.e.*, an extremely small range. The necessity of increased sensitivity in low pressure measurements, particularly in the vacuum range, is obvious.

This discussion will call low pressures those which are approximately within 1 psi above or below atmospheric pressure. Pressures in this range are usually expressed in inches of water column, where 1 psi equals 27.7 inches of water, and zero refers to atmospheric pressure. There are several systems in use to express vacua. One is negative gauge pressure; a reading of 3 psi vacuum, for example, is 3 psi below atmospheric, or approximately 11.7 psia. Another system is expressed in inches of mercury column, with 0 inch of mercury either equal to the ideal perfect vacuum, as it will be used in this discussion, or to the atmospheric pressure; hence 2.036 inches of mercury may mean either 1 psia or 1 psi below atmospheric pressure. In very high vacua the mercury column is measured in millimeters or even in microns, where 51.71 mm or 51,710 microns is equal to 1 psia. To express pressure differentials in general, practically any of the foregoing units are employed, depending upon the magnitude of the differential.

Bourdon Tube

The most frequently used pressure gauge is probably the Bourdon-tube type, since it is an extremely simple and rugged instrument and covers ranges from

0 to 15 psig (*i.e.* pounds per square inch gauge pressure) to 0 to 100,000 psig as well as vacua from 0 to 30 inches of mercury.

Figure 3-1 shows the construction of a Helicoid gauge made by the American Chain & Cable Company. The pressure enters the socket (1) and passes into

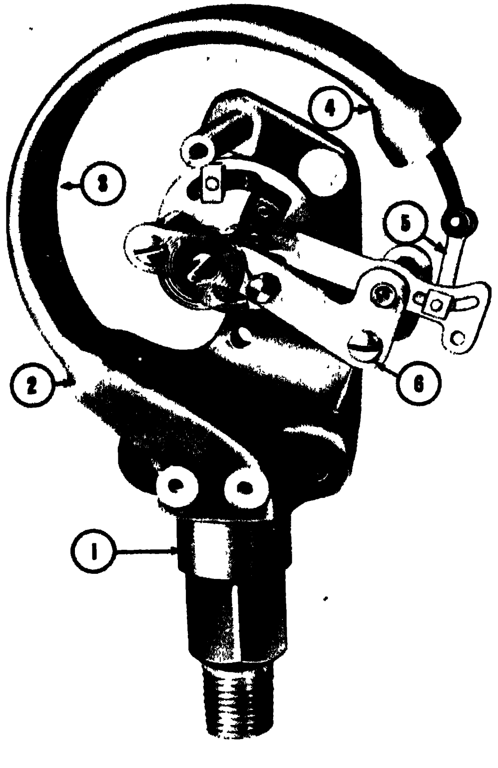


Figure 3-1. Helicoid pressure gauge. (*Courtesy of American Chain & Cable Co.*)

the Bourdon tube (3). The pressure to be measured may be that of air, steam, water, oil, and many other liquids and gases. The Bourdon tube (3) is an oval tube of circular form with a sealed end (4). Any pressure in the tube in excess of external or atmospheric pressure causes the tube to change its oval shape into a more circular cross section. The flat sides are therefore forced apart. This expands the material on the outer circumference of the tube and contracts it on the inner circumference. The resulting stresses in the tube tend to straighten out the free end, and the tip moves upward. The reverse effect occurs under vacuum, when pressure in the tube is less than the external or atmospheric pressure. The movement of the tube at the free end is called tip travel.

Connecting link (5) connects the tip of the Bourdon tube to the movement slide nut. The tip end of the link travels in a straight line while the movement cam travels in an arc around the pivot.

The movement slide nut which joins the connecting link to the movement cam is adjustable, and is used for calibrating the gauge. Lengthening or shortening the distance of the slide nut from the pivot is necessary to get the exact relationship required to translate the travel at the tip to a 270° revolution of the pointer shaft. Moving the slide nut outward decreases the deflection of the pointer; moving the slide nut inward, increases it. The Helicoid movement is made with this adjustment at the rear to allow calibration by removing the system from the case without removing pointer and dial.

The cam, which operates the movement, converts the tip travel into rotary motion of the pointer shaft. A tip travel of 3/16 inch is multiplied to a scale length of 10 inches on a 4 ½-inch dial. Usually this is done by a gear mechanism. In the Helicoid gauge, however, a helical groove is cut into the shaft and the cam rolls in the groove, producing a rotary movement of the shaft in response to its tangential movement.

A hairspring holds the lower surface of the groove on the shaft in continuous contact with the lower surface of the cam facing.

Bourdon tubes are made of a number of materials, depending upon the fluid and on the pressure for which they are used. Phosphor bronze, alloy steel, stainless steel, "Monel," and beryllium copper are frequent materials. Occasionally, none of these materials can be used because of corrosive characteristics of the fluid. To answer the need of such cases, so-called chemical gauges are available. The usual form is a standard Bourdon tube gauge and a slack diaphragm between fluid and tube. The space within the tube and its connection to the diaphragm is filled with an inert liquid, such as glycerin or a hydraulic brake fluid, to convert the diaphragm movement into a movement of the Bourdon tube. A large number of diaphragm materials are available.

The chemical gauge is also useful where the fluid may solidify in a Bourdon tube or where viscous material would tend to clog the Bourdon tube. In the latter case, as well as in any other where the bottom side of the diaphragm might require cleaning, the gauge should be constructed in such a way that the bottom of the diaphragm is easily accessible without breaking the seal of the liquid-filled space above the diaphragm.

Usually the connection between diaphragm and Bourdon tube is short and rigid. Gauges are available that have a connecting tubing of various lengths which permits mounting the gauge at a distance from the point of measurement.

Frequently, the lower part of the instrument range is unimportant from the operating point of view. It is desirable to suppress it and thus extend the scale and improve the readability. Thus an instrument that is expected to read from 400 to 500 psig, might have a scale from 400 to 1000 psig rather than from

0 to 1000 psig. The upper limit would be chosen at 1000 psig because it is a recommended practice for accurate and long-lived operation of pressure gauges to use them at about 50 per cent of full-scale reading. This, however, does not refer to recording pressure gauges, which are designed to allow temporary pressures considerably beyond their range.

Another version of Bourdon tube instruments is the differential pressure gauge, which consists of two tubes that actuate one measuring element jointly but in opposite directions, thus indicating the difference between the two measurements.

In Figure 1-30 a temperature recorder was illustrated which, as was stated, is essentially the same if used for pressure measurements. The pressure recorder differs only in the respect that the motion of the Bourdon tube is not produced by the fluid in the thermal element but directly by the process fluid. As shown in the illustration, the Bourdon tube is formed into a spiral. The spiral pressure element is essentially a series of Bourdon tubes joined end to end and wound as a flat spiral. Greater movement of the free end is thus obtained which is generally desirable in recorders of this type.

Bellows

Bourdon-tube gauges are not very sensitive as compared with other pressure gauges. Their minimum span is usually about 15 psi. The bellows-type gauge is somewhat more sensitive. It is generally used for spans down to 3 psi; but spans may go down to 40 mm of mercury if the bellows is made large enough as, for example, in the Taylor Aneroid. In this instrument the bellows is too large for the instrument case and is mounted in the back of it.

Bellows are frequently used for absolute pressure measurement. Figure 3-2 shows a Taylor bellows element for absolute pressure. The three bellows, one large and two small bellows, form two separate chambers. The one to the right has a connection to the pressure under measurement; the other is evacuated and sealed. The free ends of all three bellows are connected to a bell-shaped piece, the movement of which is transformed to a lever and from there through a link to the pen mechanism. The bell shaped piece is positioned by the expansion force of the pressure which acts against the spring inside the bell, pulling to the right. The small bellows are on one side exposed to atmospheric pressure. Since they act in opposite directions upon the bell, the effect of changes in atmospheric pressure on the position of the bell is cancelled. The vacuum in the left-hand chamber is a constant, and the measurement of the pressure as applied to the right-hand chamber is therefore not influenced by changes in atmospheric pressure.

The same assembly can be used for differential pressure measurements. In this case the left-hand chamber is not evacuated but is connected to the lower pressure. A different spring inside the bell is required.

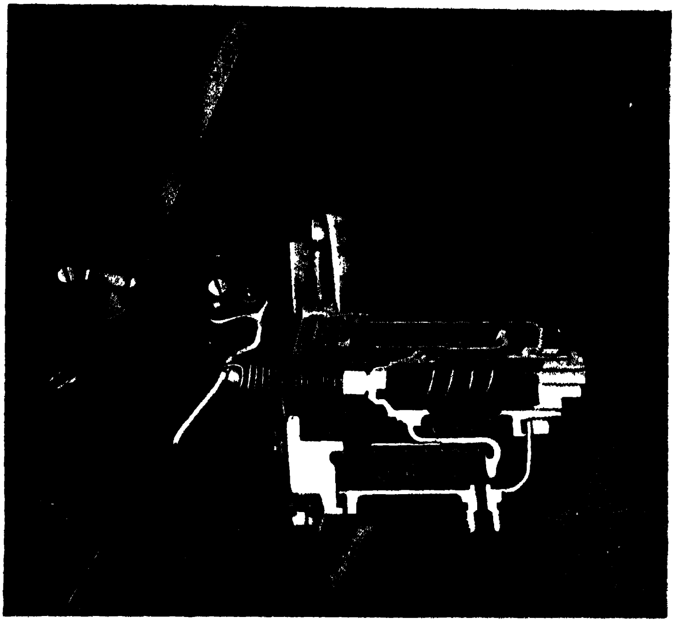


Figure 3-2. Bellows element for absolute pressures. (*Courtesy of Taylor Instrument Cos.*)

Similarly, the assembly can be adapted to the measurement of gauge pressures. In this case, the small bellows on the left hand is not required. Only one chamber—the one to the right—remains, and the measured pressure is applied to it.

Capsules

Bellows are more sensitive than Bourdon tubes, and capsules are more sensitive than bellows. They are employed not only for small spans but also where highest accuracy is demanded.

The Wallace & Tiernan capsule-type pressure gauge, for example, has an accuracy of 0.1 per cent, as compared with 0.5 per cent that is usually considered for a standard Bourdon tube pressure gauge. The capsule is made of beryllium-copper and the pressure is admitted to the inside of the capsule. In absolute pressure indicators, the capsule is evacuated and sealed, and the measured pressure is admitted to the inside of the instrument case, which is of airtight structure. Differential pressures may be measured by admitting one pressure to the inside of the capsule, and another to the instrument case.

The Fischer & Porter Press-I-Cell uses capsules for pressures up to 30 psig or psia. With higher pressures Bourdon spirals are used. The accuracy of the

Press-I-Cell with capsules is 0.05 per cent of full scale. Figure 3-3 illustrates its operation. The capsule positions the armature (ferromagnetic slug) of a differential transformer. (This is similar to the action of the pressure transmitter described at the end of this chapter.) The relative displacement between armature and differential transformer coils creates an electrical unbalance in the differential transformer. The output of the differential transformer feeds into an amplifier (not shown) which converts the unbalance to a control signal for the servomotor. Through a gear train and a lead screw the servomotor drives the follow-up beam that repositions the coils of the differential transformer relative to the armature and re-establishes the electrical balance.

The gear train that drives the lead-screw assembly also positions the indicating film strip through a drive sprocket. The film with the indicator readings printed on it, is wound on two spring-loaded storage reels. The drive sprocket draws the film scale over the fixed index on the front panel, permitting an accurate pressure reading as indicated by the film position. The film scale is 150 to 200 inches long thus assuring excellent readability even for minute changes of measured pressure.

Low Pressures

One of the most frequently used low-pressure instruments is the draft gauge. An important guide for maximum boiler efficiency is an exact indication of draft. The amount of air admitted to a fire and the amount of gaseous combustion products are both controlled by draft. Draft gauges usually read below atmospheric pressure, with part of the scale possibly above it. Their ranges generally cover from 0 to 0.5 inch to from 0 to 10 inches of water, either above or below atmospheric pressure. The draft gauge, in spite of its name, is not restricted to draft readings and can be used for any pressures and differential pressures within its range. Originally, draft was measured by manometers with the measuring tube inclined for better readability, but indicating draft gauges have found more and more acceptance, particularly because of their still easier readability. These draft gauges are of a diaphragm type, where the deflection of the diaphragm is transmitted to the pointer by suitable linkages. Diaphragms are made of leather, gold-beater skin, or other appropriate materials.

Figure 3-4 shows the mechanical action of a Bailey pressure gauge. The unit consists essentially of a calibrated leaf spring, a sealed link and a diaphragm. When the suction of the draft deflects the diaphragm toward the left, the motion is opposed by the flexing of the calibrated spring. The resulting motion is transmitted by the sealed link to the drive link which carries the motion to the indicating pointer.

The instrument is calibrated by means of a zero and a range adjustment. The range-adjusting screw causes the rigid connection to the spring to move

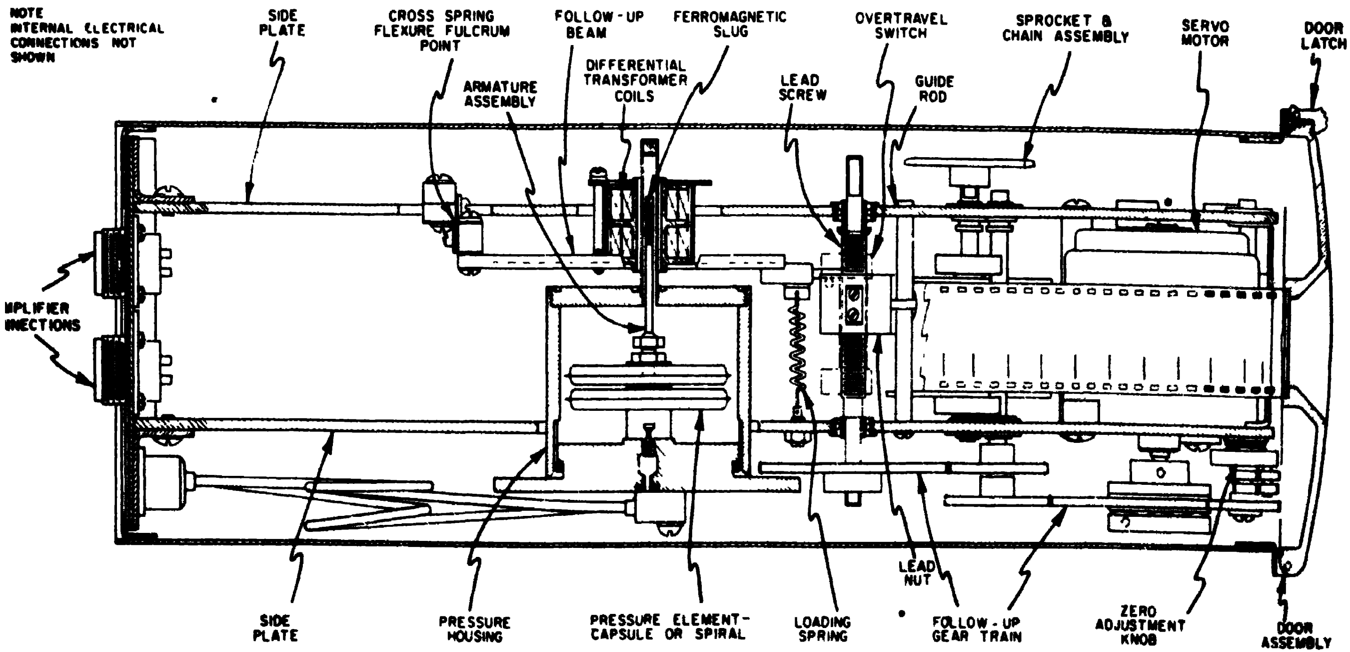


Figure 3-3. Schematic of Press-I-Cell. (*Courtesy of Fischer & Porter*)

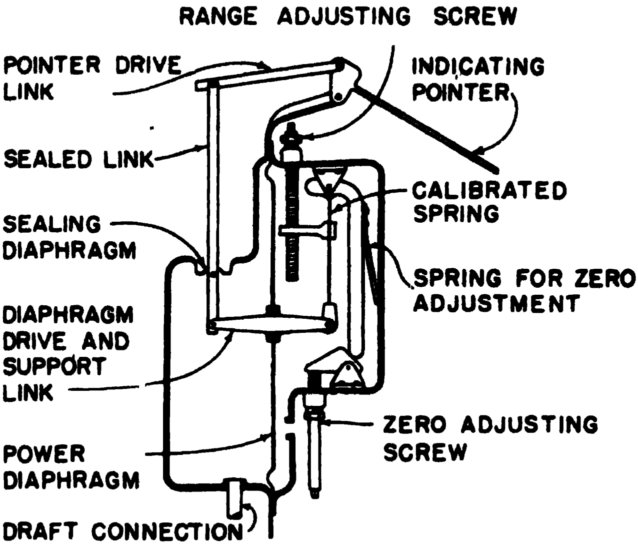


Figure 3-4. Diagram of pressure gauge. (*Courtesy of Bailey Meter Co.*)

vertically along it. The point at which this connection is clamped rigidly to the spring determines the effective length of the spring and consequently the range of the instrument. The zero adjusting screw controls the position of a cradle to which the calibrated spring is attached. Movement of this cradle about its pivot point shifts the free end of the calibrated spring together with its attached linkage, thereby providing a zero adjustment for the indicating pointer.

Using the same gauge for pressure instead of draft, the draft connection is left open to the atmosphere and the pressure is admitted to the opposite side of the diaphragm. Similarly for measuring differential pressures, the higher pressure is applied to the chamber containing the calibrated spring and the lower pressure to the chamber containing the sealed link.

The Brown Furnace Pressure Controller (Minneapolis-Honeywell Regulator Co.) is designed to keep the pressure within the combustion chamber constant. The instrument is shown in Figure 3-5. It is of the oil-immersed inverted-bell type which "weighs" the slightest change in pressure. It has two oil-immersed bells (7) suspended from a balance beam (4). The indicating pointer (8), which moves with the balance beam, indicates pressure conditions within the furnace.

One of the bells in the instrument responds to changes in the furnace pressure. The furnace pressure is applied underneath the bell and obtained through a suitable connection or tap in the furnace roof or wall. Pressure from outside

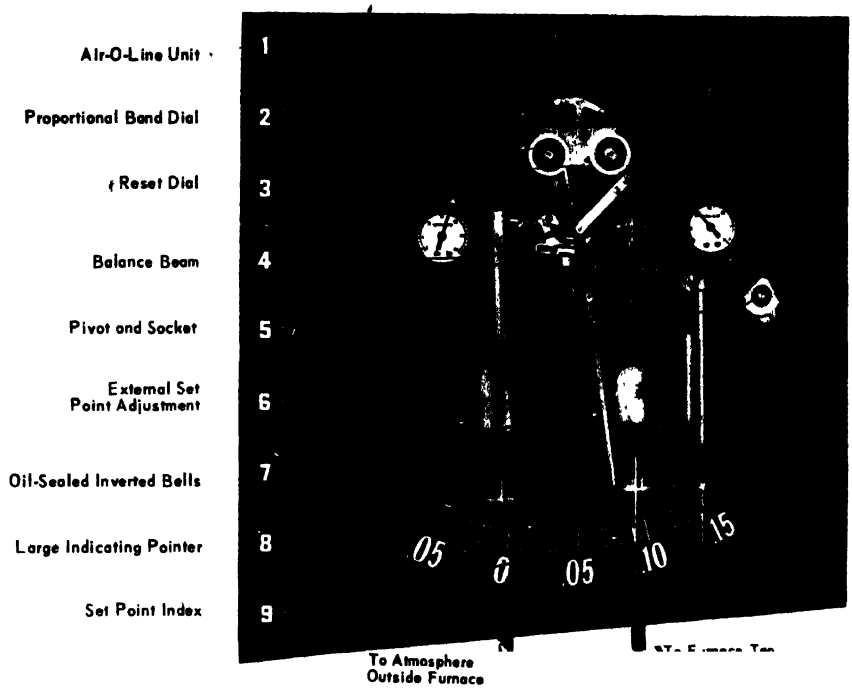


Figure 3-5. Furnace pressure controller. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

the furnace is admitted underneath the other bell. This pressure is obtained through an open connection located near the furnace tap. Being adjacent to each other at the furnace, both pressure connections to the instrument are affected in the same degree by ambient temperatures. The net result is an accurate indication of the differential pressure between the inside and the outside of the furnace.

The control index (9), which is positioned by segment (6), indicates the setting at which the instrument will control the furnace pressure. Changes in position of the balance beam in the instrument are transmitted to a Brown Air-O-Line control unit (1). This is a pneumatic control unit with proportional band (2) and reset-rate (3) adjustments, as will be described in chapter 12. The control air output from the instrument is transmitted to a piston operator which positions a damper in the stack in order to maintain the furnace pressure at its desired value.

It is obvious that this instrument can be used for differential pressures by connecting the two pressures to the respective bells. For small pressures, where compensation is not necessary, a single inverted-bell model is available.

Small Pressure Differentials

Differential-pressure meters are used extensively for flow-metering. They are described in the chapter on flow. Their application, however, is not limited to flow, and they are used wherever pressure differentials in their particular range are to be measured.

Very High Vacua

The measurement of high vacua is possible only by indirect methods. One method is to measure the impact of molecules; another is to determine the effect of heat dissipation from a heated wire; a third is to measure the ionization in the vacuum. The first method is the principle of the G.E. molecular vacuum gauge, illustrated in Figure 3-6, available for ranges between 0 and 20 mm of

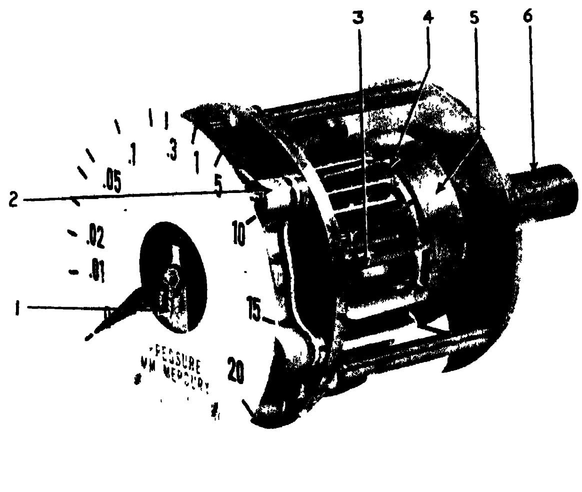


Figure 3-6. Molecular vacuum gauge. (*Courtesy of General Electric Co.*)

mercury of dry air pressure. The instrument can be used with any gas, but since its operation depends upon the molecular weight of the gas in the system, lighter gases, *e.g.*, hydrogen, will have larger ranges, and heavier gases, like xenon, will have smaller ranges than dry air.

A G.E. Telechron motor to which the rear bearing (6) is directly coupled, rotates one of the two vaned cylinders (3, 4, and 5) at 3600 rpm. The other cylinder is spring-retained and directly coupled to the indicating pointer, which is magnetically damped (2) to minimize pointer oscillation. A zero setter (1) allows initial adjustment of the pointer.

The gas molecules coming in contact with the motor-driven cylinder are set in motion in the direction of rotation. These gas molecules, receiving energy from contact with the motor-driven cylinder, strike the restrained cylinder, transferring energy to it. The restrained cylinder will move under the impact of the molecules a distance which is proportional to the amount of energy transferred. The movement of the restrained cylinder is thus proportional to the number of gas molecules present and hence to the gas pressure. The pointer attached to the restrained cylinder will read the pressure on a scale which is properly calibrated.

The Pirani gauge uses the second of the before mentioned principles: heat dissipation from a heated wire. The usual range is between 10^{-3} to 2 mm of mercury. For example, the Consolidated Vacuum Corporation makes Pirani gauges with ranges such as 10^{-3} to 5×10^{-2} and 5×10^{-2} to 2 mm of mercury. Another of their models covers the range from 10^{-3} to atmospheric pressure (760 mm of mercury).

The detecting element employs a resistance wire of very small cross section, which is heated by an electric current that flows through it. This element is exposed to the space under measurement. The heat loss from the element is due to conduction. Heat transfer by conduction depends upon the number of molecules that strike the resistance wire. This number is a function of the existing pressure. As the pressure decreases, the heat loss from the resistance wire also decreases, resulting in a temperature rise which in turn will increase the resistance of the wire. This means that the resistance will settle at a new value for any change in pressure. Connecting the resistance wire into a Wheatstone bridge and measuring the unbalance of the bridge gives an indication of the vacuum.

One provision has to be made in this arrangement: since the temperature within the vacuum chamber is generally variable, the heat dissipation will not be constant, and to compensate for this error, a second resistance wire, forming another leg of the bridge, is added. The second wire is sealed into a tube which is evacuated to a pressure of less than 1 micron. It is exposed to the atmosphere of the vacuum chamber; responding like the first resistance wire to changes in temperature, it compensates for their influence on the vacuum measurement. The compensating tube also reduces the zero drift which can be caused by slight variations in the bridge voltage.

A thermocouple-type vacuum gauge is made by several manufacturers. The one made by The Fredericks Company contains four filaments which are continuously and uniformly heated, as illustrated in Figure 3-7. Two of these four filaments are in a reference chamber which is sealed off at a pressure of ap-

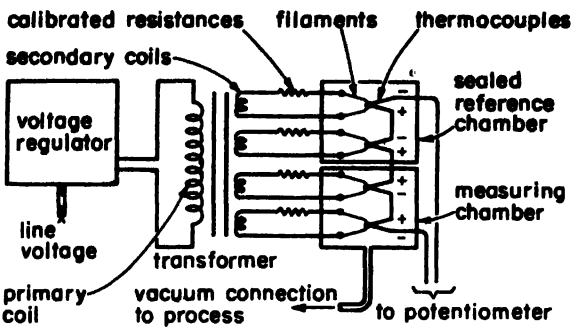


Figure 3-7. Thermocouple-type vacuum gauge. (*Courtesy of The Fredericks Co.*)

proximately one micron, while the other two filaments are in a measuring chamber exposed to the vacuum under measurement. A small, sensitive thermocouple is situated on each of the four filaments and connected so that the two in the reference chamber are in series and the two in the measuring chamber are in series. In this way, sufficient emf is obtained. The two sets of thermocouples are connected so that their emf's oppose one another. The difference between the two opposing emf's is a measure of the difference in pressure between the reference chamber and the measuring chamber. From a pressure of 10^{-3} up to 0.5 mm of mercury, this emf varies from zero millivolts to about 19.2 millivolts. This signal is applied to a Brown Electronik potentiometer which is calibrated in terms of pressure.

A typical example of the third method, ionization, is the gauge made by F. J. Cooke & Company which Bristol uses with their Dynamaster recorder. It covers a range down to 2×10^{-8} mm of mercury. The arrangement is similar to that of the familiar electronic vacuum tube, except that the normally sealed glass or metal envelope is connected to the vacuum under measurement. The main components within the envelope are the heater filament, a positively charged grid and a negatively charged plate. When the filament is heated it is made to emit electrons, *i.e.*, minute negative charges. These are attracted toward the positively charged grid. Because of the wide-open interstices within the grid structure, most electrons fly past the grid in the direction of the plate. The electrons having the speed and characteristics of extremely fast projectiles bombard the molecules of the residual gas in the evacuated system, knocking electrons out of the molecular structure and thereby producing ions. The ions are positively charged particles that are attracted toward the negatively charged plate. Those electrons which may also fly toward the plate because of their initial acceleration, will be repelled from it and return to the positive grid where they are absorbed. The ions, however, being attracted to the plate, constitute an electric current, the intensity of which is determined by the number of ionized gas molecules. Since this number depends on the total amount of gas molecules present, *i.e.,* the absolute pressure, it is possible to measure the plate current and thereby determine the pressure.

The Alphatron, made by the National Research Corporation, covers a range from 10^{-4} to 1000 mm of mercury. The principle involved is again that of ionization, but instead of using the electrons emitted from a hot cathode to ionize the gas molecules, a radium source is utilized. Radium is a continuous source of alpha particles, which act as ionizing agents. The Alphatron has a negatively charged grid collector plate which attracts the positive ions. The grid current thus produced is in the order of 10^{-12} amperes which can be measured by proper amplification.

Strain Gauge Cells

One of the reasons for using strain gauge cells for pressure measurements is that their output can easily be transmitted over long distances to potentiometer receivers. Another reason is their fast response to changes in the measured pressure. The Baldwin SR-4 strain gauge, made by the Baldwin-Lima-Hamilton Corporation, is a small slip of impregnated paper with a wire grid bonded to its surface. When the gauge is cemented to a surface which is subject to stress, the wire of the gauge is stretched, thereby decreasing its diameter and increasing its resistance. By measuring the change of resistance, the force producing the stress, *i.e.,* the pressure, is determined.

Figure 3-8 is a simplified wiring diagram of a strain gauge connected to a Brown Electronik potentiometer. The measuring circuit is a Wheatstone bridge.

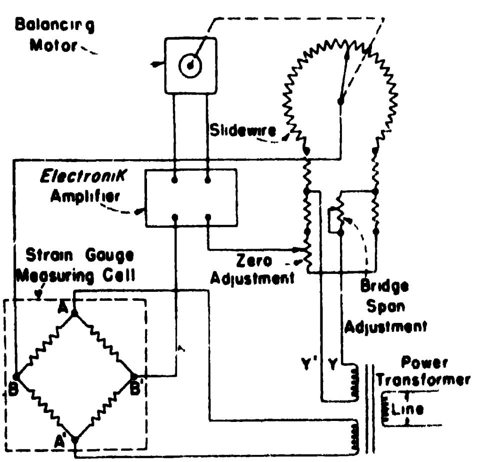


Figure 3-8. Schematic of Baldwin strain gauge connected to Electronik potentiometer. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

$A' - B'$ and $A - B$ represent the active strain gauges, while $A' - B$ and $A - B'$ are so-called dummies, which are not under stress but compensate for any temperature changes that would otherwise affect the accuracy of the gauge. A change in stress causes a corresponding change of resistance in the strain gauge. This results in an unbalance of the bridge and a consequent voltage across $B - B'$. The potentiometer contains, as shown in the illustration, a secondary bridge. Any voltage across $B - B'$ of the primary bridge is balanced against the secondary bridge voltage, and the difference is applied to the amplifier; this energizes the balancing motor to reposition the slider of the slidewire in the secondary bridge and so adjust the secondary bridge relations until they cancel the unbalance signal from the strain gauge. In positioning the slider, the balancing motor simultaneously positions the instrument pen, which reads the pressure on the calibrated scale.

Pressure Transmitters

The strain gauge cell described above has the inherent characteristic of converting pressure into an electric signal which can be transmitted.

Another device used in electrical transmission of pressure is the differential or moveable core transformer. An example is the Atcotran made by Automatic Timing & Controls, Inc. Its application as pressure transmitter is illustrated in Fig. 3-9. The transformer consists of a primary coil and two secondary coils interconnected as shown. The transformer core is suspended

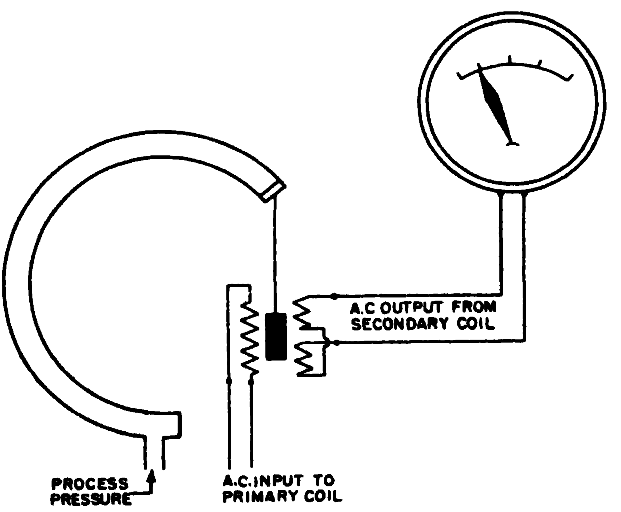


Figure 3-9. Schematic of Atcotran pressure transmitter.

from the tip of the Bourdon tube and moves up and down in response to changes in the process pressure which is being measured. The primary coil is connected to an a.c. source, and the magnetic flux generated by this coil is distributed by the core so that a voltage is induced in the two secondary windings. If the core is positioned in such a way that the voltage induced in each of the two coils is equal, the a.c. output to the indicating instrument is zero because the two coils are wound in opposite directions and the voltage induced in one is 180° out of phase with the other. As a result, the transformer output corresponds to the difference between the two voltages induced in the secondaries. An extremely small movement of the core suffices to produce a measurable voltage output. A typical receiver for such a transmitter is illustrated in Figure 5-8 and described there.

For pneumatic transmission it is necessary to convert the pressure measurement into an air pressure signal. Typical systems are described in the next chapter since the methods used for the pneumatic transmission of pressure and of flow measurements are similar.

4. Flow

Flow can be measured by many methods. This chapter will discuss those most frequently used in industrial applications, which are:

- Differential-pressure meters
- Variable-area meters
- Weir meters
- Positive displacement meters
- Current meters
- Electronic meters
- Mass flow meters
- Solid flow meters

DIFFERENTIAL-PRESSURE METHODS

Primary Elements

In flowing through a restriction in a pipe line, the cross-sectional area of flow contracts and the velocity increases. The physical relations (Bernoulli theorem) are such that the static pressure decreases as the velocity of the flow increases. The static pressures* at two points of different flow velocities are measured by a differential-pressure instrument. Since this pressure differential is a function of rate of flow, the instrument can be calibrated accordingly and becomes a flow meter.

As the flow continues downstream, it returns to its original cross-sectional area (provided upstream and downstream pipes are of the same size). In the ideal case, *i.e.*, one where the restriction would not cause turbulence of the fluid flow, there should be a minimum difference between downstream and upstream pressures. Since ideal cases do not exist, a permanent pressure loss due to turbulence will result.

The restriction in the flow for the purpose of flow-metering is called a primary element and can be an orifice plate, a flow nozzle, a Venturi tube, etc.

The pressure differential measured by a number of devices like Pitot tubes and Gentile flow tubes is, however, not produced by a restriction. These de-

*Static pressure is the pressure at right angle to the flow, such as would be indicated by a pressure gauge. Dynamic pressure is the pressure exerted by the fluid in the direction of flow.

vices measure the difference between dynamic and static pressure—the so-called impact pressure.

Orifice Plates. The orifice plate, Figure 4-1, is the most simple and flexible of the primary elements. It is the least expensive in initial cost, but can become the most expensive in operation because of the high permanent pressure loss which may amount to 60 to 80 per cent of the differential pressure produced by the orifice plate. It is a thin, flat disc, with an orifice for the passage of the fluid, and is inserted between flanges in the pipe. It can be readily re-bored or replaced to accommodate flow capacity changes. Within its application range, it is as accurate as the Venturi tube or the flow nozzle.

(a) (b) (c)

Figure 4-1. (a) Concentric orifice plate; (b) Eccentric orifice plate, (c) Segmental orifice plate. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

Orifice plates are generally built of 1/16 to 1/8-inch material (thin type) for orifices up to 10 inches; 1/4-inch material (thick type) is used for larger sizes or where it is required by special conditions.

Orifice plates are sometimes provided with an additional small hole for the passage of condensates and gases. When gases are measured, this hole is located at the bottom to allow condensate to pass in order to prevent its building up at the orifice plate. When the fluid is a liquid, the additional hole is at the top so that gases can pass and gas pockets cannot build up. The use of such a drain hole is frequently considered a disadvantage because it may produce errors in measurement.

Usually, orifices are concentric but they may also be eccentric or segmental, as shown in Figure 4-1. Where liquid fluids contain a relatively high percentage of dissolved gases, the eccentric type of orifice plate is recommended. Furthermore, this plate serves especially well when gases are metered, which contain large quantities of condensate. The eccentric orifice plate is installed with the bore tangent to the *upper* surface of the pipe when the flowing material is liquid, and tangent to the *lower* surface of the pipe when the fluid is a gas.

Liquids containing solids, provided they are not sticky or abrasive, can be metered by using a segmental or eccentric type orifice plate. The segmental plate is installed with the dam horizontal and with the curved section of the opening coincident with the lower surface of the pipe. Eccentric and segmental orifices also have the characteristic that under some given conditions they permit the low-pressure tap to be located farther downstream than would be possible with a concentric plate. Thus, they are of advantage in cases where high hub flanges limit the available distance between the low-pressure tap and the orifice plate.

The tolerance in boring orifice plates is 0.1 per cent of the orifice diameter. Although a higher accuracy is frequently offered, the over-all accuracy of the measuring system is hardly high enough to derive an advantage from it. For applications requiring orifice plates for 1 ½-inch pipe or smaller, a pre-calibrated assembly, consisting either of orifice, flanges, and pipe run, or an all-welded form is recommended. With such an assembly, an accuracy of better than 1 per cent can usually be met. Otherwise, an error of up to 12 per cent may well result.

The orifice of the standard orifice plate is tapered and it is installed with the sharp edge on the upstream face. This conforms to data published by the American Society of Mechanical Engineers and will give accurate readings at the fluid viscosities for which it is designed. However, when the viscosity changes, the Reynolds number* is no longer a constant, and a correction of the reading becomes necessary.

The quadrant-edged orifice plate, made by the Foxboro Company, is so designed that the pressure differential across it remains constant over a wide Reynolds number range. Instead of the sharp edge of the standard orifice plate, it has the upstream edge rounded to a quarter circle. It measures accurately with Reynolds numbers below 20,000 and down to approximately 500. It is used where utmost accuracy is required in flow measurements of viscous fluids of which the viscosity either varies or is unknown.

*The Reynolds number is expressed by vds/u, where v is the mean velocity, d is the pipe diameter, s is the specific gravity, and u the absolute viscosity of the fluid. Flow through an orifice for a given differential pressure varies with the Reynolds number.

If it is desirable to remove the orifice from the line under pressure without switching to a bypass, a specially constructed orifice assembly made by Daniel Orifice Fitting Company may be used. This orifice plate is part of a fitting which consists of an upper and a lower chamber separated by a slide valve which enables the orifice plate to be cranked in and out of its position in the line.

The pressure differential across the orifice as a function of the flow rate under given conditions depends upon the diameter of the orifice. Two methods are in general use: the direct-reading orifice plate and the even-sized orifice plate. With the first method, the required bore size of the orifice plate is calculated from the flow under consideration and the range of the flow meter, so that chart readings directly express rate of flow, provided that the characteristics assumed in the calculations are met with and maintained in the actual installation. The second method is based on the even-sized orifice plate and builds up on certain standard sizes of bore diameter of orifice plates, such as 1.000, 1.250, 1.375, etc. inches. The chart readings are then multiplied by coefficients to obtain actual rate of flow. The even-sized orifice plate has the advantage of making possible standardization in stocking certain orifice plate sizes and charts in a given plant. The advantage becomes small when orifice plates are made by the user in his machine shop, instead of being bought and stocked.

One of the reasons for the excellence of the orifice plate as a primary device in flow measurement is the great wealth of data which were collected in a joint undertaking of the U. S. Bureau of Standards, the American Society of Mechanical Engineers, and the American Gas Association. These data are used by the industries and by science as the basis of flow metering with orifice plates.

Flow Nozzles. The flow nozzle is illustrated in Figure 4-2. It allows measurement of rates of flow which are about 60 to 65 per cent higher than the maxi-

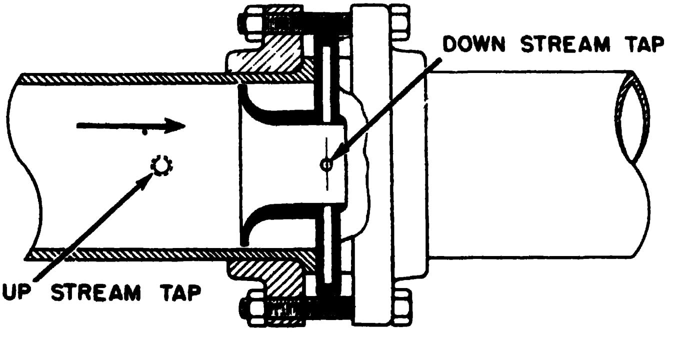


Figure 4-2. Flow nozzle (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

mum rates of flow for which an orifice plate can be used. Hence, the flow nozzle will find its main application where under high operating pressures great capacities must be measured through lines which are reduced to a minimum size for some reason. Let W be the rate of flow in pounds per hour, D, the internal pipe diameter in inches, w, the fluid density in pounds per cubic foot, h, the differential across the primary element in inches water column. When $W/(D^2 \sqrt{wh}) > 140$ a flow nozzle should be used rather than an orifice plate.

It would be erroneous to select a flow nozzle in order to reduce the permanent pressure loss caused by the orifice plate. In order to obtain the desired pressure differential as a measurable function of flow, it is necessary to use a flow nozzle with a smaller opening than it would be necessary for the orifice plate. The result is a permanent pressure loss of about the same magnitude.

There is, however, another advantage that occasionally favors the use of the flow nozzle. Piping requirements for orifice plates and flow nozzles are such that there is a minimum amount of straight pipe before and after the primary element. The length of straight pipe required increases rapidly with an increase of orifice or nozzle opening for a given pipe diameter. Since the nozzle requires a smaller opening, less straight pipe is required.

Venturi Tubes. A Venturi tube (Figure 4-3) is recommended where the measured fluid contains large amounts of suspended solids. It is also used where

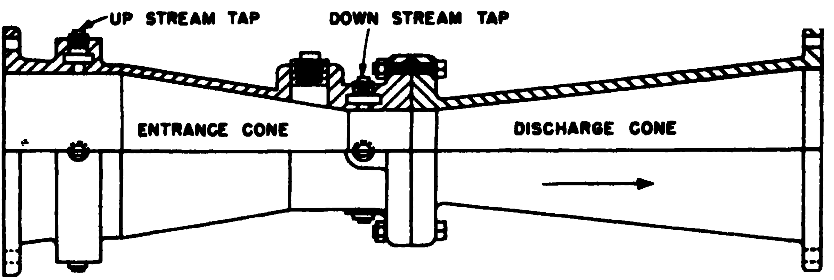


Figure 4-3. Venturi tube. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

maximum accuracy is desired in the measurement of highly viscous fluids, and where the favorable pressure recovery characteristics of the Venturi tube are desirable. The latter advantage usually does not suffice to decide in favor of the Venturi tube. Its initial cost is high and other devices have similar or better recovery characteristics. The permanent pressure loss of Venturi tubes is about 12 per cent. The loss of some types of flow tubes, which are described further below, is less than that. A combination of flow nozzle and Venturi (Figure 4-4), although not of the same low-loss efficiency as a Venturi tube, will usually lose less than 20 per cent of its upstream pressure, and is in cost considerably less than a Venturi tube. The combination shown in Figure 4-4 is the Venturi Insert Nozzle made by B-I-F Industries, Incorporated.

Elbows, etc. All the above described primary elements average the flow rate through the cross section of a pipe. To do this, certain conditions of minimum straight runs before and after the element must be fulfilled. Under conditions where dimensions cannot be fully kept straightening vanes must be inserted in the pipe. Occasionally, however, a pipe line is so full of bends that no appropriate straight run can be found.

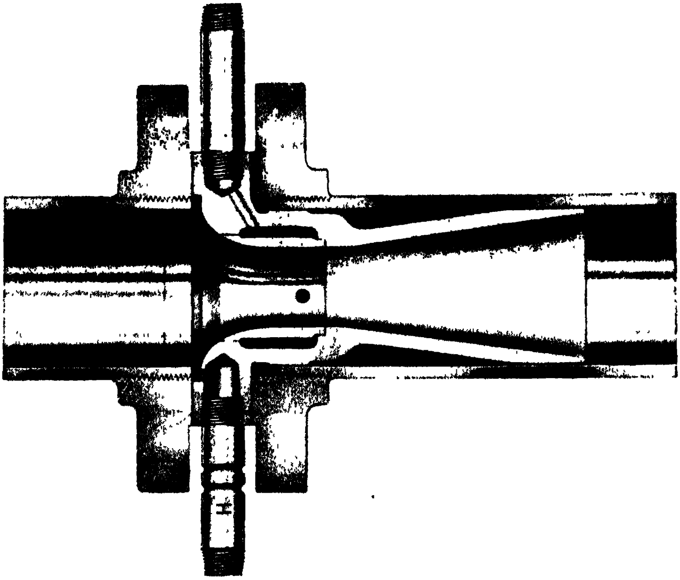
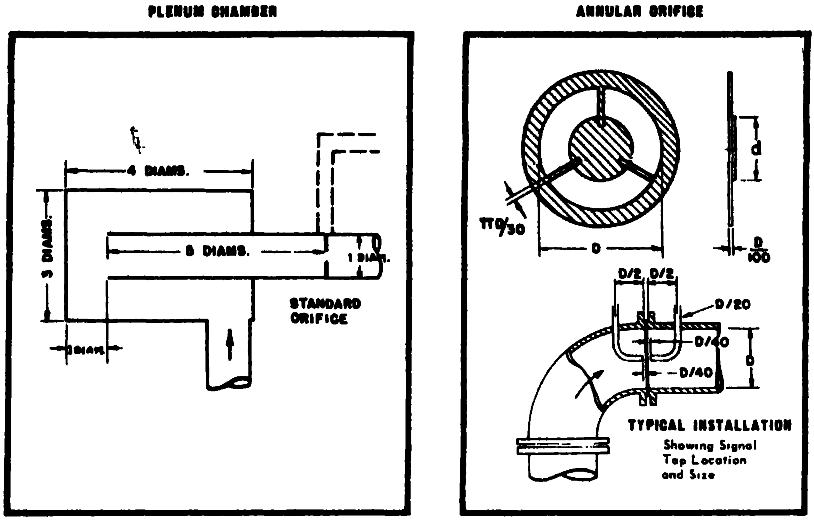


Figure 4-4. Venturi insert nozzle. (*Courtesy of B-I-F Industries, Inc.*)

In such a case, an ordinary pipe elbow may be used as a primary element. The pressure differential measured is that between the inside and outside curves of the elbow, which must be tapped at these two points. Because of the centrifugal force of a fluid flowing around an elbow, a pressure differential will develop between these two points which will change with the rate of flow. The disadvantage of this arrangement is that it requires individual calibration of each installation in order to obtain reasonable accuracy.

Two other methods have been successfully used to obtain a pressure differential as a function of rate of flow when sufficient straight run of pipe was not available. They are recommended by GPE Controls, Inc. for such conditions and are illustrated in Figures 4-5, *a* and *b*. In Figure 4-5*a*, a plenum chamber is used ahead of the standard orifice, and in Figure 4-5*b*, an annular orifice is used instead of the conventional plates shown in Figure 4-1.

Flow Tubes. The Dall Flow Tube, illustrated in Figure 4-6, is made by B-I-F Industries. Its permanent pressure loss averages about 5 per cent, which is better than that of most Venturi tubes. It consists of a short, flanged cylin-



(a) (b)

Figure 4-5. (a) Orifice with plenum chamber
(b) Annular orifice (*Courtesy of GPE Controls, Inc.*)

drical body designed with an abrupt decrease in diameter, followed by a conical restriction and a diverging outlet. The reduced area at the cone entrance, together with the design of the annular throat aperture, induces a pressure differential appreciably higher than can be obtained with Venturi or nozzle type devices of comparable dimensions. It is much shorter, much lighter, and lower in cost than a Venturi.

The Gentile Flow Tube made by General Controls Company is a short pipe insert as shown in Figure 4-7. The inner periphery is equipped with two groups of pressure nozzles. One group points upstream and is exposed to the dynamic pressure. The other group points downstream and therefore does not respond to the impact pressure, but measures the static pressure. The nozzle groups are interconnected by two separate pressure rings from which connections are made to the high- and low-pressure sides, respectively, of a conventional flowmeter. The Gentile Flow Tubes are being used not only for clear

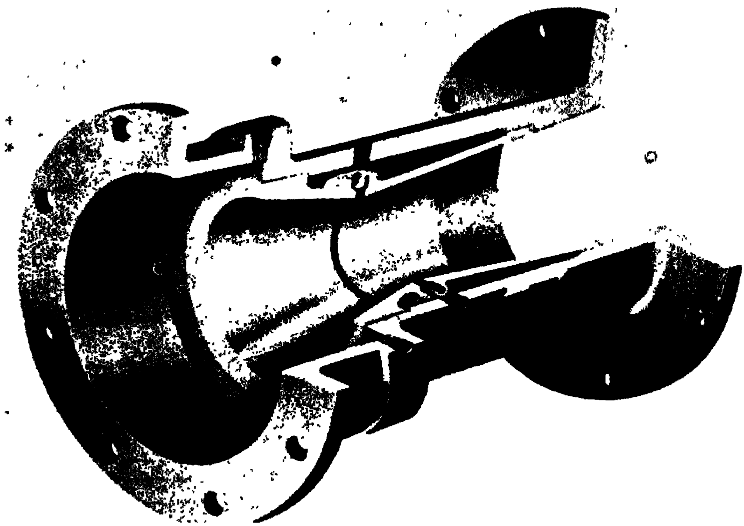


Figure 4-6. Dall flow tube. (*Courtesy of B-I-F Industries, Inc.*)

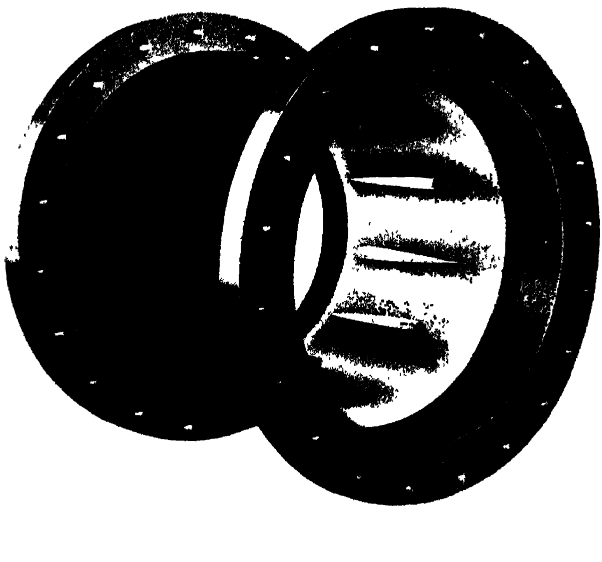


Figure 4-7. Gentile flow tube. (*Courtesy of General Controls Co.*)

fluids, but also (with suitable purge or back flushing system to counteract any possibility of clogging their nozzles) in metering raw sewage, sludge, river water, white water, black liquor, casing-head gas and other fluids carrying solids in suspension.

Pitot Tubes. The Pitot tube is inserted in a pipe or duct so that the flow directly strikes a small opening of the tube, called the nozzle. The difference between the pressure thus produced (dynamic pressure) and the static pressure, which are determined simultaneously, is measured. The Pitot tube does not average the flow through the cross section of a pipe, as do the Venturi tube, flow nozzle, and orifice plate, but measures the flow only at the point to which its nozzle is exposed. In a pipe or duct where the velocity distribution is not uniform, no primary element is able to measure the average rate of flow directly. If the distribution is known, or is determined by locating the Pitot tube at different points in the cross-sectional area, then it may be used continuously in one position and give an indication of the total flow. Its high accuracy for flow within the immediate proximity of its position renders it invaluable as a secondary standard for checking flowmeter installations, since by taking a number of readings in different positions, the exact average flow rate can be determined.

In large pipe sizes it is frequently economical to use a Pitot tube. For example, in a 20-inch pipe the Pitot tube would cost only about 1/3 of an orifice plate and 1/10 of a cast iron Venturi tube. Conversely, in a 4-inch pipe the Pitot tube would be about 70 per cent more expensive than an orifice plate. In an 8-inch pipe the cost for Pitot tube and orifice plate is about the same.

As previously mentioned, the Pitot tube has the great advantage that its pressure loss is negligible. Since it measures the dynamic and the static pressure, the difference between the two being a function of the rate of flow, the pressure difference becomes very small with insufficient velocities of the flowing fluid. This makes the use in practical industrial instruments difficult.

Pitot-Venturi Tube. To obtain larger pressure differentials, the Pitot-Venturi tube was developed, which is a small Venturi tube inserted in the center of a pipe line, the same way a Pitot tube would be inserted. Since a small part of the flow will pass through the insert, the flow can be measured through a piezometer ring around the throat of the Venturi tube and connected by a small pipe to the outside of the main pipe.

A further development is the Pitot tube with double Venturi heads. Figure 4-8 shows the cross section through the latter device, which is made by Taylor Instrument Companies. The pressure differential is 7 to 10 times as large as that obtained with the conventional Pitot tube. The tube illustrated consists of two concentric Venturis arranged so that their openings lie in the same plane, the exit cone of the inner Venturi terminating in the throat section of the outer

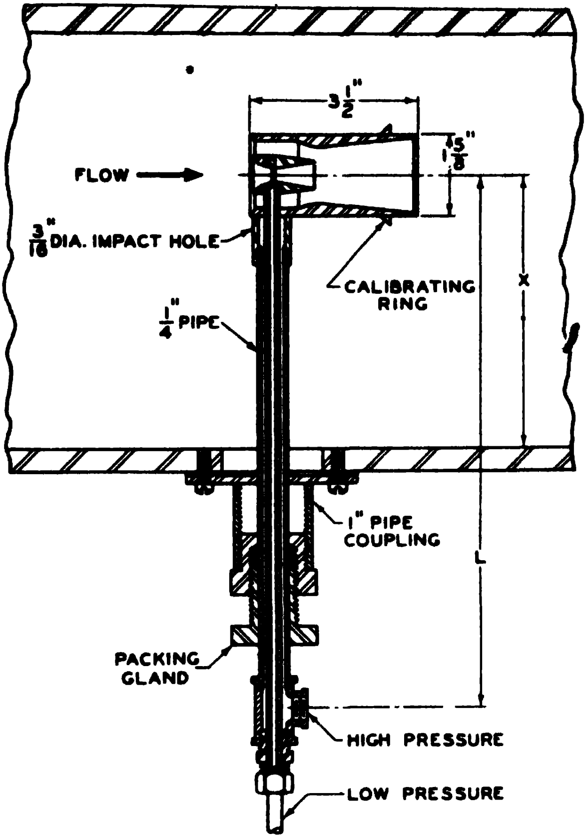


Figure 4-8. Pitot-Venturi flow element. (*Courtesy of Taylor Instrument Cos.*)

Venturi. The flow passes through the inner Venturi and also through the area between the two Venturi tubes. Because of the decreased pressure in a Venturi throat, more fluid passes through the inner tube, the exit passing into the low-pressure zone of the throat of the outer Venturi. This action provides a multiplying effect within the element, which produces a pressure differential sufficiently high to be measured by conventional flowmeters.

Mercury-type Flowmeters

The flowmeter measures the pressure differential produced by any of the primary devices described above, and expresses it in units of rate of flow. Since the rate of flow is proportional to the square root of the pressure differential, the resulting deflection of the pen is a function of the square of the flow rate, unless some means is used to translate the square relation into a linear movement. Otherwise the chart of the instrument will be a so-called square-root chart, *i.e.*, a chart calibrated in units of flow, but with very close divisions for the lower flow rates which gradually expand toward the upper limit of the chart. This makes it difficult to read the chart in the lower regions, but increasingly easier in the upper ones. It is shown below that differential-type flowmeters may become excessively inaccurate below 25 per cent of their range. Therefore, a flowmeter of this type should not be used in the lower part of its range; consequently the difficulty of reading the chart in that region is unimportant. Nevertheless, a number of flowmeters include conversion of the square-root relation between pressure differential and flow rate into a linear one. Whatever the method of conversion, the increasing inaccuracies in the lower regions of the range hold true for all instruments. The conversion results in a chart of even graduation throughout the range. These linear charts have the advantage of being easier to read in the lower region of the range and more difficult to read in the upper regions, as compared with square-root charts.

A linear inaccuracy, *i.e.*, one of equal magnitude over the entire range of the instrument, produces a rapidly increasing percentage error as the flow rate decreases. If, for example, an installation with 32 inches of mercury differential at full flow is inaccurate by 0.2 inch of mercury over the entire range, the result is about as follows: at 100 per cent of flow the inaccuracy is 0.6 per cent; at 75 per cent of flow, 1.1 per cent; at 50 per cent of flow, 2.5 per cent; at 25 per cent of flow, 10 per cent. It is thus seen that the inaccuracy increases rapidly with a decrease of flow. As mentioned, below 25 per cent the differential-pressure type of flowmeter is generally not considered an accurate device. Above 25 per cent the combined accuracy of the flowmeter instrument with the primary element in an industrial installation is about 1 to 2 per cent.

The U-Tube Meter Body. The U-tube meter body is a manometer. Figure 4-9 shows a cross section through the mercury chamber of a Westcott Orifice Meter made by the American Meter Company. It consists of a high-pressure chamber and a low-pressure chamber both connected by a U-tube and filled with mercury. A float in the low-pressure chamber moves up and down with the mercury level. Its movement is transmitted by means of a lever arm to a shaft which positions the pen of the instrument. The float has to be large enough to obtain sufficient leverage for accuracy and sensitivity in the pen movement. This requires the enlarged cross-sectional area of the chamber in which the float is located. The float may be either in the low-pressure or the high-pressure chamber, depending upon the basic design selected.

The pressure differential as produced by the primary element will depress the mercury level in the high-pressure chamber in relation to the level in the low-pressure chamber. The consequent movement of the float positions the instrument pen to record the corresponding rate of flow.

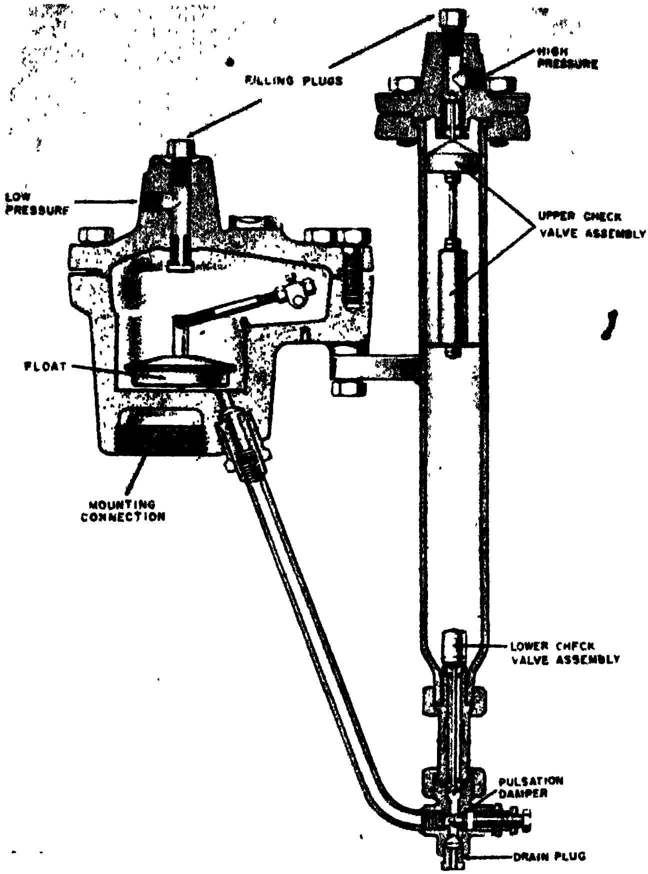


Figure 4-9. Cross section through mercury chamber. (*Courtesy of American Meter Co.*)

The loss of mercury is prevented by check valves in the high-pressure chamber of the manometer. The lower check valve, which is normally submerged in mercury, gives over-range protection. The upper check valve which is actuated by a plastic float, protects against mercury loss under conditions of reversed differential pressure. The extended construction of the high-pressure side permits the plastic float and upper check valve assembly to be normally above the mercury level and maintained in an open position by the weights of the parts. Closure of the valve is effected by the buoyant action of the mercury on the plastic float under conditions of reversed differential pressure.

Pulsation dampers are provided in practically all makes of this type of flowmeter. These dampers do not cancel the reading error caused by pulsation of flow even though they may eliminate the pulsing response of the instrument. Their main purpose is to prevent oscillations of the mercury level for non-oscillating changes in flow. In the Westcott Orifice Meter of Figure 4-9 the pulsation check is in the lower right corner of the meter body. It consists essentially of an adjustable needle valve.

While one of the pressure chambers has an enlarged cross-sectional area for the housing of the float, the other chamber, usually called the range tube, is mounted in such a way that it is easily interchangeable. For a given pressure differential, the change in level in the float chamber depends upon the relation of the cross-sectional areas in the two chambers. The smaller the range tube area with respect to the float chamber, the less will be the change in level, and hence the displacement of the float, in the float chamber. Flowmeters cover a number of pressure-differential ranges. In order to obtain approximately the same float level movement between minimum and maximum flow for the various pressure-differential ranges, interchangeable range tubes with different cross-sectional areas are used. It is thus possible to have one instrument that covers as many different ranges, as there are range tubes available for it. The instrument can be changed from one range to another, by replacing the corresponding range tube, which can be done in the field.

Ranges vary between wide limits. For liquid service the 100 inches of water is the most commonly used differential range. In a number of cases it will be found necessary to use a greater differential range in order to pass the required maximum flow. In other applications maximum allowable loss of head may be the governing factor, making it necessary to choose a lower differential range. The interchangeable range tubes, mentioned above cover such ranges as 20, 25, 50, 100, and 200 inches of water.

The Ledoux Bell-type Flowmeter. The Ledoux bell is a method to obtain a movement which is a function of the *square root* of the pressure differential, *i.e., linear* to the rate of flow. The Bailey fluid meter, which uses a Ledoux bell, is shown in Figure 4-10. The high pressure is admitted through the standpipe above the mercury level inside the bell, and the low pressure is applied to the mercury level outside the bell. Changes in pressure move the bell up and down. As it rises, its walls emerge from the mercury, changing the buoyant force and thereby counterbalancing the upward force of the differential pressure. The shape of the bell is such that when the pressure inside the bell depresses the mercury level, the surface area diminishes while the surface area outside the bell remains the same. As the pressure differential rises, an increasing amount of change is needed to produce the same amount of bell movement as at low pressure differentials. The bell is shaped so that the over-all movement is linear to the rate of flow. Changes in range may be obtained by replacing the Ledoux bell assembly with another of different maximum differential and changing the lower part of the meter body.

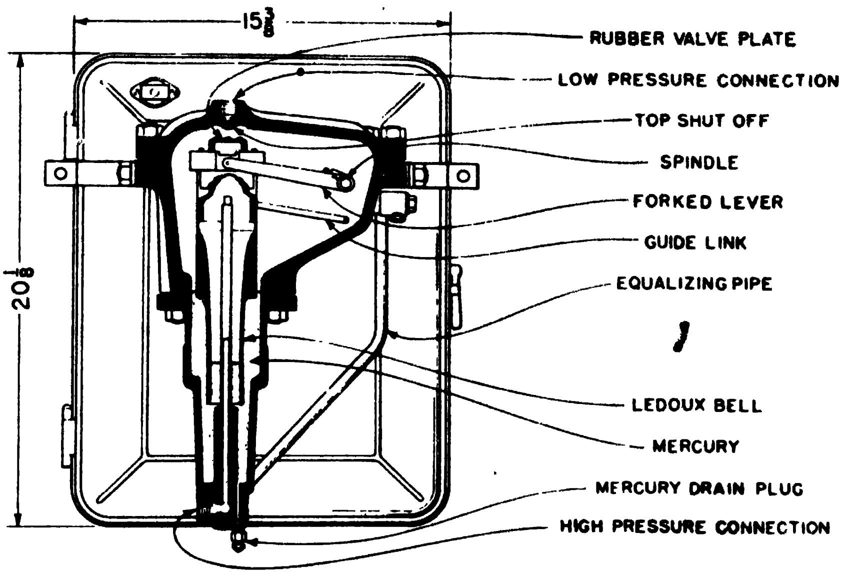


Figure 4-10. Ledoux bell meter. (*Courtesy of Bailey Meter Co.*)

Another Ledoux-bell meter body, this one by Minneapolis-Honeywell, is shown in Figure 4-11. In this arrangement, the low pressure is *inside* the characterized bell. Due to its particular shape its vertical movement in the mercury in which it is partially immersed again will be such that its position is proportional to the square root of the differential pressure applied to the meter body, *i.e.,* equivalent to a linear response to the rate of flow. The movement of the bell is converted into an electric signal as described on page 109. The expansion of the upper part of the bell into an overload chamber is provided to prevent the mercury from being forced upward to the top of the bell and out through the low-pressure tube in case an excessive pressure differential develops. Further protection is provided by a sealing disc which closes off the outside connection to the low-pressure tube if the bell moves below its normal operating level. If a change in the range is desired, it is necessary to replace the meter body by one of suitable size.

Ring-balance Meters. Figure 4-12 shows the operation of a ring balance meter as made by Hagan Chemicals & Controls, Inc. This is a mercury-type flowmeter without float. The U-tube is bent into a ring which is supported in its center by a knife-edge bearing. The pressure connections are made by flexible tubes of reinforced synthetic rubber or corrosion resistant metal. The pressure differential causes the ring to tilt until it is balanced by the force which the range spring exerts over the push rod.

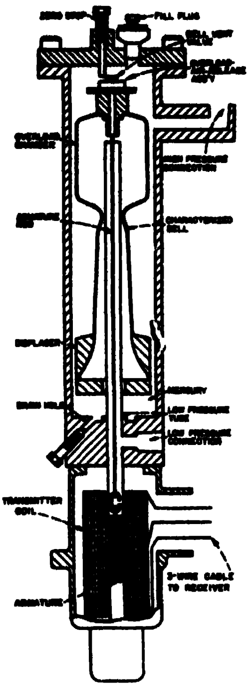


Figure 4-11. Ledoux bell meter. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

This range spring is a leaf spring of adjustable length. By lengthening it, the spring rate is decreased, and vice versa. A low spring rate produces the same ring deflection with a small pressure differential as a high spring rate with a large pressure differential. Thus relatively wide range adjustments are possible. One standard model is adjustable for full-scale pressure differentials between 20 and 140 inches.

The balance system, due to the leverage of the push rod, is such that at low flows the motion of the ring actually overcompensates for the square root relation of differential pressure to flow. The cam which is described further below must correct for this overcompensation to obtain linear readings. The overcompensation has the advantage that it magnifies the sensitivity at the lower end and thus increases the accuracy at low flows.

The ring rotation is transmitted to the recording pen through the cam and the cam follower. The cam contour imparts a movement to the recording pen which is directly proportional to the flow rate, thus giving a uniform flow chart. It is one of the distinct advantages of a ring balance flowmeter that due to the absence of the float, no problem arises of transmitting its movement from inside the chamber to the outside in order to position the pen.

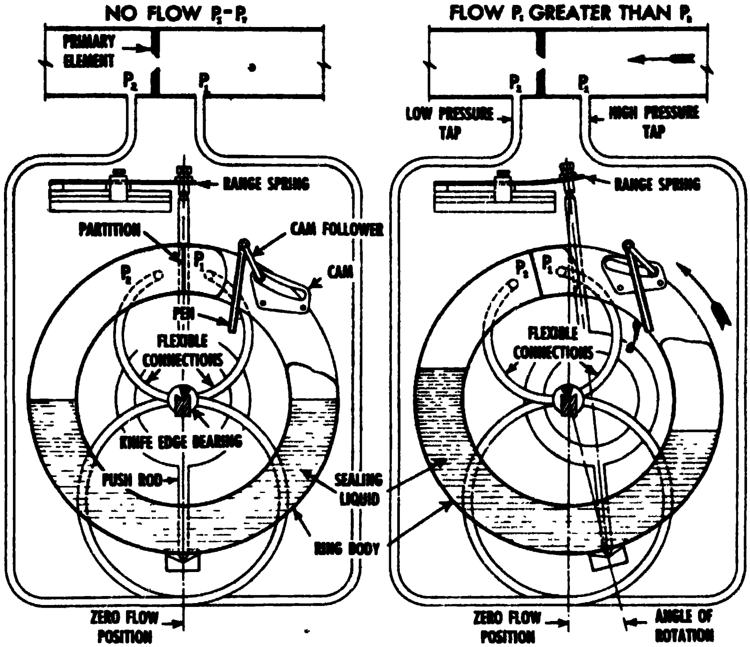


Figure 4-12. Ring balance meter. (*Courtesy of Hagan Chemicals & Controls, Inc.*)

Such ring balance meters are available for differential pressure ranges down to 0.5 inches.

Hagan Chemicals & Controls, Inc. also makes a dual-type meter which combines two ring balance meters in one instrument. It is possible with this meter to record two independent flows on a single chart. It is also possible to record the sum or difference of two flow measurements, or record one flow and use the other measurement to correct these readings for changes in density or pressure of the measured fluid.

An interesting modification of the ring-balance meter is used in the Leeds & Northrup Centrimax flowmeter. The usual design of pressure-differential flowmeters is for reading of *rate* of flow as a function of the pressure differential measured by the manometer. Where it is desired to read total quantity of *accumulated* flow, integrators must be added. These integrators are described under separate headings. However, the Centrimax flowmeter, illustrated in Figure 4-13, integrates flow directly by making use of the fact that the centrifugal force of a flyball system has the same square-root relation to rate of rotation that differential pressure has to rate of flow.

The manometer is mounted on a beam, and the beam is balanced on a knife

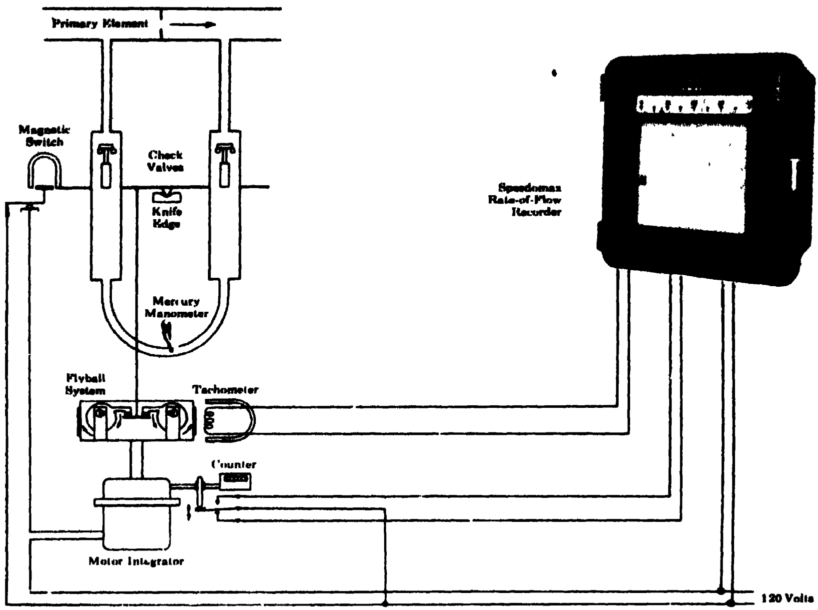


Figure 4-13. Centrimax flow meter. (*Courtesy of Leeds & Northrup Co.*)

edge. (Occasionally, the term "manometer" is considered incorrect when referring to this arrangement. This is of rather academic interest and for the purposes of this discussion it is freely used.) Differential pressure across the manometer, which varies as the square of rate of flow, is balanced directly against centrifugal force, which varies as the square of the speed of the flyball rotation. The squares cancel. Flyball speed is directly proportional to rate of flow. Counting the flyball revolutions is equivalent to integrating the total flow.

The motor integrator shown in the illustration rotates the flyball system, simultaneously driving the counter and a cam required for the remote integration described below. A magnetic switch at the end of the beam cuts the motor-integrator in or out. When the beam tilts clockwise, the switch closes and the motor accelerates. When the beam tilts counterclockwise, the switch opens, decelerating the motor.

If the pressure differential rises due to increased flow through the primary element, the beam tilts in a clockwise sense, and the motor integrator begins to run. As the motor gains speed, the flyball system will act in the direction indicated by the arrows in the illustration. This will exert a counterclockwise force on the beam opposing the clockwise force caused by the pressure differential. As the counterclockwise centrifugal force becomes stronger, the beam will tilt sufficiently to open the magnetic switch de-energizing the motor. This will slow down the motor and decrease the centrifugal force. The result is that the beam starts tilting again in a clockwise direction, repeating the cycle. The motor-integrator will thus run at an average speed determined by the balance of the centrifugal force due to the rotation of the flyball system versus the force of the tilting manometer and beam. The result is an integration of motor revolutions which are a function of total flow.

In addition to integrating the flow, it is also possible to measure the rate of flow. For this purpose, an induction tachometer and a thermal converter are made part of the flowmeter. The induction tachometer is an electrical generator which generates an emf in proportion to the rpm with which it is driven. It is coupled to the motor-integrator. The resulting emf is applied to an electrical resistance, and the thermal converter measures the temperature of the resistor, which is a function of the current passing through it. This temperature is measured by a Speedomax rate-of-flow recorder which is calibrated to read directly in pounds of water (or steam) per hour, or in other specific units.

Remote integration of total flow is made possible by means of electric impulses set up by cam-actuated contacts in the meter body. The cam is driven by the motor integrator, as mentioned before. The pulses are transmitted to a solenoid-type counter which reads the accumulated flow.

Bell Meters. Bell meters not of the Ledoux type (previously described) are frequently used where the available pressure differentials are very small, such as 1, 2 1/2, and 5 inches. Bell meters are preferred in these cases, since they are more sensitive than other flowmeters. Figure 4-14 shows a typical low-differential bell meter made by American Meter Company. The operation is the same as described for the Ledoux bell, with the high pressure applied underneath the bell; but movements of the bell are in direct proportion to the pressure differential, and therefore in square root relation to the rate of flow. Variations in range are obtained by altering the thickness of the side walls of the bell. For example, decreasing the thickness makes the bell lighter and increases the area of the mercury surface inside the bell as compared with that of the outside surface. The result is that the vertical travel will increase for a given change in differential pressure.

Conversion of the movement of the bell into a linear flow rate response of the pen is obtained in an air flowmeter by Republic Flow Meters Co. A schematic diagram of the arrangement is shown in Figure 4-15. The differential pressure forces the bell downward, turning the cam assembly counterclockwise about the axis A. As the cam rotates the tape is brought into contact with the cam screws in succession. Tension is maintained in the tape by weight W acting about the axis B. This weight maintains an almost constant tension force in the tape. The further the cam rotates the greater becomes the length of the lever arm of the force, *i.e.,* L becomes L'. The bell moves very easily at low differentials and encounters increasing resistance as the pressure differential in-

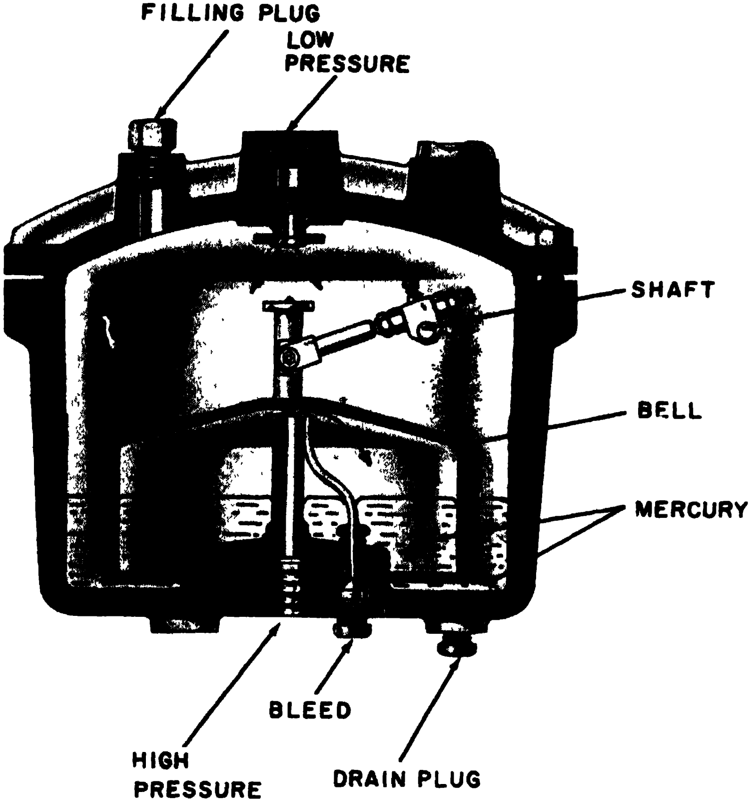


Figure 4-14. Bell meter. (*Courtesy of American Meter Co.*)

creases, in such proportion that the pen motion is proportional to the square root of the differential pressure changes.

The Foxboro bell meter applies the low pressure underneath the bell and opposes the motion by means of a precalibrated spring. Changes in range only necessitate changing the spring.

Special Meters. The *dual flowmeter* consists of two manometers mounted on the back of a single instrument, making it possible for both of the manometers to record on the same chart. This arrangement is sometimes helpful in maintaining balanced conditions between two flow rates, *i.e.*, conditions where one rate is always supposed to be in a fixed relation to another. The two rates can be recorded on the same chart, and by proper sizing of the orifices, the readings of the pens can be made to coincide when the ratio of the flows is correct.

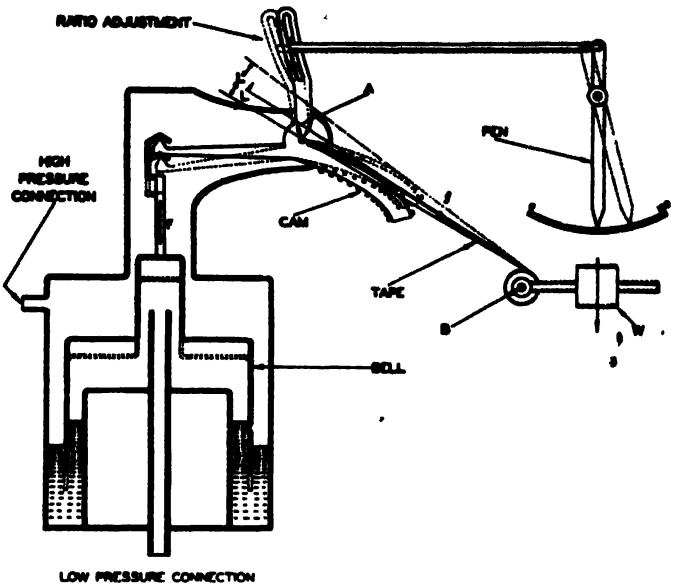


Figure 4-15. Schematic of air flow meter. (*Courtesy of Republic Flow Meters Co.*)

The separation of the pens will then be an instantaneous visual indication of an improper operation.

The *duo-range flowmeter* consists of a flowmeter connected to two range tubes, as shown in Figure 4-16, illustrating the version of Taylor Instrument Companies. The purpose is to overcome the lack of sensitivity in the low region of the range of the pressure-differential meter. Inaccuracies due to the orifice plate installation are thereby not reduced. One range tube is usually chosen for 0 to 25 per cent of maximum flow rate, while the high-range tube is used for flow rates between 25 and 100 per cent of maximum. By manually operating two of the valves on a 4-valve manifold, either range tube can be cut into operation and will then position the instrument pen.

Where this valve manipulation is objectionable, a *wide-range metering layout* can be used. This is simply a combination of a high-range and a low-range meter, both operating continuously and both connected to the same orifice. Small pressure differentials up to 25 per cent of flow rate are recorded by both meters, but are read and integrated on the low-range instrument. When the range limit of the low-range meter is reached, its operating mechanism, inherently protected from over-range effects, positions the pen at the outer edge of the chart. The high-range meter then records and integrates the flow.

Compound range meters allow measurement with flow in either direction, for-

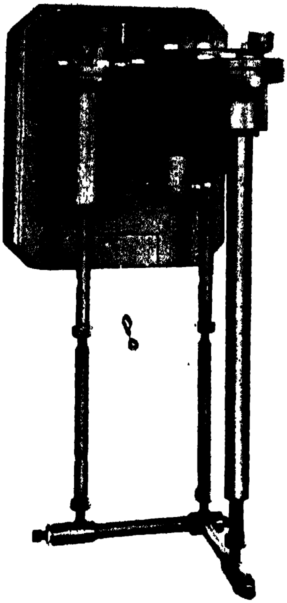


Figure 4-16. Back view of duo-range meter. (*Courtesy of Taylor Instrument Cos.*)

ward and reverse. This is made possible by mounting the range tube lower than with the standard meter. The mercury level can then change around a mid-position, depending on whether the flow is in one direction or the other. The charts used with these meters have their zero position in the middle, and flow readings are taken toward either side, depending on the direction of flow.

Mechanical Meters. If the flowmeter uses a float or bell which moves with changes in flow rate, the movement must be transmitted to the pen of the instrument. This is obtained by either mechanical or electrical transmissions. In the mechanical flowmeter, the up-and-down movement of the float rotates a shaft which passes from the float chamber to the outside through a pressure-tight bearing; the pen is fastened to it either directly or through a linkage. It is, of course, necessary that the friction of the rotating shaft, as of all other parts of this mechanism, is minimum. "Teflon" provides a pressure-tight bearing and its greasy texture is practically frictionless. It has largely replaced other bearing-and-shaft assemblies which, although quite efficient, were somewhat more difficult to manufacture since clearances like 0.000 05 inch had to be maintained.

Electrical Meters. If the instrument is located far from the orifice plate, electrical transmission systems are frequently used. Several methods are available.

The conductivity method used by the Republic Flow Meters Company utilizes the mercury rise in the low-pressure leg of the meter body (Figure 4-17) to vary the resistance of an electrical circuit. The electrical current flowing through this circuit will thus be a function of the pressure differential applied to the meter body, and hence to the rate of flow of the fluid. A large number of contact rods, a few of which are shown in the illustration, extend into the pressure chamber. The mercury, which rises with an increase in flow, makes contact with an increasing number of rods. The lengths of the rods and the resistances between them are such that the change in electrical conductance which results from short-circuiting of the resistances by the rising mercury is a function of the square root of the differential pressure imposed on the meter body, *i.e.*, proportional to the rate of flow.

Instrument response is obtained by means of solenoid coils *A* and *B*, which are provided with a common armature. A constant current flows through coil *A*, which, through its electromagnetic action on the armature, tends to hold the instrument pen at zero. Coil *B* carries the current that flows through the meter body, the mercury, and the contact rods immersed in the mercury. This current varies with the change of the mercury level. As it flows through coil *B* it tends to move the pen or pointer away from zero. A balanced position of the pen or pointer is thus obtained, corresponding to the relative amount of current flowing through coils *A* and *B*—a relationship which is determined only

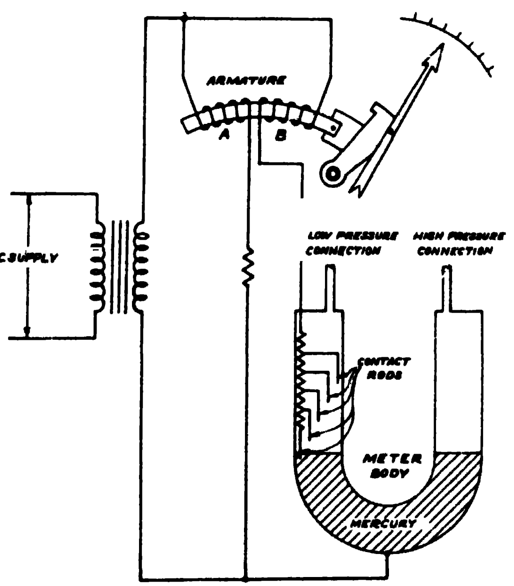


Figure 4-17. Schematic of conductivity method.

by the amount of change of level of the mercury and the arrangement of the contact rods, *i.e.*, it is proportional to the rate of flow.

The Bristol Metameter system comprises a transmitter and an electrically connected receiver. The transmitter is partly built like a mechanical flowmeter as described above. It is in fact used as a flow indicator, but its main purpose is one of transmitting. Readings are transmitted in the form of successive impulses of current sent out from the transmitter. Every 15 seconds a switch is closed. It remains closed for a period, the length of which is determined by the position of the pointer in the transmitter, which in turn depends on the differential pressure applied to the flowmeter chamber. For maximum pressure differential, the switch remains closed through the full 15-second interval. For all other values, the closure time and hence the current pulses are correspondingly shorter. The position of the pen on the chart in the receiver depends on the pulses transmitted.

The transmitting mechanism (Figure 4-18) consists of a constantly rotating spiral cam, a rocket plate, and a switch. The arm is linked to the movement of the flow indicator and moves with its lower end and its offset finger attachment between the rocker plate and a motor-driven, continuously rotating cam.

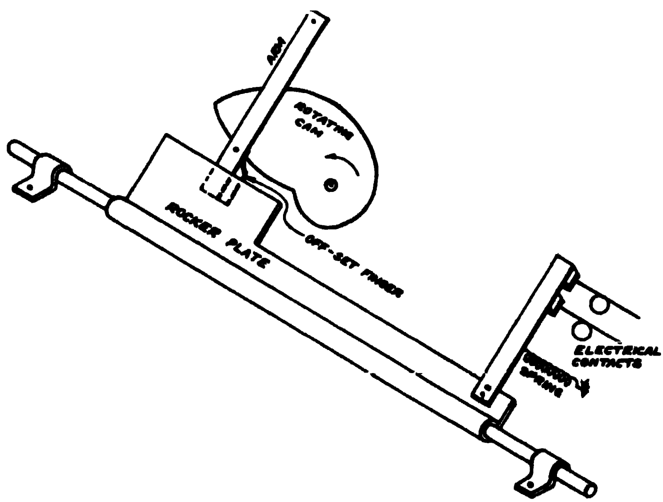


Figure 4-18. Schematic of Bristol's flow transmitter.

The arm is also free to move with its lower end in a plane vertical to the plane of the cam. When the cam starts contacting the offset finger, the arm is pushed forward and transmits its forward motion to the rocker plate, which thus swings through a limited angle to open the electric contacts. The cam is so shaped that it contacts the offset finger at the same instant during each cycle, and that the total time it remains in contact with the offset finger depends on the position of the arm, which is determined by the rate of flow being measured.

The receiver, which is housed in the flow recorder, contains an electromagnet which becomes energized each time the contacts close in the transmitter. There are two discs, alternately clutched and unclutched to a continuously running motor by electromagnetic action. Both discs are driven back to their initial positions by spring action as soon as they become unclutched from the motor drive. Disc No. 1 becomes clutched and disc No. 2 unclutched when the electromagnet is energized. When it de-energizes, disc No. 2 becomes clutched and disc No. 1 unclutched. Out of a period of 15 seconds, disc No. 1 is thus driven for the duration of the current pulse from the transmitter, while disc No. 2 remains at zero position. During the remainder of the period, disc No. 2 is driven, while No. 1 spins back to zero. Both discs are linked to the instrument pen in such a way that if the angle becomes greater through which disc No. 1 is rotated in successive periods, it will push the pen up-scale by a corresponding amount. If the angles become smaller, there is no effect on the pen position. Conversely, if the angles of rotation of disc No. 2 increase, the pen is pushed down correspondingly, while shortening of its rotation angle has no effect. Thus the pen adopts a position which corresponds to the duration of the electric impulses from the transmitter. The pen position is proportional to rate of flow and the chart scale is linear.

The Metameter system as described here is a pulse-type telemetering system. The advantage is that a signal can be transmitted over long distances. Weakening of the signal—within certain limits—is without effect since the magnitude of the transmitted signal depends only on the pulse duration.

Figure 4-19 shows the Brown inductance bridge. It consists of the windings

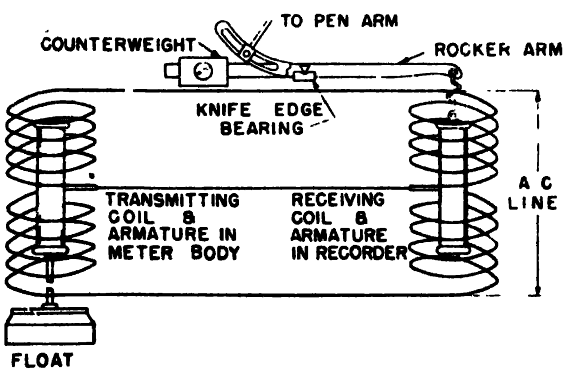


Figure 4-19. Inductance measuring bridge. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

of the transmitting and the receiving coils. A core or armature is attached to the float or bell in the meter body. This armature moves within the transmitting coils, which from the outside surround the tube of non-magnetic material in which the armature is hermetically sealed. Another armature is suspended within the receiving coils from one end of a counterweighted rocker arm linked to the instrument pen. A change in differential pressure resulting from a change in the measured flow alters the position of the armature in the transmitting coils. By momentarily unbalancing the bridge circuit, unequal voltages and currents are produced, and a magnetic force is caused to act upon the receiving armature. As a result, it moves into a new position corresponding to that of the transmitting armature. At this point, the voltage ratios again become equal across the two sections of the divided coils, and the armature movement ceases. The movement of the receiving armature positions the rocker arm and pen to a position corresponding to the new rate of flow.

The electrical transmission circuit used by the Bailey Meter Company is illustrated in Figure 4-20. A differential transformer is used as transmitter. The

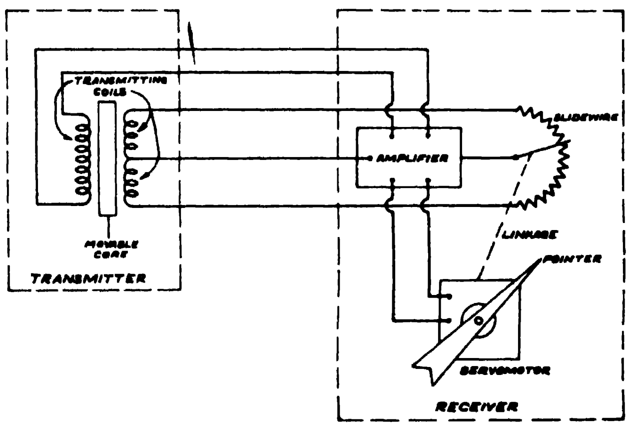


Figure 4-20. Bailey differential-pressure transmitter and receiver

principle of this transformer has been described on page 84. The left-hand coil is the primary of the transformer. The movable core is positioned by the float of the meter body. The position of the core determines the magnetic flux linkage between the primary winding and the two secondary windings of the transmitter. The voltage induced in either of the two secondary windings depends upon the magnetic flux linkage from the primary to the corresponding secondary. The voltage ratio between the two secondaries is thus a function of the displacement of the core from its center position.

An electrical bridge is formed by the two secondary coils of the transmitter and the resistances on each side of the slide-wire contact at the receiver. The amplifier and servomotor circuit is so arranged that whenever there is the slightest unbalance of this system, the current will flow in such a direction as to cause the motor-driven slide-wire contact to rotate until the circuit is rebalanced. Thus, the motor-driven slide-wire contact always assumes a definite position for every position of the transmitter core. By moving the pointer simultaneously with the slide-wire contact over a scale calibrated in units of flow rate, a reading of the measured flow is obtained.

Pneumatic Transmissions. Instead of electrical transmission, it is also possible to transmit the response from the meter body by means of a pneumatic signal. The movement of the float or bell, if used, has to be first converted into a mechanical movement outside the meter body by one of the previously described methods before it can be transmitted by pneumatic means. An example is the Brown pneumatic transmission system by Minneapolis-Honeywell Regulator Company. Figure 4-21 is a schematic diagram of the transmitter arrangement.

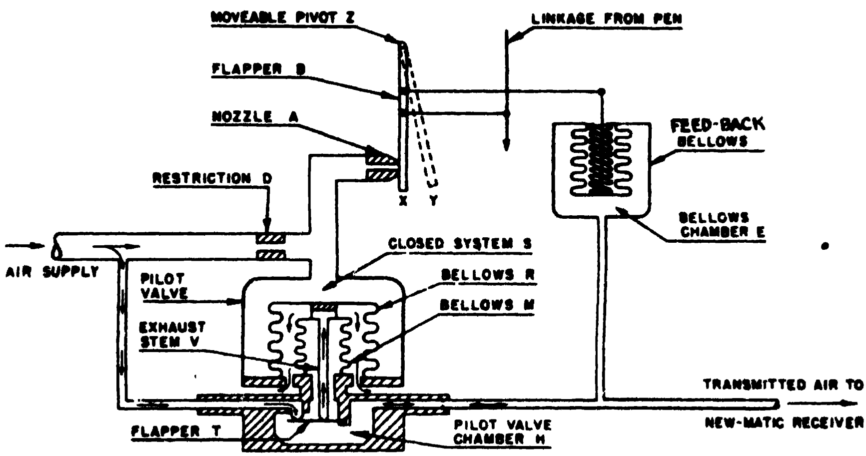


Figure 4-21 Brown pneumatic transmission system. (*Courtesy of Minneapolis Honeywell Regulator Co.*)

The purpose is to vary the air pressure in the closed system, *S*, in response to the pressure differential measured by the flowmeter body. The receiver reconverts the air pressure into units of flow rate. The air pressure depends on the relative position of flapper, *B*, to nozzle, *A*. If the flapper fully closes the nozzle, the pressure in the closed system is equal to the supply pressure. If the nozzle is fully open, the closed system pressure will be at a minimum, its magnitude depending upon the pressure drop across restriction *D* and nozzle *A*. The surface of bellows *R* is five times that of bellows *M*. The transmitted air pressure is also applied to the inside of bellows *M*. When the system is in a balanced position, the nozzle back pressure on bellows *R* balances the higher pressure on bellows *M*, and the pilot-valve flapper *T* covers both the inlet port and the exhaust port on the end of exhaust stem *V*. With a change in rate of flow the linkage from the pen repositions the flapper *B*.

Suppose it moves from position *Y* to *X*. The nozzle back pressure will increase, causing both bellows to move downward. Since exhaust stem, *V*, pushes against flapper *T*, the inlet port opens and air at supply pressure enters pilot valve chamber *H*. As the transmitted air pressure now increases, pressure in bellows chamber *E* will also increase, and the feedback bellows consequently pushes against flapper *B* to close nozzle *A*. The positions of both the linkage from the pen and the linkage from the feed-back bellows will determine the final position of the flapper *B* and hence of the flapper *T*; this in turn will determine the air pressure transmitted to the receiver. If, however, the rate of flow changes in the other direction, then flapper *B* moves away from nozzle *A*, the pressure in the closed system *S* decreases, the bellows *R* and *M* move upward, and flapper *T* now closes the supply port to pilot valve chamber *H* but opens the exhaust through exhaust stem *V*, reducing the pressure transmitted to the receiver.

The transmitter unit, Figure 4-22, shows the mechanical details. An increase in flow causes a downward movement of the float. The pressure-tight shaft, connected to the float by the float arm, is rotated counterclockwise. The flow calibrating lever rotates in the same direction as the shaft, and moves the connecting link pinned to its lower end to the right. The movement of the connecting link rotates the flapper, lifting the lever to the left around movable pivot *A*, and moves the flapper pin away from the flapper, allowing it to move downward and throttle the nozzle opening. When the nozzle is throttled, the pressure in the bellows chamber is increased and the bottom of the bellows moves upward, compressing the bellows spring. This movement of the bellows forces the bellows rod upward, rotating the bell crank about its fixed pivot, and carries the flapper-lifting lever with it. The movement continues until the flapper is in the position for maintaining the pressure at exactly the value that represents the new float position, *i. e.*, the rate of flow.

The receiver unit is simply a pressure recorder which measures the transmitted pressure and indicates it on a chart calibrated in flow rate units.

Other pneumatic transmission systems differ mainly in the design of the pilot valve or relay, as it is also called. Figure 4-23 shows a pilot valve which is used in the Foxboro pneumatic flow transmitter. This is of the continuous-bleed type, while the previously discussed pilot valve is of the non-bleed type,

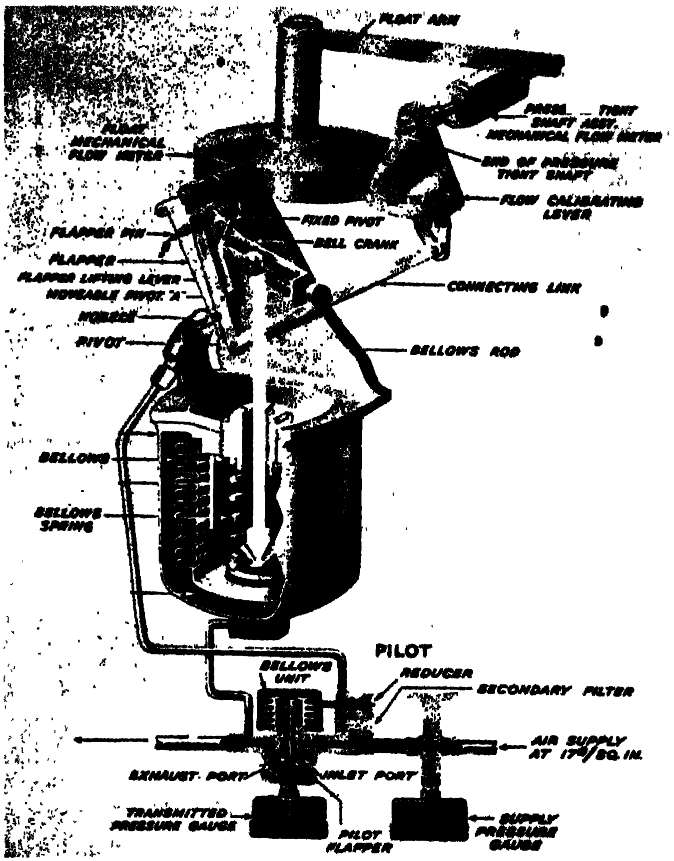


Figure 4-22. Brown pneumatic transmitter. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

which means that after any change in transmitted air pressure. it always returns to a balanced condition at which no bleeding of air occurs. The continuous-bleed type exhausts continually a small amount of air except in the fully open and fully closed position. This loss of air is relatively small. A hundred pneumatic transmitters with continuous-bleed pilot valves will require an air consumption involving no more than 3 to 4 kwh in the compressor.

Figure 4-24 shows the American Meter pilot valve. Its particular feature is the use of two diaphragms, each of which can position the valve opening. The free area of the secondary diaphragm is considerably larger than that of the primary diaphragm. The action of the secondary diaphragm is, therefore, more powerful, but it is also retarded because of the secondary restriction,

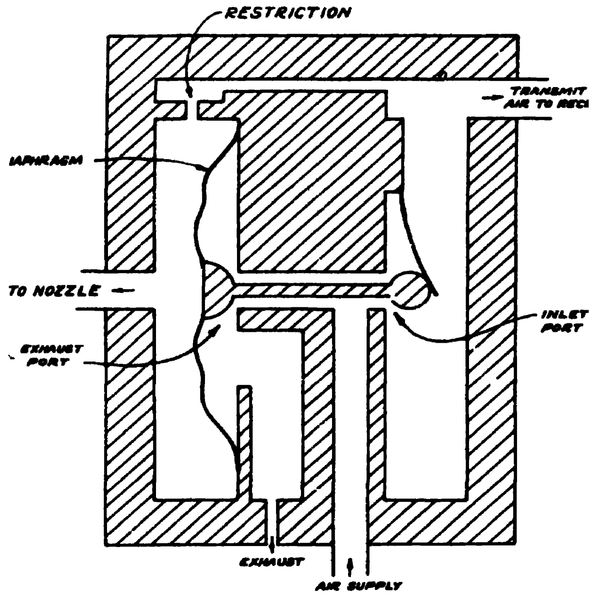


Figure 4-23. Schematic of Foxboro pilot valve.

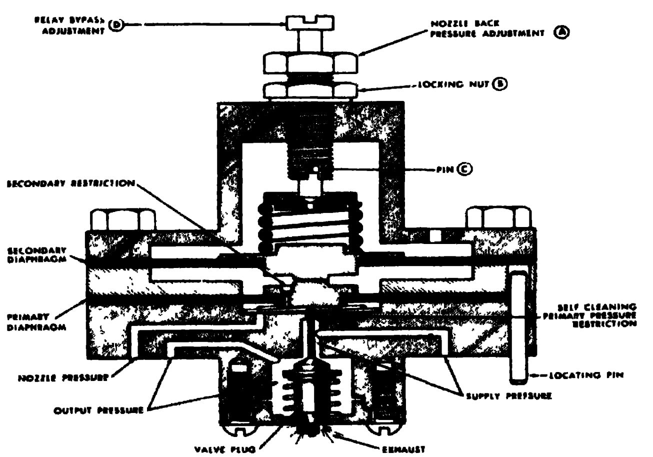


Figure 4-24. American Meter's pilot valve. (*Courtesy of American Meter Co.*)

which separates the secondary diaphragm from the nozzle back pressure. This produces a damping action which is sometimes helpful for smooth operation.

Mercury-less Flowmeters

The trend is definitely toward mercury-less type flowmeters of either the bellows or the diaphragm type. The mercury type will eventually be retained only in some special applications.

Bellows Type. Taylor makes an aneroid manometer which covers approximately the same ranges as previously described flowmeters. A cross-sectional view is shown in Figure 4-25. The high pressure is connected with the outside of the bellows. The inside connects with the low pressure. The bellows is

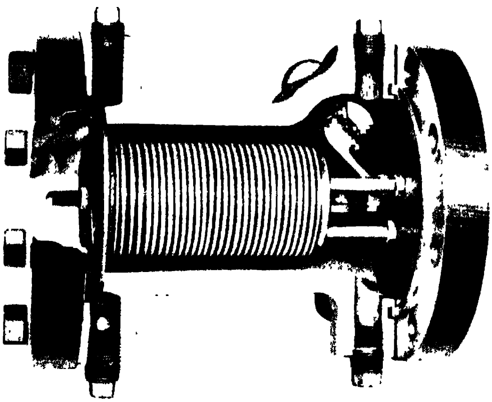


Figure 4-25. Cross section through aneroid manometer. (*Courtesy of Taylor Instrument Cos.*)

clamped on the left-hand side and is free to move on the right. As it moves in response to a change in pressure differential acting between the inside and the outside of the bellows, the torque tube assembly is acted upon. The torque tube is a piece of thin-walled metal tubing sufficiently elastic in its lengthwise direction to allow twisting through a limited angle. It is usually closed at the end which is exposed to the twisting torque. The other end is open and firmly clamped to a solid surface. It offers thus a means of transmitting a limited rotary movement from one chamber to another where the chambers must be hermetically sealed from each other. The torque tube itself is twisted along its lengthwise axis by the bellows movement, and in so doing it positions a shaft inside the torque tube which is rigidly fastened to the closed end of the tube. A pen is actuated from the shaft movement to record the flow rate. This arrange ment provides a no-bearing, leak-tight transfer of movement from the pressure chamber to the pen. Additional details of the torque tube will be described in connection with Figure 4-27. The range of the meter can be changed by replacing the interchangeable torque tube assembly of one size by another size. The brass bellows element is designed to withstand a maximum differential pressure of 20 psi while a stainless steel element will withstand a differential pressure of 50 psi. To protect the bellows from pressure differentials that may temporarily exceed these limits, it is necessary to provide a relief valve in a bypass between low-pressure and high-pressure lines outside the instrument. The fluid in these lines is usually still, but when there is excessive pressure differential and consequent opening of the relief valve, a sudden flow through the bypass will occur. This may dislodge scale or other particles in the pipe and plug up the bypass, defeating the purpose of the bypass valve. Frequent cleaning is therefore necessary to secure safe operation.

The Barton Instrument Corporation makes a flow meter body, the cross-sectional view of which is shown in Figure 4-26. The bellows unit assembly con-

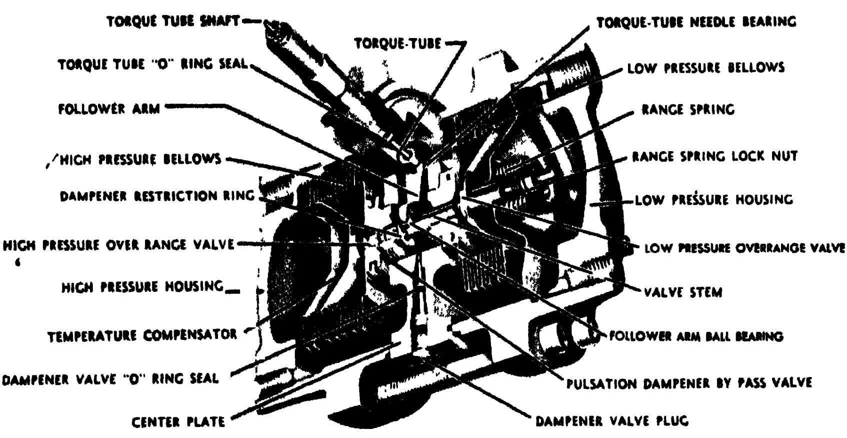


Figure 4-26. Cutaway view of Barton flow meter body. (*Courtesy of Barton Instrument Corp.*)

sists of a pair of bellows, a center plate, over-range valves, a temperature compensator, a torque tube assembly, dampener valve, and a range spring assembly. The metal bellows are mounted on opposite sides of the center plate. The outer ends of the bellows are sealed, and are rigidly connected internally, by the valve stem passing through an annular passage in the center plate. The opposed over-range valves, located on the valve stem, are arranged to seal against corresponding valve seats on the center plate. The internal volume of the bellows and center plate is completely filled and sealed with a clean, non-corrosive, low freezing point liquid.

The temperature compensator is an additional free-floating bellows. It is attached to the high-pressure side of the bellows unit to allow for expansion and contraction of the fill liquid, thus providing temperature compensation through a wide range of ambient temperatures.

The differential pressure range of this flow meter body is determined by the force required to move the bellows through their normal travel. In order to provide for the various calibrations necessary, a range spring assembly is incorporated which balances the applied differential pressure.

In operation, the bellows move in proportion to the difference in pressure applied across the bellows unit assembly. Should the bellows be subjected to a pressure difference greater than the differential pressure range of the unit, they will move through their calibrated travel plus a small amount of overtravel until the valve mounted on the center stem seals against its corresponding valve seat. As the valve closes, it traps the fill liquid in the bellows and since the liquid is essentially non-compressible, the bellows are fully supported and cannot be ruptured regardless of the over pressure applied.

Internal dampening is accomplished by restricting the flow of liquid through its normal channel—the annular passage in the center plate—and bypassing it through an alternate route controlled by an adjustable needle valve. Pulsations can thus be reduced or eliminated and response time of the instrument can be continuously controlled from approximately one second to several minutes for full-scale travel of the bellows.

The linear motion of the bellows in response to a change of the measured pressure differential is picked up by a follower or drive arm. A torque tube is employed to transmit motion of the drive arm to the exterior of the unit. Figure 4-27 illustrates additional details of the torque tube assembly. It consists of a tube, a shaft, and supporting members. The tube is made from thin-walled beryllium copper tubing. The torque tube shaft is made from stainless steel. The outboard end of the tube is sealed to the center plate. The torque tube shaft passes through the center of the tube and is welded to the tube at the inboard end. Because the outer end of the torque tube is sealed to the center plate, it must twist when subjected to torque. The shaft which is freely supported within the tube at its outer end, but rigidly attached to the tube and drive arm at the inner end, rotates through the same angle as the drive arm.

Moore Products Company combines the Barton meter body with a Moore Motion Transmitter, as shown in Figure 4-28. The rotary movement of the Barton output shaft is converted into vertical motion by a rod connected to the pilot. The position of the pilot is controlled by the movement of the connecting rod as well as by the bellows movement resulting from the pilot back pressure

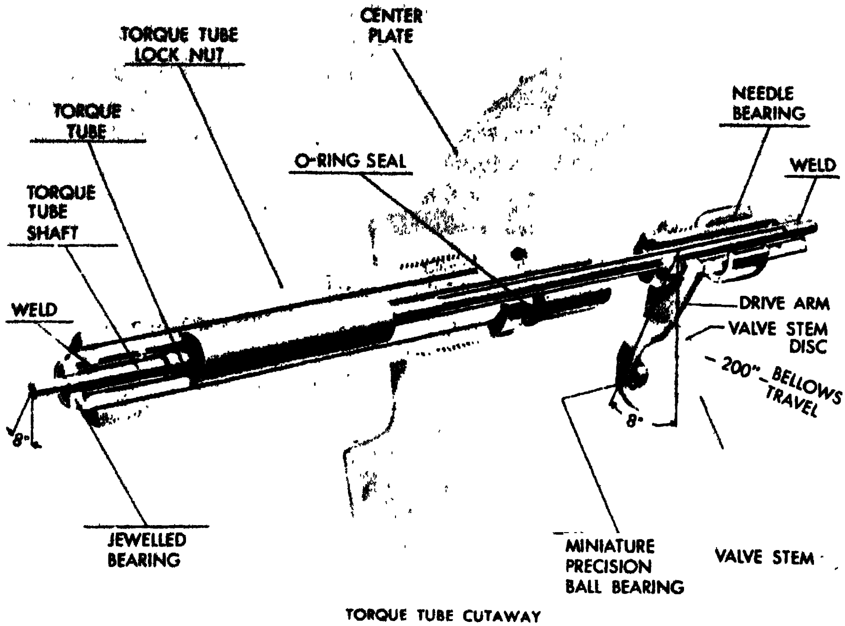


Figure 4-27. Cutaway view of Barton torque tube assembly. (*Courtesy of Barton Instrument Corp.*)

and the feedback pressure. Conversely, the pilot back pressure determines the motion of a diaphragm. When the pilot back pressure increases, the valve opens and supply air is admitted increasing the transmitted pressure, including the feedback pressure, and rebalancing the system. A decrease in pilot back pressure reverses the operation, exhausting the transmitted pressure through the bleed valve to rebalance the system. Thus rate of flow is converted into an air pressure signal which can be received by any suitable indicator or recorder.

Minneapolis-Honeywell's ΔP/I transmitter uses a similar bellows meter and converts the bellows motion into an electric signal. The method of operation is illustrated in Figure 4-29. The torque tube motion of the meter body is connected to the input linkage of the transmitter. The linkage exerts a force on a force balance beam via the input spring. The resulting deflection of the beam changes the air gap in the detector assembly which consists of an iron slug mounted to the beam and an electromagnet mounted rigidly on the transmitter chassis. When the iron slug approaches the electromagnet, its air gap decreases changing the inductance of the coil of the electromagnet. This coil is part of an electronic oscillator. As the inductance of the coil changes, the oscillator

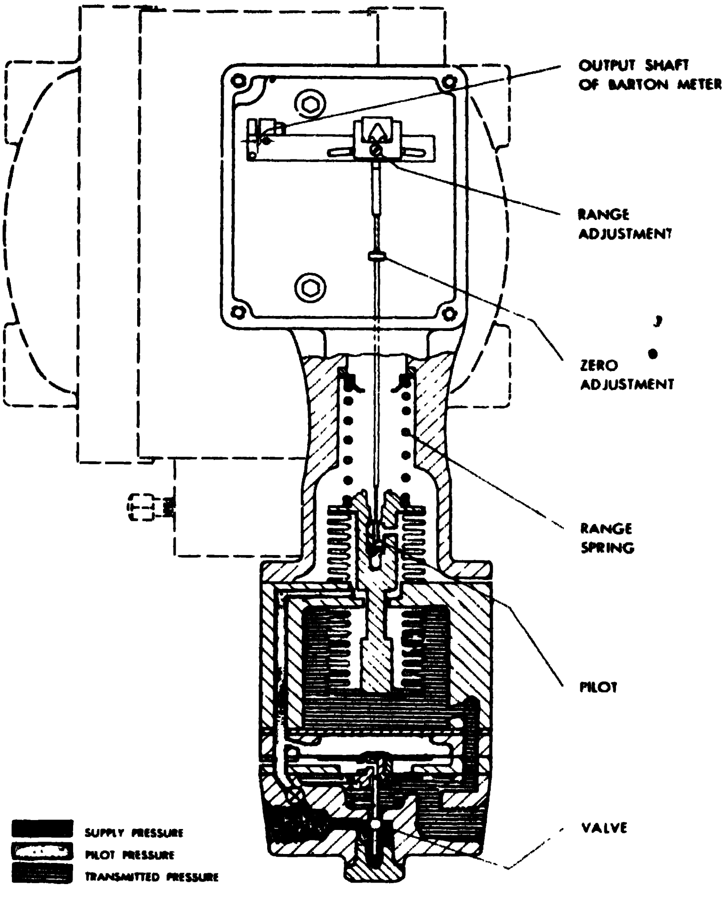


Figure 4-28. Barton meter body with Moore transmitter (*Courtesy of Moore Products Co.*)

acts like a variable resistor. It thus modulates the current in the output circuit between 4 and 20 milliamperes d.c. A portion of this current output is fed back to the magnet unit, which is similar to the moving coils described further below. A balancing force is produced on the beam through the magnet unit which is equal and opposite to the input force. The full-scale motion at the outer tip of the beam is about 0.001 inch. The span-adjusting resistors control the amount of feedback current through the magnet unit, and thus permit a range adjustment of the unit.

Diaphragm Type. In the mechanical flowmeter, the meter body and the recording instrument are a unit. A separation of meter and recorder, as required

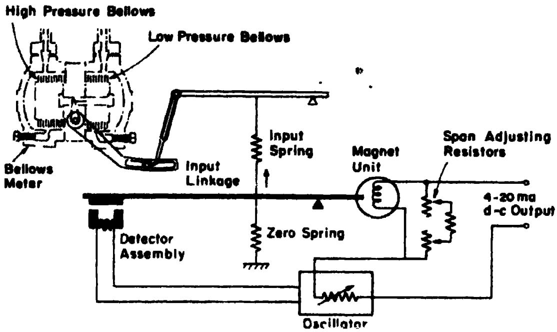


Figure 4-29. Schematic of Δ P/I transmitter.
(*Courtesy of Minneapolis-Honeywell Regulator Co.*)

in many cases, is obtained by means of electric and pneumatic transmission systems. Similarly, the bellows-type meter is designed mainly for mechanical connection to the recorder, although it is also adaptable for electric and pneumatic transmission, as shown in the example of the Moore Motion Transmitter and Honeywell's Δ P/I transmitter.

In the diaphragm type, the design of the meter body as a transmitter is a basic principle from the beginning. Transmission of the signal is either by electrical or pneumatic means. The names for the diaphragm-type meter body vary. They are known as differential pressure transmitters, differential converters, pressure transducer, etc.

One particular problem with diaphragms is that they change their effective area. The force produced in the center of a diaphragm is equal to the product of pressure and area. However, not the entire area of the diaphragm is active, because of its catenary shape and the absorption of some of the force in the mounting rings. Hence, we speak of an effective area, as opposed to the free area. The effective area when multiplied by the pressure gives the force available in the center of the diaphragm. This effective area changes with the deflection of the diaphragm. To minimize this effect it is necessary to limit the deflection to a few thousandth of an inch. This is best accomplished by feedback arrangements as described in the following.

The Taylor differential pressure transmitter is a simple, small and comparatively inexpensive instrument.* Its operation is illustrated in Figure 4-30. The differential pressure, measured across an orifice plate, is applied across the sensing diaphragm. An increase in differential pressure moves the sensing dia-

*A more elaborate model from the same manufacturer is also available but not covered in this text.

phragm with its center stem and the baffle to the left, reducing the distance between nozzle and baffle, and thereby increasing the pressure in the feedback chamber. This exerts a force on the feedback diaphragm, balancing the increased differential pressure. The pressure in the feedback chamber thus is proportional to the differential pressure. It is transmitted through the output to the receiving instrument.

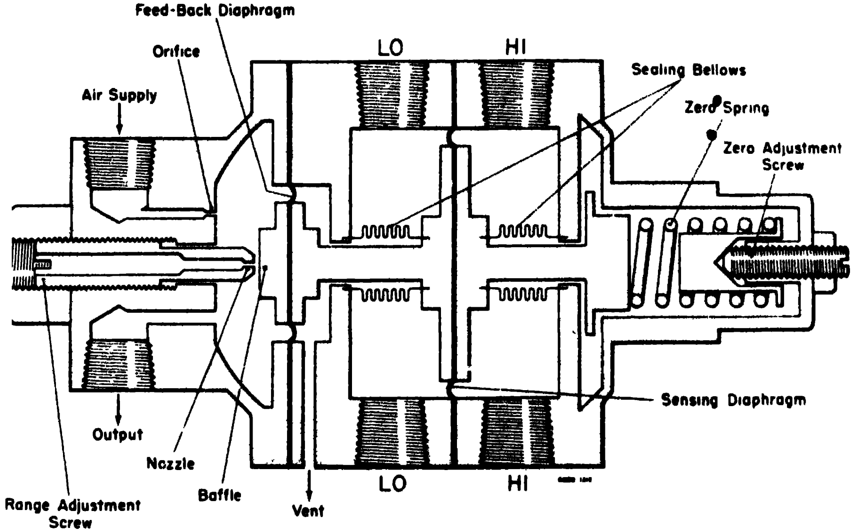


Figure 4-30. Schematic of Taylor's differential-pressure transmitter. (*Courtesy of Taylor Instrument Cos.*)

The Foxboro Company is the originator of the d/p cell shown in Figure 4-31 (d/p stands for differential pressure). The differential pressure which is measured as a function of flow, is applied to the high pressure and low pressure sides across the twin-diaphragm capsule. Any difference between these pressures causes the capsule to exert a force on the lower end of the force bar. Let the force bar respond to a decrease of differential pressure. In this case it pivots clockwise about the Elgiloy metal diaphragm seal and pushes against the range rod to which it is attached by a flexing connection at its upper end. The range rod now pivots clockwise about the range wheel. The flapper moves with the range rod, opening the nozzle. The resulting decrease in nozzle back pressure, amplified through the Model 40c relay, becomes the transmitted signal. It is also applied to the feedback bellows, thus exerting a counterclockwise torque on the range rod and balancing the change in pressure differential across the twin-diaphragm capsule. In actual operation, all these steps follow

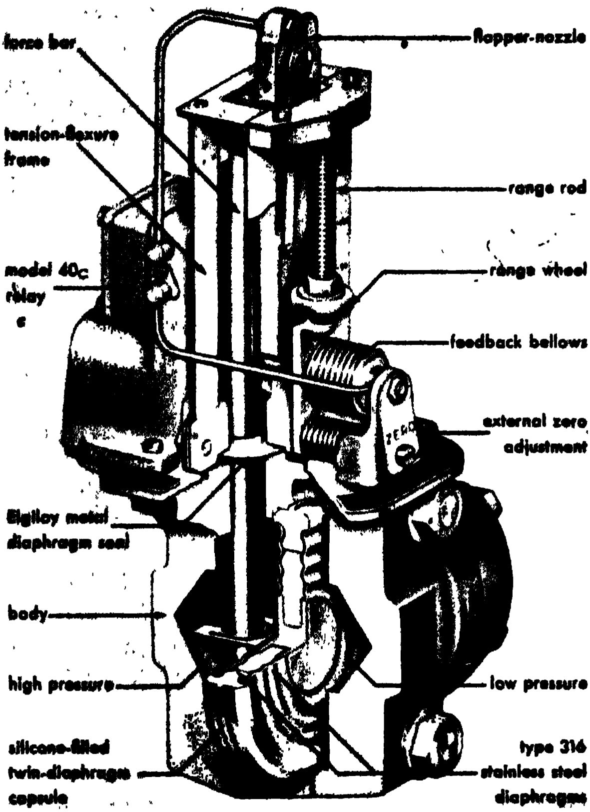


Figure 4-31 Cutaway view of Foxboro's d/p cell. (*Courtesy of Foxboro Co.*)

so closely that they may be considered simultaneous action. Thus, any change in differential pressure across the twin-diaphragm capsule produces a minute movement of the flapper. This movement results in a change in output pressure of the relay and changes the feedback bellows balancing pressure. The continuously adjusting bellows pressure maintains a force balance between bellows and twin-diaphragm capsule.

The range rod is adjustable from 0-50 to 0-250 inches of water column. The twin-diaphragm capsule is filled with silicone. Small passages through the core permit the silicone to flow from one side to the other but restrict the rate of flow and thus provide damping action. The action of the air relay was illustrated in Figure 4-23.

Differential pressure is proportional to the square of the flow rate through the primary element. In order to obtain a signal which is proportional to the flow rate, it is necessary to extract the square root of this signal. Figure 4-32 illustrates the transmitter built by Republic Flow Meters. The pneumatic output pressure of this unit is proportional to the square root of the differential pressure across the measuring diaphragm, hence it is proportional to the flow rate being measured. The force produced by the differential pressure across the diaphragm is applied through a push rod to the upper weigh-beam of the trans-

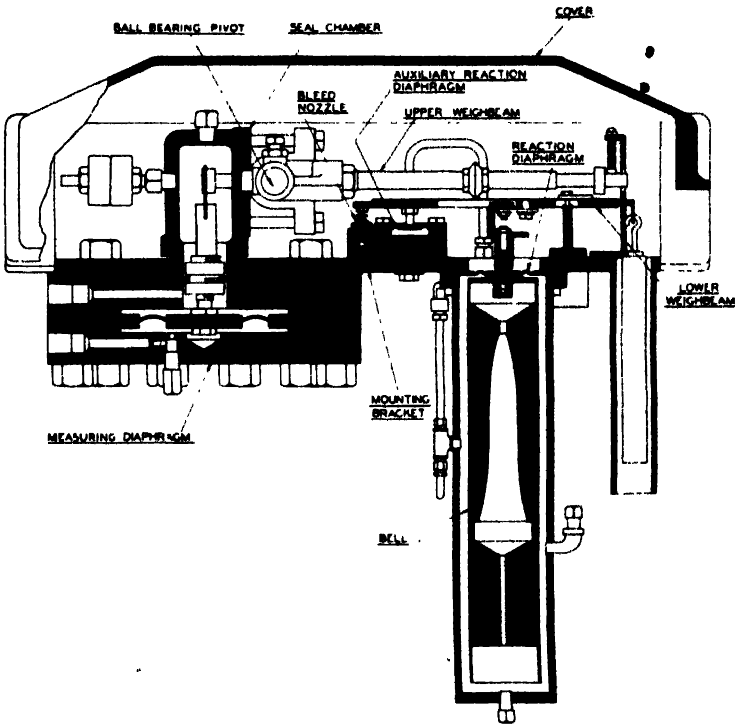


Figure 4-32. Republic flow transmitter. (*Courtesy of Republic Flow Meters Co.*)

mitter. The range adjustment wheel riding on the upper weigh-beam transfers this force to a lower weigh-beam and through it to two feedback or reaction diaphragms. The left end of the lower weigh-beam acts as a flapper that regulates the back pressure of the bleed nozzle by adjusting its opening. The back pressure is transmitted to the reaction diaphragms. Any motion of the lower weigh-beam, *i.e.*, of the flapper, will therefore produce variations in pressure in *the reaction diaphragms proportional to the changes in force produced by the measuring diaphragm.*

If the force produced on the reaction diaphragms multiplied by the lever arm to the pivot point is not sufficient to counteract the force produced by the measuring diaphragm multiplied by its lever arm to the pivot point, the flapper end of the lower weigh-beam will approach the bleed nozzle until pressure builds up and creates a balancing force. Conversely, if the reaction diaphragms build up too great a force, the flapper will be pushed away from the nozzle, thus reducing the pressure on the reaction diaphragms. The result is a stable balance maintained by the flapper being held constantly at the proper distance from the nozzle.

A bell it attached to one of the two reaction diaphragms. The area of this diaphragm is made smaller than would be necessary if used by itself and an auxiliary reaction diaphragm with adjustable leverage is added for calibration purposes. The inside of the bell is vented to atmosphere through the center of the main reaction diaphragm. The lower end is submerged in mercury which buoys up the bell and produces an upward thrust that adds to that produced by the nozzle back pressure on the reaction diaphragm. As the back pressure increases, the mercury is depressed around the outside of the bell and rises inside, with a consequent decrease in buoyancy of the bell. As the bell loses buoyancy, its weight must be supported by the reaction diaphragm and therefore subtracts from the upward force produced by the reaction diaphragm. The bell is shaped so that the variation in buoyancy with change in nozzle back pressure produces a back pressure which is proportional to the square root of the differential pressure across the measuring diaphragm.

The nozzle back pressure is also the signal pressure which is transmitted by means of tubing to any desired location up to 1000 feet from the transmitter.

Other instruments extract the square root by suitable linkages in the feedback system. For example, the Bailey flow transmitter, uses a square root extracting mechanism which is based on a cosine relationship between motions of two beams. One responds to the input signal. The other feeds back corresponding displacement angles. Within design limits, the square root relationship is virtually identical to the cosine relationship.

The Yarnall-Waring Company developed a differential-pressure transmitter illustrated in Figure 4-33. A neoprene-coated "Dacron" diaphragm is mounted between the backing plate and the rear housing, and differential pressure is applied across it. The picture illustrates how the diaphragm is free to move only through very small displacements. Should the pressure differential exceed its normal limits, then the diaphragm flexes against the support of either the backing plate or the inside surface, and no damage can be done to it. The force which the diaphragm exerts is counteracted by the deflection plate. The spring

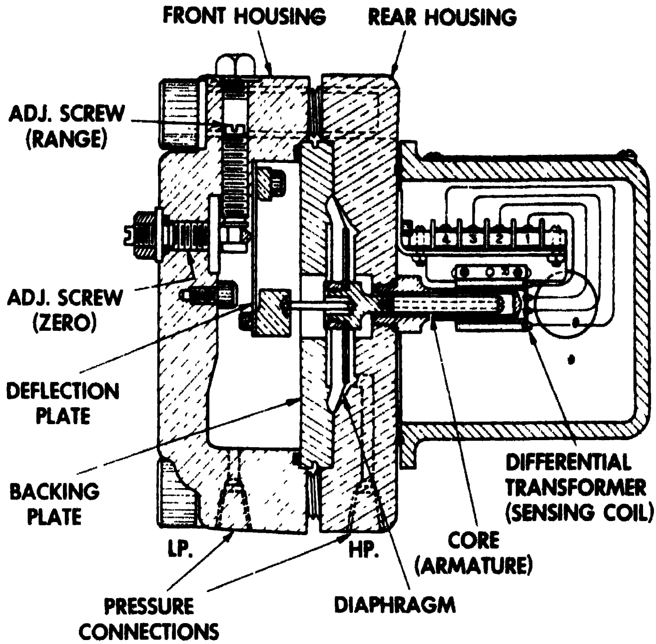


Figure 4-33 Electrical differential-pressure transmitter. (*Courtesy of Yarnall-Waring Co.*)

rate of the deflection plate can be changed by means of the adjustment screw which raises or lowers the fulcrum about which it flexes. This adjusts the range. Another adjustment screw provides zero adjustment by simply displacing the deflection plate to the left or right. The armature of a differential transformer is directly displaced by the diaphragm. A sealed tube separates armature and coils of the differential transformer with very little detriment to the electromagnetic relation between them. Voltage output from the differential transformer varies linearly with change in armature. This transmitter is an exception insofar as it does not contain a feedback of its output signal. However, the differential transformer is extremely sensitive so that the motion of the diaphragm can be maintained within limits that assure relatively constant effective area. The receiver for this transmitter is illustrated in Figure 5-8 and described there.

The previously described Foxboro d/p cell is also available in an electric version illustrated in Figure 4-34. The flapper-nozzle and relay of Figure 4-31 are now replaced by the detector and amplifier, respectively, and a feedback motor takes the place of the feedback bellows. The detector is a differential transformer of a construction slightly different from the conventional form. The

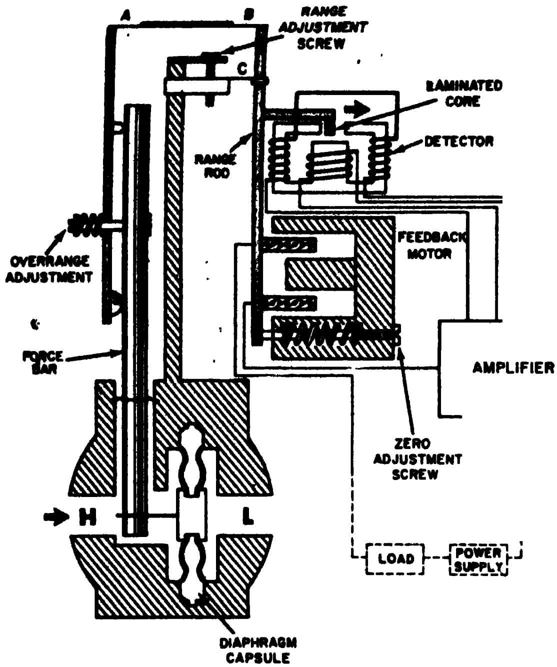


Figure 4-34. Electrical flow transmitter. (*Courtesy of Foxboro Co.*)

center leg of the iron core carries the primary winding connected to a 115 V., 60 cps source. The two secondary windings are on the outer legs and are wound in opposition as is customary with differential transformers. As long as the laminated core is in the center position, the inductive coupling between primary and each one of the two secondaries is equal and opposite. Consequently the net output from the secondaries is zero. As the laminated core is displaced toward either side the linkage to one secondary is increased and diminished to the other. Hence, a net voltage results which is proportional to the core displacement.

The output from the transistorized oscillator amplifier varies with the detector signal and is applied to the coil of the feedback motor. This feedback motor is also known as the voice coil, moving coil, force motor, or force coil. The center piece of its E-structure is a permanent magnet creating magnetic flux in the air gap in which the coil moves. The moving coil is pulled into the air gap (or repelled—depending upon the polarities) with a force which is proportional to the flux density in the gap, the length of wire on the coil and the current flowing through the coil.

Hence, any change of pressure differential across the diaphragm capsule deflects the laminated core of the detector with a consequent increase of current through the moving coil. The resulting change of force balances the force produced by the differential pressure across the diaphragm capsule.

The load, which may be a recorder or the input side of an electronic controller, is in series with the moving coil. Thus, the balancing current is also the output signal of the flow transmitter.

Another electric transmitter of the diaphragm type is GPE Control's device, as illustrated in Figure 4-35. Differential pressure applied across the diaphragm

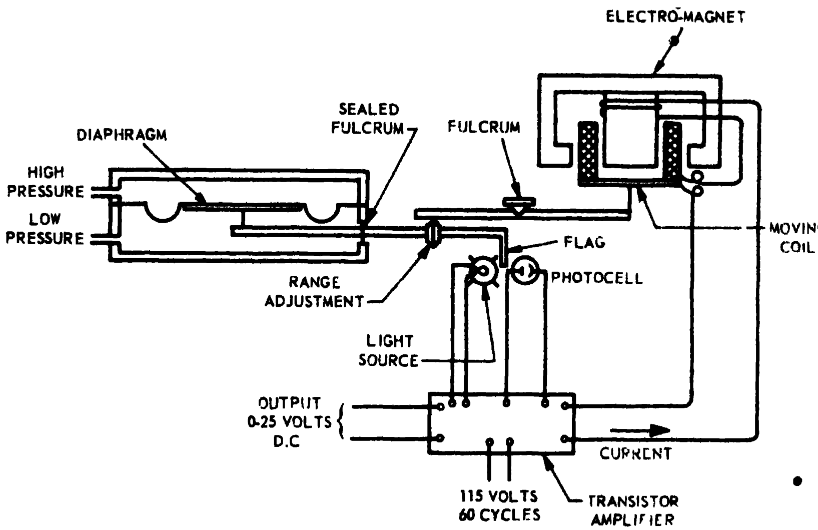


Figure 4-35. Electrical flow transmitter. (*Courtesy of GPE Controls, Inc.*)

moves the flag between the light source and the photocell. The signal from the photocell varies in strength according to the flag position, and is fed to the transistor amplifier. The amplifier output, consisting of a *d.c.* current proportional to the photocell output, flows through the moving coil and the coil of the electromagnet. The magnetic field which in the previous example was produced by a permanent magnet is now produced by the electromagnet. The two coils, the moving coil and the electromagnetic coil, are in series. The result is that the moving coil is attracted by the magnetic field of the electromagnet with a force proportional to the square of the current. This force is transmitted through the balance arm to the range adjustment wheel which bears on the lever arm and balances the force exerted on the lever arm by the diaphragm. Thus, differential pressure across the diaphragm is measured by the square of the current. The relation between differential pressure measured across an orifice plate and the flow rate passing through it is expressed by

$$Q = kA\sqrt{\Delta p}$$

where Q is the flow rate, k is a constant, A is the cross-sectional flow area of the orifice plate, and Δp is the differential pressure across the plate. This equation may also be written

$$Q^2 = k^2 \times A^2 \times \Delta p$$

In the GPE transmitter, the square of the balancing current is made proportional to the differential pressure. Hence, it must also be proportional to the square of the flow rate. However, if the square of the current is proportional to the square of the flow rate, it follows that the balancing current is proportional to flow rate. The current is thus a direct measure of flow rate. Current is converted into the output voltage signal, in the range of 0 to 25 volts *d.c.*

Compared with U-tube meter bodies, the diaphragm types have considerable faster response. The time constant* of a U-tube meter body is in the order of two or three seconds, while a diaphragm meter body has a time constant in the order of 0.01 second. On the other hand, the diaphragm type is inherently less accurate than either the U-tube or the bellows meter. The accuracy of the former is usually rated at ± 1 per cent of full scale, while the latter types will approach ± 0.5 per cent.

Integrators. The previously described Leeds & Northrup Centrimax flowmeter integrates flow directly. However, in general the differential-pressure type of flow meter reads *rate* of flow. If it is desired to read *total* flow during a given time from a chart that records rate of flow it is necessary to compute the area under the curve drawn by the recording pen. This computation can be done by means of planimeters. The work and inconveniences of integrating with a planimeter can be avoided by integrators which are part of the instrument. In the following the most representative types of integrators are described.

The escapement type is represented by the Bailey integrator. Its operation is illustrated by the diagrammatic drawings in Figure 4-36. The heart-shaped cam which has a uniform angular rise, is geared to a Warren synchronous motor and rotates at the constant rate of 2 rpm. By means of a friction clutch between the cam and the escape wheel, the motor also drives the escape wheel and the integrating counter at constant speed as long as the pawl is not engaged. Whenever the pawl engages the escape wheel the integrator counter is held stationary, but the friction clutch slips allowing the cam to continue rotating.

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*The time constant expresses the time it takes for the output of a device to go through 63.2 per cent of its full change in response to a sudden change of input.

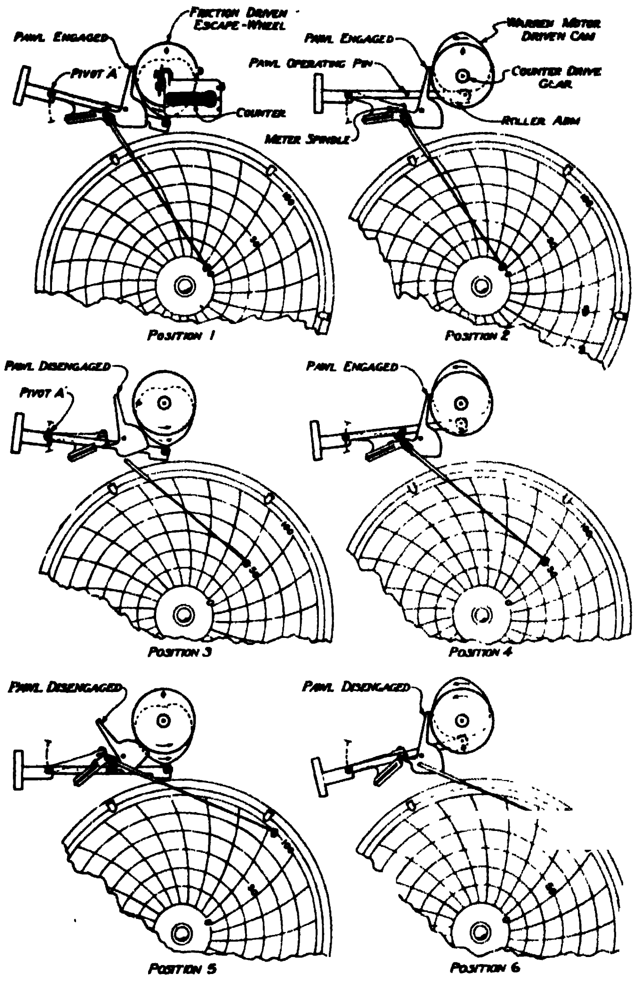


Figure 4-36. Escapement-type integrator (*Courtesy of Bailey Meter Co.*)

The roller arm is pivoted near its left end to the meter flow arm, so that the position of the pivot varies only with changes in the rate of flow. The right end of the roller arm moves up and down under the action of the rotating cam, causing the pawl operating pin to move up and down also. This operating pin is responsible for engagement and disengagement of the pawl with the escape wheel.

Referring to Figure 4-36, positions 1 and 2 show the flow recorder at zero rate of flow. In position 1 the cam and roller are at maximum throw, and in position 2 they are at a point of minimum throw. In both of these extreme cam positions with zero rate of flow the integrator counter is stationary because the path of the pawl operating pin does not come sufficiently low to disengage the pawl.

Positions 3 and 4 also show the cam and roller in their extreme positions, but the flow recorder is now at 50 per cent of maximum capacity. The increased rate of flow has resulted in lowering point *A*, thus lowering the path traveled by the operating pin. Consequently, during 180° rotation of the cam, the pawl remains engaged with the escape wheel, but during the remaining 180° rotation, it is kept disengaged by the pin. Under these conditions the integrator counter runs 50 per cent of the time, which is equivalent to the rate of flow at 50 per cent of the maximum.

Positions 5 and 6 show cam and roller in similar position, but with the rate of flow increased to 100 per cent. At this rate of flow the pawl operating pin keeps the pawl disengaged during 360° rotation of the cam; consequently the integrator counter runs continuously.

Using a mechanism which, in principle, resembles the electric Bristol transmitter illustrated in Figure 4-18, the American Meter Company makes an integrator for flow which includes corrections for pressure changes. The significance of pressure correction is described under *Pressure and Temperature Compensations*. The mechanism of the integrator is shown in Figure 4-37. The movement of the pen, which indicates differential pressure or rate of flow, is linked to the right-hand or differential arm which has at its free end an offset finger. The left-hand or pressure arm is positioned by a linkage to the pressure-measuring element. The right-hand cylinder which is part of the differential pressure computer is called the differential cylinder. The left-hand cylinder which corrects for pressure changes is called the pressure cylinder.

Both cylinders have raised cam surfaces, which are so shaped that in taking successive cross sections from right to left of either cylinder, the proportion of raised surface continually increases. The free end of the differential arm with its offset finger moves between the differential cylinder and the corresponding rocker plate, *B*. The differential cylinder is driven by a motor over a drive gear at 1 or 2 rpm in a counterclockwise direction. As the raised portion of the cylinder contacts the offset finger, the arm—which is free to move through a certain angle forward toward the front of the instrument—is pushed and swings the top of the rocker plate forward also. Since the rocker plate moves about a shaft, *C*, the forward movement of its top portion will cause the lower horizontal part to swing forward. This will make gears *E* and *F*, attached to the horizontal part of the rocker plate, engage gears on the differential cylinder, *D*, as well as on the pressure cylinder, *G*.

The rotary motion of the differential cylinder is now transmitted to the pressure cylinder, but only until the rocker plate on the differential cylinder swings

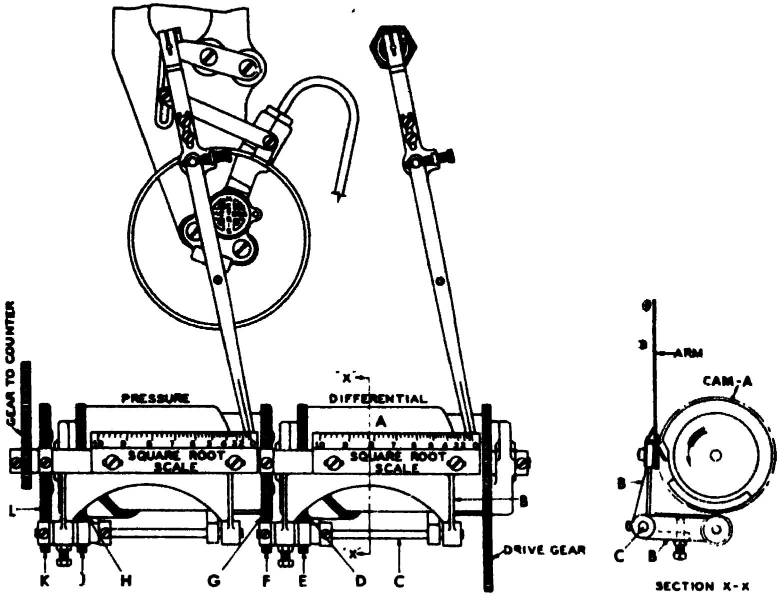


Figure 4-37. Mechanism of American Meter integrator. (*Courtesy of American Meter Co.*)

back, *i.e.,* the pressure cylinder will move as long as the raised portion of the cylinder is in contact with the offset finger of the differential arm. Since the proportion of raised surface is continuously increasing from right to left along the axis of the cylinder, the length of time the arm is pushed forward depends on the position of the arm, hence on the differential pressure being measured.

The action on the pressure cylinder is similar to that on the differential cylinder. On the left it connects to the gears, *L*, that drive the counter, but the gears, *K* and *J*, are meshed only as long as the pressure arm with its finger is between the raised surface of the pressure cylinder and the rocker plate. Since rotary motion of the pressure cylinder is obtained only when it is driven over the gear train from the differential cylinder, it is obvious that the counter gears are only rotating when both arms, differential and pressure, are on the raised portions of their respective surfaces. The shape of the raised surface on the pressure cylinder determines the amount of correction of the flow measurement. With proper gearing, the motion transmitted to the counter is proportional to the pressure differential times a correction factor which corresponds to the pressure, and results in a reading of the counter representing total flow.

In the Republic flowmeter, the arrangement of Figure 4-17 is utilized for integration of the flow by measuring the power consumption, since this is a function of the flow rate. The power consumption is measured by an instrument that resembles a conventional watt-hour meter. The permanent magnet, however, is replaced by an electromagnet to provide automatic compensation for voltage and frequency variations. In the watt-hour meter, the speed of the disc depends upon the ratio of the magnetic field force of a permanent magnet to the electromagnetic force produced by the watts consumed. In the Republic integrator the force ratio between the magnetic field from the applied voltage to the field obtained from the flowmeter current determines the speed of the disc. By gearing the disc to the counter an indication for total flow is obtained.

The Brown electronic integrator employs a vane moving into the electromagnetic field between two oscillator coils. The oscillator coils are continuously cycled over a fixed area and the vane is interposed between the coils for a period of time dependent upon the flow rate, since the vane is positioned by the instrument pen. When the leading edge of the vane is intercepted by the coils, the electronic detector relay is energized and the counter motor is permitted to operate. The counter motor operates as long as the oscillator coils are intercepted by the vane and stops instantaneously when the vane and coils are separated. Thus the counter motor runs for a period which is proportional to the rate of flow and accurate integration is the result.

The GPE Controls Electric Integrator is essentially a small d.c. motor with the jeweled bearings and a precious metal commutator, which drives a precision gear train and counter. The motor speed is proportional to the applied voltage. Hence the electric d.c. input of any flow transmitter can be applied across the terminals of this integrator.

Signals that indicate by their duration the magnitude of the flow rate (cf. Figure 4-18) can be fed in the Chronoflo Totalizer made by B-I-F Industries. Inc. The time duration signals are applied to an electromagnetic clutch which, when energized, couples a counter to a synchronous motor. The counter is calibrated to read directly in the desired units.

Electric integrators are usually available in explosion-proof housing, but in explosive atmospheres pneumatic integrators may be preferred. Figure 4-38 shows the schematic arrangement of the Foxboro pneumatic integrator. A 3 to 15 psi signal, proportional to 0 to 100 per cent of differential pressure from a flow transmitter, is applied to the integrator receiver bellows *A*. The force exerted by the bellows positions a force bar *B*, which acts as a flapper, in relation to nozzle *C*. With an increase in differential pressure the flapper approaches the nozzle. The resulting increase in nozzle back pressure regulates—through air relay *D*—the jet which drives turbine rotor *E*.

Weight *F* is mounted on the flexure-pivoted bell crank *G*. As the rotor revolves, the centrifugal force of the weight *F* is applied to force bar *B*, through thrust pin *H*, to balance the force exerted by the bellows *A*. Therefore, a condition of force balance is continuously maintained.

The centrifugal force is proportional to the square of the rotor speed. This force balances the signal pressure which is proportional to the square of the

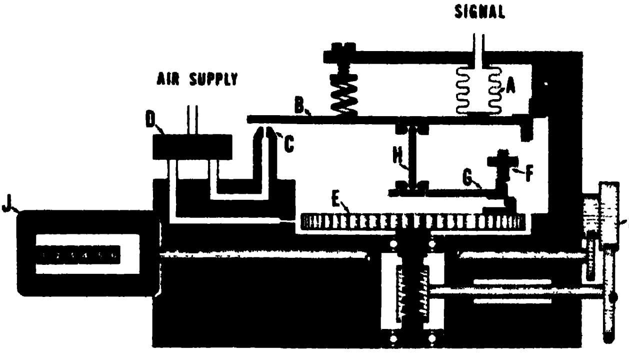


Figure 4-38 Pneumatic integrator. (*Courtesy of Foxboro Co.*)

flow. Therefore, rotor speed is directly proportional to flow. Since the counter *J* is connected to the turbine rotor through gear train *K*, integrator count is also directly proportional to flow.

An interesting mechanism is the Fischer & Porter integrator, illustrated in Figure 4-39. The calibration cam is moved by the input link through a sector gear to a position which corresponds to the measured flow rate. At intervals of 2.5 seconds the sweep arm moves from the zero flow position until it strikes the rim of the calibration cam. Since the distance between hub and rim of the calibration cam increases over its circumference, the amount of upward movement of the sweep arm is determined by the position of the calibration cam, and hence by the rate of flow. A 100-rpm synchronous motor drive (or a

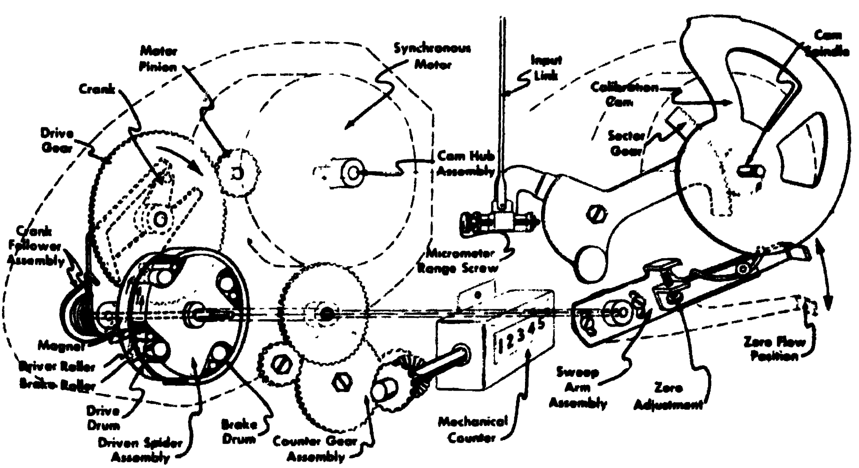


Figure 4-39. Ratographic integrator (*Courtesy of Fischer & Porter*).

pneumatic drive) operates the sweep arm by means of a crank. An overtravel release spring attached to two crank follower arms permits the crank to complete its rotation after the sweep arm motion is stopped by the cam, yet assures motion of the sweep arm until it does strike the cam. To obtain a positive drive for the counter gear train from the forward and backward movements of the sweep arm, a clutch mechanism is used.

The drive drum of the roller clutch is fastened to the sweep arm shaft and moves with it. The driven spider assembly, together with the drive gear of the counter gear assembly, is mounted on a second shaft, which is hollow and concentric to the sweep arm shaft. The brake drum is mounted outside and does not move at all. As the sweep arm returns from the calibration cam, the drive drum rotates in a clockwise direction, as indicated by the arrow. In doing so, the driver rollers become jammed between the drum and the narrow ends of the slots provided for them in the spider assembly. Engagement of the driver rollers is instantaneous, because they are held lightly in position by the magnets, which are inserted as shown. When the driver drum ceases its clockwise motion and commences its return stroke, pressure on the rollers is in the direction of the large end of their slots. Thus they roll free and the spider does not undertake a retrograde motion. However, to assure positive action, a brake drum—identical with the driver drum, but non-rotating—is provided and contains its own set of rollers and magnets. If the spider seeks to make a retrograde motion, the brake rollers promptly lock against the brake drum and hold it in fixed position till the next forward motion of the driver drum frees the spider.

Since the shaft of the spider is connected with the counter gear train, the amount of the integrator counts will be determined by the angular length of the sweep arm's return stroke.

This completes the survey of typical flowmeter integrators as they are in use today. In addition to the integrator, flowmeters are frequently equipped with a planimeter pen which records the integrated flow along the edge of the chart. Actuated by the integrator, the pen makes a small mark every time a predetermined number of flow units are integrated. The record eliminates the necessity for frequently taking note of the integrator reading and furnishes a convenient record for current use as well as for future reference.

Pressure and Temperature Compensations. Where compressible fluids, such as steam, air, and gas, are being measured, the rate of flow does not only depend on the pressure differential but also on the static pressure. Furthermore, changes in temperature may alter the density of the measured fluid sufficiently to produce undesirable errors. It is frequently necessary, therefore, to take these factors into account, either by measuring them, and using a correction factor for the flowmeter reading, or by automatically compensating in the flowmeter for changes in static pressure or temperature. To facilitate the first method, practically all flowmeters allow the addition of pressure and temperature elements, so that the same chart can record flow rate, pressure and temperature. Automatic compensation is obtained, for example, in the Foxboro Air Weight Compensator which corrects measurements of gas flow for changes in process air pressure from minus 3.5 up to 7 psi and temperatures up to 250°F.

The compensating device is a gas-filled, sealed bellows housed in an air-tight compartment mounted on the back of a flow recorder. The flow meter orifice is bypassed by a continuous sample flow from the process line. This sample flow circulates through the compensator compartment. Within the compartment, increasing pressure of the surrounding process air or gas compresses the compensating bellows and, increasing temperature expands the gas in the compensating bellows. Bellows motion resulting from these two forces is transmitted to the pen movement of the recorder through a pressure-tight bearing and a simple linkage. The compensator corrects the differential pressure measurement for any deviation caused by temperature and pressure variations. Corrected flow is read directly from the recorder chart.

A typical example for pressure compensation in connection with integration is that of the American Meter Company, described above and illustrated in Figure 4-37.

The Republic pressure compensator uses a variable transformer which consists of a rotor, the secondary, and a stator, the primary of the transformer. Moving the rotor through a small angle changes the magnetic flux linkage between primary and secondary and hence alters the voltage across the secondary of the transformer. The rotor is positioned through the counteracting forces of a bellows and a spring. The bellows is exposed to the pressure for which the flowmeter reading is to be compensated. The rotor is connected in series with the meter body scale resistance elements (Figure 4-17), while the stator, or primary, is connected directly across the secondary of the transformer which supplies the electrical circuit of the meter (also shown in Figure 4-17). At pressures below normal, the secondary voltage of the compensator opposes that of the meter transformer and the instrument readings are reduced. Conversely, at pressures above normal, the secondary voltage of the meter transformer is boosted and the instrument readings are increased. The compensator is effective over a ratio of maximum to minimum pressure of approximately 2.5. Similar arrangements are available for temperature compensation.

TARGET METERS

The target meter uses a target instead of the orifice plate or some other flow restriction. It measures the force of the flowing stream impinging on the target, as shown in Figure 4-40. This particular instrument is made by the Foxboro Company. The circular sharp-edged target, proportioned for the required rate of flow, is attached to the lower end of the force bar so that it is exactly concentric with the bore of the pipe. The force exerted on the target tends, by means of the force bar to change the distance between flapper and nozzle. Any such tendency, however, produces changes in back pressure to the relay and simultaneous changes in relay output pressure. Relay output is supplied to the feedback bellows of the transmitter and to remote receivers. The pressure in the feedback bellows, applied to the force bar, is exactly proportional to the force on the target. Thus, the force of the feedback bellows continuously balances the force on the target to maintain flapper-nozzle equilibrium throughout a relay output range of 3 to 15 psi.

An oil-filled, piston-type dashpot is mounted atop the frame with its piston rod attached to the flexure. This dashpot dampens the force-balance mechanism against the effects of "noisy" flows impinging on the target.

The target meter provides dependable repeatability of measurement in the high viscosity region with Reynolds numbers of 1000 and less. Typical fluids that can be thus measured are hot asphalt, tars, synthetic dopes, oils, viscose and slurries.

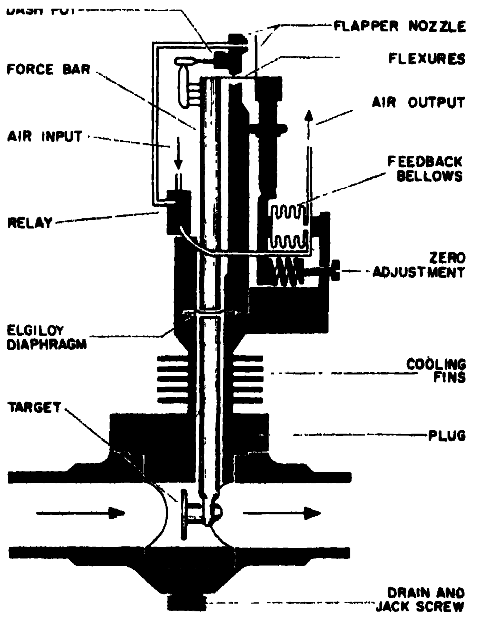


Figure 4-40. Target meter. (*Courtesy of Foxboro Co.*)

VARIABLE-AREA METERS

In the differential-pressure instruments described above, the flow restriction is of fixed size and the pressure differential across it changes with the rate of flow. The variable-area meter adjusts the size of the restriction by an amount necessary to keep the pressure differential constant when the flow rate changes. The amount of adjustment required is a function of the flow rate.

One of the great practical differences between differential-pressure meters and variable-area meters is the square-root relationship between flow and differential pressure and the linear relationship between flow and area. Therefore, the rangeability of the instrument, *i.e.*, the ratio of maximum to minimum flow rate that can be accurately measured, is basically larger with the variable-area meter.

In many applications, especially in smaller pipe sizes, cost of the meter and its installation is in favor of the variable-area meter.

The commercial application of the variable-area principle is found in the area meter and in the rotameter.

Area Meters

The area meter has applications similar to target meters which means primarily the measurement of tarry, sticky and highly viscous liquids that preclude the use of an orifice plate. It is installed directly in the pipe line and is usually equipped with an electric transmitter.

In Figure 4-41 the Bailey area-meter transmitter is shown as a typical example. As the flow pushes the metering plug upward, the calibrating spring exerts a downward force on the metering plug. The ports are rectangular in shape and their area varies in proportion to the height of the metering plug. The differential pressure across this plug is counterbalanced by either a calibrating spring, as shown in Figure 4-41 or by a calibrating weight.

If the rate of flow increases, the differential pressure across the metering plug tends to increase. This raises the plug and increases the port area in proportion to the rate of flow. The opposite is true when the flow decreases. The metering plug is connected with the transformer core, and both move together. The transformation into an electric signal is the same as previously described and illustrated in Figure 4-20.

Rotameters

The flow range of a rotameter is about 10:1, which means that the range of the instrument can be ten times that of the minimum flow which is to be accurately measured. In other words if the range of the rotameter is, say, 50 gallons per minute, flow of 5 gallons per minute is the minimum rate of flow

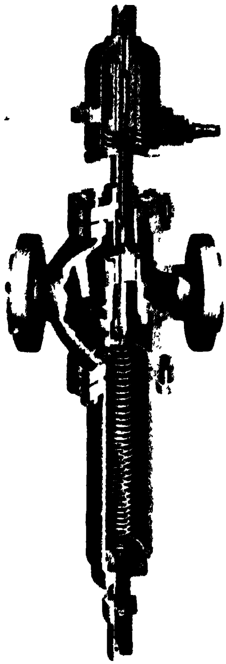


Figure 4-41. Area meter transmitter. (*Courtesy of Bailey Meter Co.*)

to be measured. At smaller flows the inaccuracies would very rapidly increase, hence the meter should not be used for flow ranges greater than 10:1. In the differential-type flowmeter, which is generally used between 25 and 100 per cent of its range, the flow range is 4:1, *i.e.*, maximum flow is 4 times the minimum flow. Hence, in the above example, a differential-type flowmeter should not be expected to measure accurately flow rates below 12.5 gallons per minute.

While the flow range of the rotameter is thus larger, its accuracy is generally listed at 2 per cent of its range, which is lower than the accuracy of differential-pressure meters. However, by individual calibration the accuracy of the rotameter can be increased to 1 per cent.

The rotameter does not depend on straight pipe runs as do most primary elements for differential-pressure meters. The cost of its installation is relatively low provided that the location of the rotameter does not require detours for the pipe line.

The rotameter consists of a float that is free to move in a tapered glass, porcelain, or metal tube with the taper directed downward, so that the inner cross section of the tube is wider toward the top. Figure 4-42 shows a rotameter made by the Brooks Instrument Company.

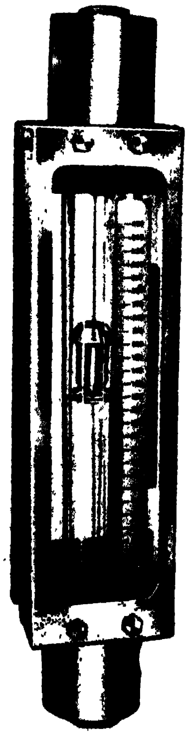


Figure 4-42. Rotameter.
(*Courtesy of Brooks Instrument Co.*)

The free area between float and inside wall of the tube forms an annular orifice. As the float moves up, the flow area of the annular orifice increases. The pressure differential across the annular orifice is proportional to the square of its flow area and to the square of the flow rate. The float is pushed upward until the lifting force produced by the pressure differential across its upper and lower surface is equal to the weight of the float. If the flow rate rises, the pressure differential—and hence the lifting force—increases temporarily. The float then rises, widening the annular orifice, until the force caused by the pressure differential is again equal to the weight of the float. Thus, the pressure differential remains constant and the area of the annular orifice, *i.e.*, the height to which the float moves, changes in proportion to the flow rate. The position of the float becomes an indication of the rate of flow.

The float is often guided (Figure 4-43) by a float guide which extends through its center. The float is free to move longitudinally along the float guide, but its sidewise motion is limited.

Another method is to use glass tubes with inner-wall guides. Equally spaced ribs, usually three, are an integral part of the inner surface of the tube. The

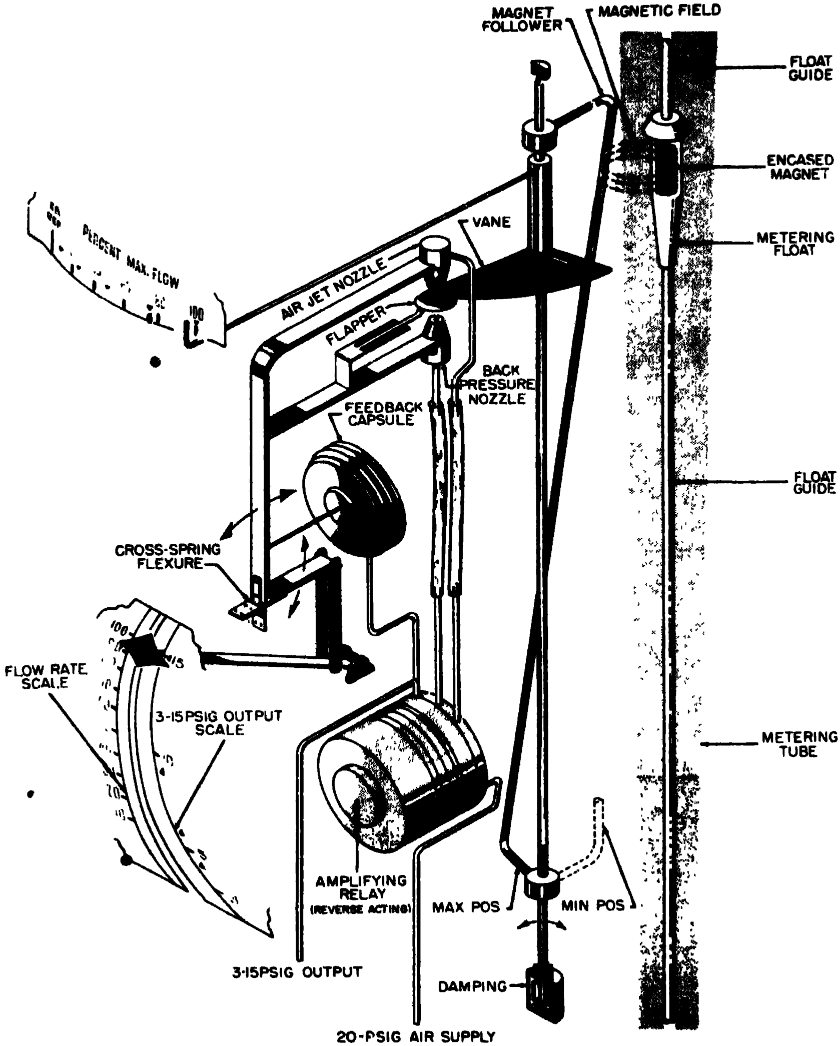


Figure 4-43. Magnarator. (*Courtesy of Fischer & Porter.*)

axes of these ribs are parallel to the axis of the metering glass tube. The ribs run straight while the tube is tapered; at the smaller end of the tube, the rib edges are tangent to the bore. Thus the ribs guide the metering float at three points of its periphery. The clearance between the float edge and the inner surface of each rib is only a few thousandths of an inch. This arrangement has the advantage that it not only guides the float but also allows observation of it in very dark fluids because of the small clearance between float and ribs. The disadvantage is that suspended solids may be caught between float and ribs and jam the float.

At pulsations of small amplitude, the average reading of the rotameter represents approximately the true value of flow. If the amplitude of the pulsations increases, it becomes necessary to dampen the movements of the float. Rotameters with dashpots are available for this purpose. The piston of the dashpot is attached to a rod that extends from the float into the dashpot. With the dashpot, the average reading is no longer the true value of flow. An error is introduced which increases with the amount of damping required to keep the float oscillations within reasonable limits.

As long as the flow tube is made of glass, the pressure of measured fluid is generally limited to 600 psi or less—depending largely on the tube size. Furthermore, the possibility of breakage frequently precludes its use with hazardous fluids. In such cases, metal tube rotameters may be used. The metal tube is tapered like a glass tube. It has a vertical inlet and a horizontal outlet. An extension tube extends vertically up from the rotameter tube. Since the flow branches off between rotameter tube and extension tube into the horizontal outlet, the extension tube remains outside the flow passage. The extension tube is of nonmagnetic material. A magnetic ring is fitted over the extension tube with enough clearance to permit its sliding up and down. The float in the metal meter tube carries an extension rod with a magnet at its end which moves inside the extension tube. Since the magnetic ring outside the tube follows the magnet inside the tube, a visual indication is obtained.

The principle of a magnet follower can be expanded in a number of ways. For example, in the Fischer & Porter Magnarator, it is used to indicate the flow rate and to convert it into a proportional pneumatic signal for transmission. This is illustrated in Figure 4-43. The encased magnet is part of the metering float. The magnet follower is a rod bent in such a way that in following the motion of the magnet, it rotates through a 45-degree angle. The shape of the magnet follower is equivalent to the leading edge of a helix, a shape which also finds use in the inductance type integrator described further below.

Attached to the follower is a segmental vane, the edge of which is continuously sensed by the flapper-nozzle assembly. As the vane edge moves, there is a change in the air flow directed by the jet against the flapper. This flapper, moving with the pressure change, varies the nozzle back-pressure. An amplifying relay changes the output pressure in inverse proportion to the change in nozzle back-pressure. Output pressure is simultaneously fed back to the feedback capsule which provides the motion to reposition the nozzle assembly with respect to the vane. Thus the flapper-nozzle assembly follows the contour of the vane, and the output signal is proportional to the vane position.

The transmitter output indicator has a vertical scale, 4 inches long, graduated in both flow units and output pressure. A pointer, attached to the magnetic follower, indicates flow rate independently of the transmitter or air supply on a 2 ½-inch horizontal scale.

A method not only to indicate but also to integrate flow is illustrated in Figure 4-44. This Brooks inductance type integrator uses the same principle of magnet follower as the previous design. In this case it is a long helix: the magnetic position indicator. The leading edge of the helix is constantly attracted to the magnet. It therefore rotates as the magnet moves up and down

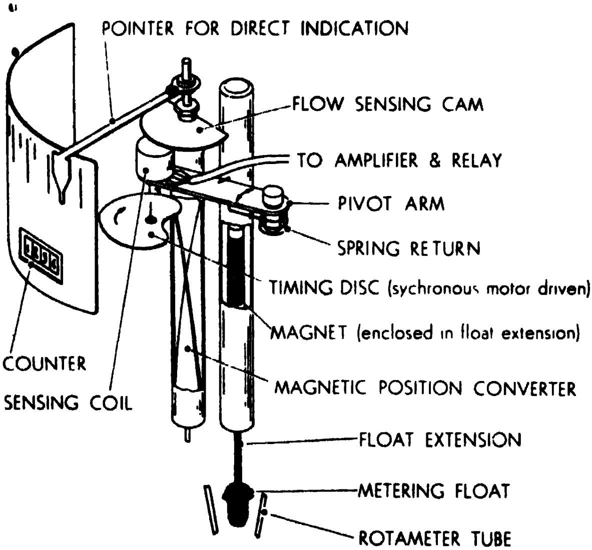


Figure 4-44. Flowmeter with integrator. (*Courtesy of Brooks Instrument Co.*)

converting the linear motion of the metering float and magnet into an angular motion of somewhat less than 90 degrees. The flow sensing cam rotates with the magnetic position converter. A timing disc is driven by a synchronous motor. Through a pivot arm and its spring return, it cycles the sensing coil back and forth under the characterized flow cam. The counter itself is also driven by a synchronous motor. When the sensing coil is under the cam, the counter motor is actuated through the amplifier and relay. When the sensing coil is out from under the cam, the counter motor is stopped. The length of time in each cycle that the coil operates the counter motor is determined by the characterized flow cam. Hence, the counter runs in direct proportion to rate of flow and indicates total accumulated flow. In addition, the indicator reads the rate of flow at any given instant.

As pipe lines increase in size, the cost of rotameters increases rapidly. For 4-inch and larger pipes, a different metering method is generally preferred. One way is to combine the differential-pressure with the variable-area method. This is done in the bypass rotameter, such as Fischer & Porter's Ori-Flowrator. An orifice plate is inserted in the main flow line. A bypass with the rotameter in series is provided around the orifice plate. Thus, a portion of the total flow is diverted from the main line through the bypass and passes through the rotameter before it returns to the main line. The pressure differential across the orifice determines the flow through the bypass, *i.e.*, through the rotameter. A second orifice is provided in the bypass. This permits precise proportioning between main line flow and bypass flow. Since the bypass flow varies directly as main line flow, the linear scale of standard rotameters can be used.

American Measurement & Control, Inc., makes a flow transmitter which is a modified variable-area meter balancing the pressure differential against a preloaded spring. Figure 4-45 shows a schematic of this transmitter. While in the

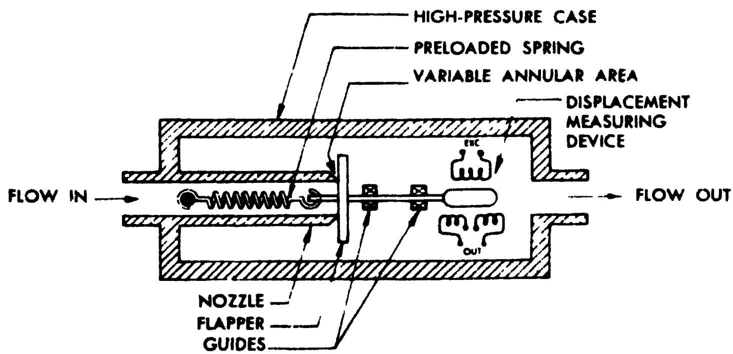


Figure 4-45. Flow transmitter. (*Courtesy of American Measurement & Control, Inc.*)

conventional rotameter the weight of the float is used as a counterbalance, the spring now replaces the weight. As the pressure drop across the variable annular area increases, the flapper moves toward the right, increasing the annular area. However, contrary to the conventional rotameter the balancing force is not a constant, since the spring force increases with deflection. The resulting non-linearity is made negligible by making the flapper motion relatively small. A differential transformer senses the displacement of the flapper and converts it into an electric signal.

WEIR METERS

The flowmeters so far described are for measurement of flow in pipe lines. Where the fluid moves through open channels, different measuring methods are used. Usually, some kind of weir or a flume is required. Both provide restrictions in the flow: the weir by means of a rectangular or V-notched dam over which the liquid flows, and the flume by constricting the passage of the liquid. Figure 4-46 shows a V-notch weir as used for measurements of up to approximately 6000 gallons per minute. The rectangular notch shown in dotted

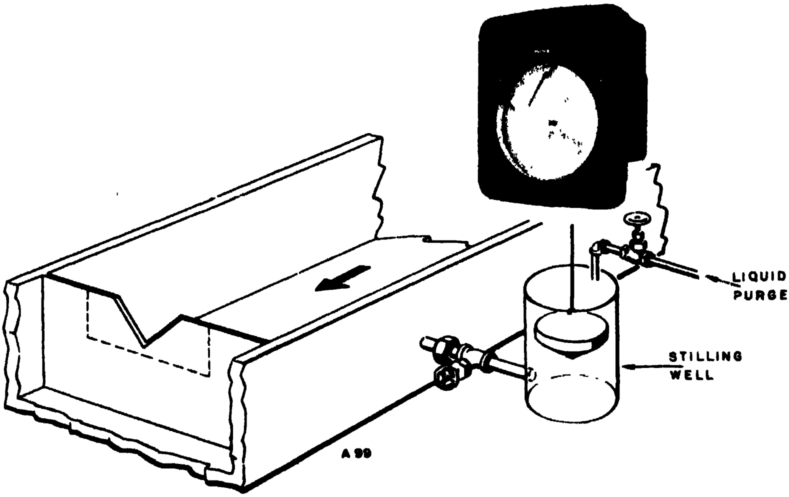


Figure 4-46. V-notch weir (rectangular notch shown in dotted lines). (*Courtesy of Foxboro Co.*)

lines is usually recommended for larger flows. Where head losses must be held at a minimum or where the measured liquid contains considerable amounts of solids, sediments, etc. a flume is preferred. One of the forms frequently used is the Parshall flume shown in Figure 4-47.

B-I-F Industries markets a one-piece plastic Parshall flume liner. It is made of fiberglas-reinforced polyester plastic resins and accurately duplicates Parshall flume dimensions.

The rate of flow of liquid over the weir or through the flume is determined from the head, *i.e.,* the depth of water, at a specified distance upstream from the weir plate or the flume neck. At this distance, a connecting pipe from the so-called stilling well is tapped into the liquid. A float in the stilling well will then move up and down with the head and can thus be used to indicate the rate of flow of the liquid.

The measuring mechanism is usually a float-and-cable type instrument. As the float rises and falls, it causes the rotation of a cam attached to the inner end of the cable drum shaft. A spiral groove in the cam guides a follower which is linked directly to the pen arm, converting head readings into flow-rate readings.

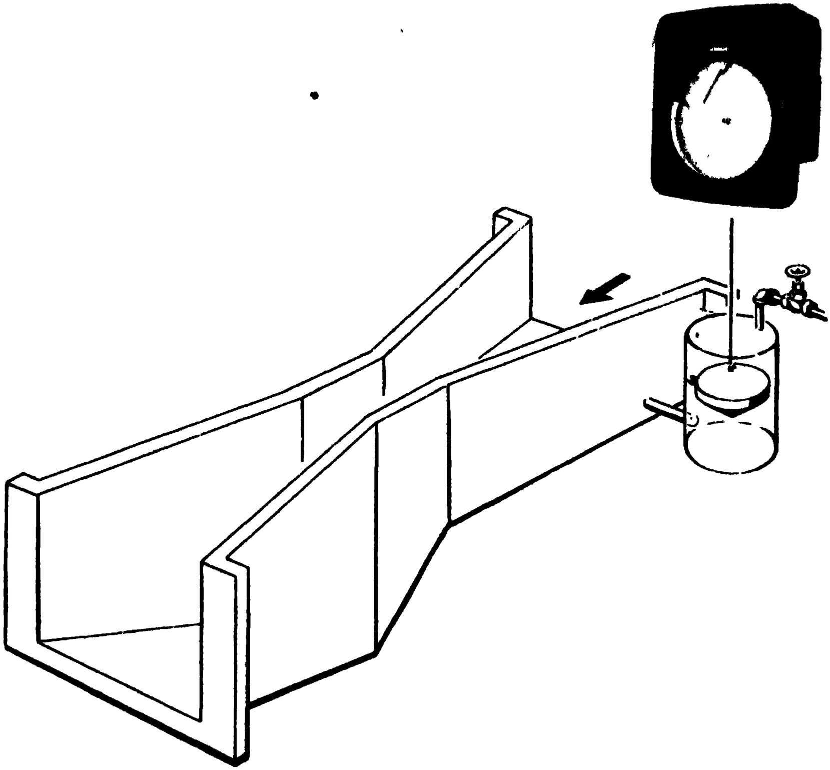


Figure 4-47. Parshall flume installation (*Courtesy of Foxboro Co.*)

POSITIVE-DISPLACEMENT METERS

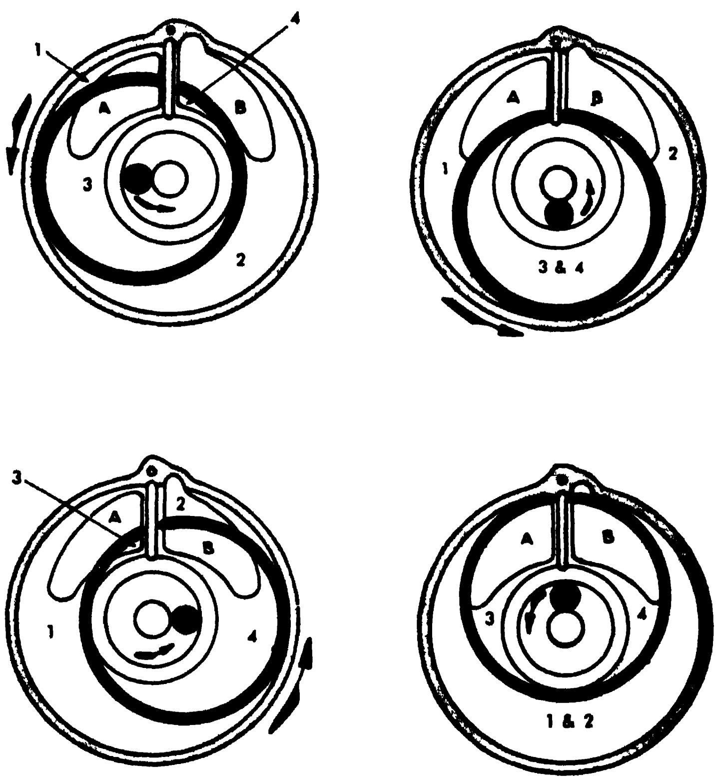
All types of flowmeters so far discussed, except Leeds & Northrup's Centrimax, are basically *rate-of-flow* instruments. They are frequently equipped with integrators that make readings of accumulated flow possible, but these are considered accessories to the basic instrument. Positive-displacement meters are essentially *flow quantity* instruments. They are most frequently used for batch-metering of process liquids. For continuous processes rate-of-flow instruments are generally preferred.

The positive-displacement meter takes a definite quantity or portion of the flow, and carries it through the meter. It then proceeds to the next portion, and so on. By counting the portions, an account of the total quantity carried through the meter is obtained. The accuracy of positive-displacement meters is high—usually rated at 0.1 to 1 per cent.

The close clearances necessary for the measuring mechanism of positive-displacement meters limit them to the measurement of absolutely clean liquids. There are, however, some exemptions which measure gases and not liquids.

Oscillating-piston Meters

Figure 4-48 shows the principle of operation of a Rockwell meter. The so-called piston is the black ring that moves around the inside periphery of the cylinder, or measuring chamber. The movement is a combination of (1) a sliding motion of the slotted end of the piston along a division plate which is part of the measuring chamber and (2) an oscillatory motion of the piston around the division plate. The division plate in the measuring chamber separates the inlet port *A* from the outlet port *B*. The first sketch of Figure 4-48 shows the moment where spaces 1 and 3 are receiving liquid entering through port *A*, while spaces 2 and 4 are discharging through port *B*. In the second



3 4

Figure 4-48. Operating principle of oscillating-piston meter. (*Courtesy of Rockwell Mfg. Co.*)

sketch, the piston has advanced and space 1 has increased. Space 2, has decreased, while spaces 3 and 4, which have combined, are about to move into position to discharge through the outlet port. In the third sketch, space 1 is still admitting liquid from the inlet port and space 3 is just opening again to the inlet port, while spaces 2 and 4 are discharging through the outlet port. In the fourth sketch, the liquid is being received into space 3 and discharged from space 4, while spaces 1 and 2 have combined and are about to begin discharging as the piston moves forward again to occupy the position of the first sketch.

The piston is moved by the pressure difference between inlet and outlet ports. The higher pressure at *A* causes the piston to move into the different positions shown. The oscillating, shifting movement of the piston causes its hub to move in a circle. In doing so it imparts a rotary motion to the counter.

The volume of liquid moved from the inlet to the outlet port is the same for each cycle, and these cycles are added by the counter. The liquid must be free from gas or air; otherwise the expected accuracy will not be obtained. An air eliminator is frequently desirable to improve operation.

Nutating-disc Meters

The Niagara meter made by Buffalo Meter Company is a nutating-disc type. A sectional view is shown in Figure 4-49. Actual measurement is obtained within the measuring chamber by the disc piston which has a round flat sec-

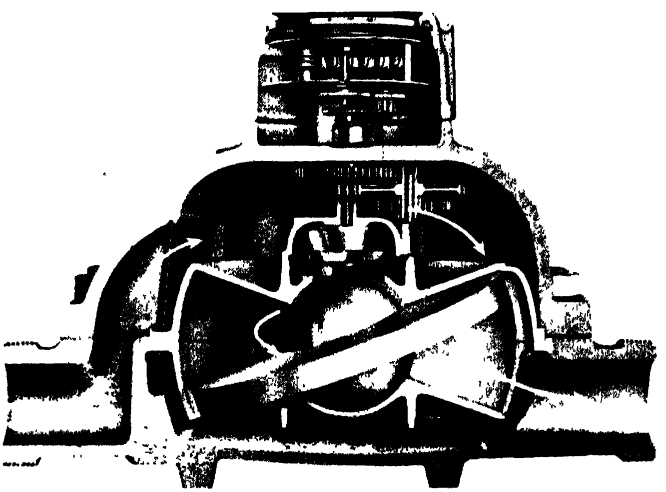


Figure 4-49. Cross section through nutating-disc meter. (*Courtesy of Buffalo Meter Co.*)

tion and a central ball. A partition (not shown) is part of the measuring chamber, and a slot in the disc (also not shown) allows the disc to slide along the partition in a vertical motion, but prevents the disc from rotating around its axis. The mechanism which transmits the movement of the disc to the gear train keeps the axis of the disc at a fixed and constant angle from the vertical. The resulting nutating movement of the disc keeps its lower face in contact with the bottom of the measuring chamber on one side, while the upper face is in contact with the top of the chamber on the other side, thus sealing the chamber off into separate measuring compartments. In Figure 4-49, one compartment is on the upper left of the measuring chamber, the other is on the lower right. As the nutating movement continues, the compartments become gradually transposed, and after one-half revolution, the upper left becomes the lower right, and vice versa.

The liquid enters through the inlet port and fills the spaces above and below the disc. The advancing volume of liquid moves the disc in the manner described until the liquid discharges from the outlet port.

The sectional illustration in Figure 4-49 shows how the measuring disc and its chamber are completely enclosed by liquid so that variations in line pressure cannot distort the chamber and affect the accuracy. The reducing gear train transmits the motion of the drive shaft which passes through the stuffing box to the register. The weight of the gears is carried on internal bearings bushed with hard rubber, agate or other suitable material, and resting on the tops of pivots. The strainer inside the meter body is for emergency protection only, and does not preclude straining out sediments or solids ahead of the meter.

The Niagara Electrovolume meter uses the same Niagara meter as described. It adds, however, a provision for automatically repeating deliveries of a preset quantity of liquid, which may at any time be changed to a different quantity. A dial permits setting the desired quantity. A push-button starting switch is pressed. A red cycle-progress hand then starts from the preset quantity and travels to zero, always showing the quantity yet to be delivered. When this hand reaches zero, an electric circuit opens and the counter recycles instantly to the preset quantity. Quantity settings can be changed at any time between deliveries.

Contacts are provided which usually control a solenoid valve at the beginning and end of the preset delivery thus starting the flow and cutting it off when the desired quantity has been delivered. Pump motors or other equipment may also be controlled in this manner.

Another modification has similar features but does not automatically repeat. A predetermined quantity is dialed in, and a Microswitch actuates once this quantity has been delivered. A solenoid valve can be operated from the Microswitch. Still another version provides a Microswitch to signal the delivery of each unit (gallon, pound, etc.) of metered liquid. These unit impulses can be transmitted to a remotely located impulse counter which shows the integrated flow.

The equipment that provides this control of predetermined quantities is generally called batch control totalizer.

The Veriflow Meter made by the Hays Corporation uses a Niagara meter body with the drive shaft connected with an electric generator. The register is mounted directly on top of the generator and is connected with an extension of the generator shaft. The speed of the generator and consequently its emf output is proportional to the flow rate. A receiver which responds to the emf output of the generator and is calibrated in units of rate of flow can be mounted remotely from the rest of the meter with a connection that consists of two wires to the generator.

This arrangement has been expanded to include within one integral unit: a positive-displacement meter, a rate-of-flow indicator, an integrating register, and a controller with valve. The inside of the unit is shown in Figure 4-50.

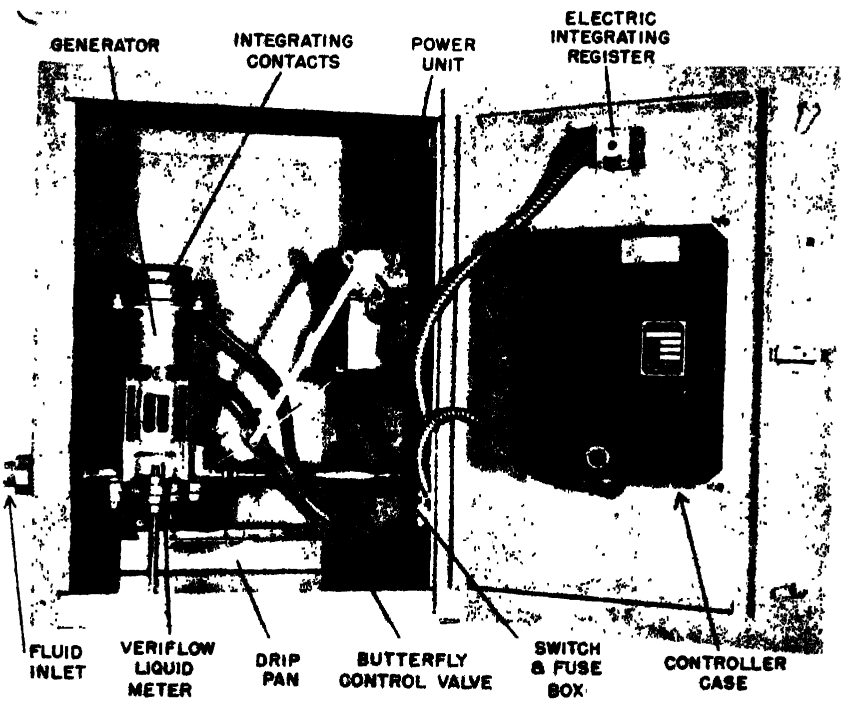


Figure 4-50 Veritrol flow controller (inside). (*Courtesy of Hays Corp.*)

The liquid which is piped through the Hays Veritrol, which is the name of the unit, passes through it at a controlled rate. The operation is as follows;

The Veriflow Meter portion of the Veritrol causes the flow rate of the liquid to be indicated on the indicating meter and to be totalized in the register. The controller consists mainly of a voltage-dividing potentiometer, a standard voltage supply, an electronic amplifier and a power unit. The potentiometer is manually adjusted to provide a set point at which the flow rate is to be maintained. The standard voltage supply furnishes a constant potential for the flow rate control potentiometer. Part or all of this potential, depending on the potentiometer adjustment, is used to equal and cancel the voltage of the generator connected with the meter body, as described above. When the generator voltage and potentiometer voltage are equal, no signal appears as the input to the electronic amplifier. This indicates that no correction in flow is called for, and conditions remain unchanged. If either the generator speed or the manual potentiometer is changed, a signal will be transmitted to the electronic amplifier. The amplifier increases the signal sufficiently to energize one or the other of two relays, depending upon whether the signal is negative or positive, and the power unit operates the valve accordingly. A change in flow through the meter causes the generator voltage to again balance the potentiometer voltage.

Lobe Meters

The Ralph N. Brodie Company uses a measuring element with two rotors, shown in Figure 4-51. The measuring chambers are the spaces between the lobes of the rotors. The meter is similar to the gear pump, only that in the gear pump the water is moved by the pump, while in the Brodie meter the water is the driving agent. This is quite generally the common characteristic of positive-displacement meters, *i.e.,* they can also be used as pumps when driven by some prime mover.

These meters are widely used in measuring and controlling of petroleum crudes and finished products. They are available in a large variety of modifications, such as direct-reading registers, electric transmission by impulses for remote integrated flow reading, or with flow generators for remote rate of flow readings. One model provides a batch control totalizer, *i.e.,* it permits presetting to provide automatic delivery of any quantity from 50 to 9999 gallons. It is designed particularly for high-velocity flows. To prevent line shock, the counter which controls closing of a special valve, causes it to shut off in two stages. The first stage occurs 30 gallons prior to the end of a delivery.

The Brodie meter is designed primarily for the measurement of *liquids.* Measurement of *gases* is the object of the Roots-Connersville meter. Figure 4-52 illustrates its principle. The arrows indicate the direction of the gas flow. As the gas flows into the meter cylinder, it rotates the impellers. The two

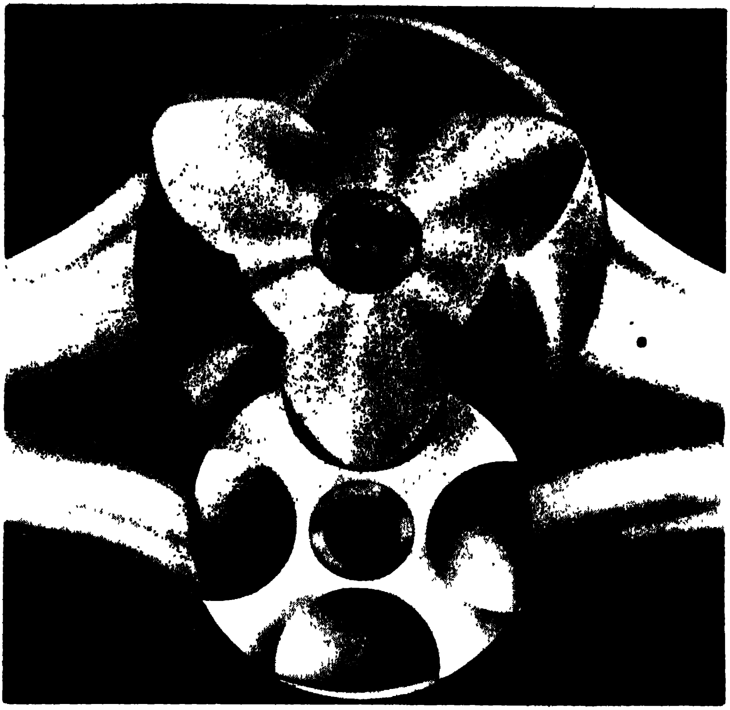


Figure 4-51. Rotors of lobe-type meter for liquids. (*Courtesy of Brodie Co.*)

broken circle lines indicate gears. There is one pair of such gears at each end of the meters. (On the smallest size, there is only one pair.) The impeller on the right rotates clockwise. It is shown in a position where it is about to entrap a predetermined volume. The left-hand impeller, rotating counterclockwise, is discharging an equal amount into the outlet line.

The impellers do not touch each other or the casings. Clearances are extremely small, ranging from 0.003 inch in small meters to 0.015 inch in large sizes. Accuracy is within one per cent of the calibration curve over a range from 11 to 150 per cent of rated capacities. Flow capacities from 4,000 to 1,000,000 cubic feet per hour are available.

Vane Meters

A typical example of the vane-type positive-displacement meter is the Rockwell Manufacturing Company's Rotocycle meter. Its principle is illustrated in Figure 4-53. It consists of four half-moon shaped vanes spaced equidistant on

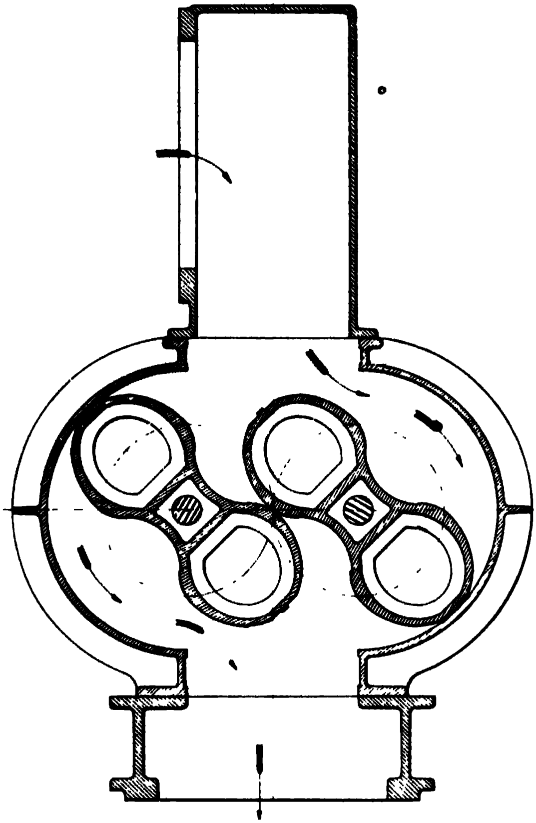


Figure 4-52. Schematic of lobe-type meter for gases. (*Courtesy of Roots-Connersville Blower Division*)

the rotor circumference. Liquid enters the measuring chamber through the inlet port as shown in step 1, and encounters vane No. 1 which seals the space between vane and rotor and between vane and meter case. The pressure under vane No. 1 forces the rotor to turn on its centershaft. This brings vane No. 2 to the position occupied at first by vane No. 1 (step 2), where it seals with the wall. Enclosed between vanes 1 and 2 is a definite volume of liquid. This is the measured segment of flow. In the third step, vane No. 3 has reached the seal position. Between it and vane No. 2 is another measured volume. In the last step, vane No. 4 has reached the seal position. Another measured volume is segregated. The volume between vanes No. 1 and 2 is now discharging through the outlet port. These measured volumes are integrated on the register in terms of gallons passed through the meter. The accuracy of these meters

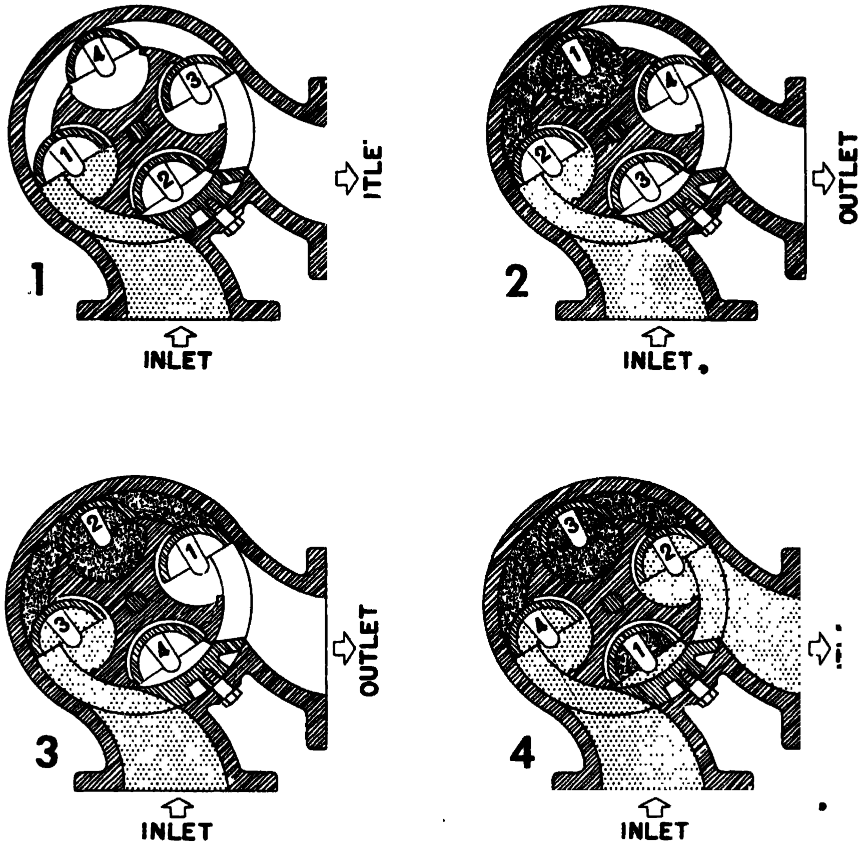


Figure 4-53. Operating principle of Rotocycle meter. (*Courtesy of Rockwell Mfg. Co.*)

may be as high as 0.2 per cent. Batch control totalizers are available with these meters similar to those described for nutating-disc meters.

Reciprocating-piston Meters

Another meter of the highest accuracy is the reciprocating meter. Their capacity ranges are generally from 0.05 to 100 gpm. Their operation is comparable to piston pumps, except that they are driven by the pressure differential of the metered liquid and not by a motor. The reciprocating movement of one or more pistons is transmitted to the counter.

Figure 4-54 shows a cut-away view of the Bowser, Inc. Xacto meter. There are five pistons, *E* being one of them, which in their respective movements nutate the control plate *H*, with which they are connected by piston rod *F*. The control plate pivots on its adjusting ball *I*. The adjusting ball can be positioned by a screw which passes through the bowl *C* and can be turned from the outside. This makes it possible to adjust the piston displacement slightly and thus calibrate the meter. The nutating motion of the control plate with the attached drive arm *B* is transmitted to the valves *D* which control admission and exhaust of the piston cylinders, and through packing gear *A* to the counter mechanism.

In addition to the different kinds of signal transmission and batch control totalizers, this meter is also available with an automatic temperature compen-

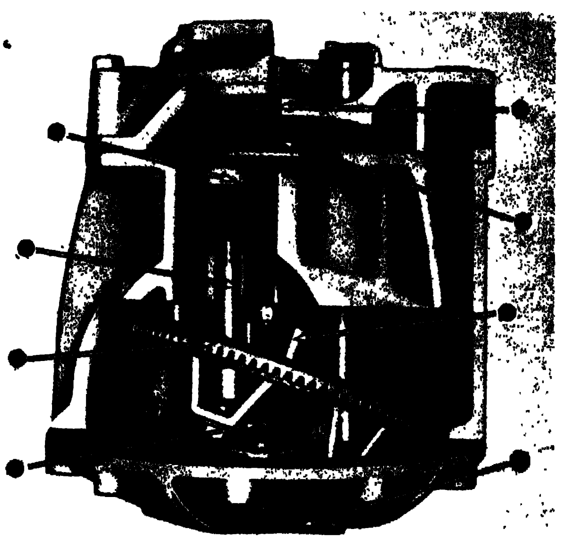


Figure 4-54. Xacto meter. (*Courtesy of Bowser, Inc.*)

sating unit. The latter not only compensates to measure liquid at a 60°F basis, regardless of fluctuations in handling temperatures, but also provides a manual adjustment for various gravities or coefficients of expansion.

A particular application of the piston meter is found in the combination of the Rockwell Oil Field Meter and Sampler. The meter measures the liquid produced while periodically the sampler virtually grabs a small sample of the liquid. The number of grabs is proportional to the total flow. A direct reading from the graduated sampler tube determines the percentage of oil contained in the total flow, and this figure applied to the total meter reading establishes the true degree of well production.

Gas Meters

Gas meters using the principle described in the following have been made for more than a century. They are of high accuracy and require a minimum of maintenance. Figure 4-55 shows the operational sequence in four steps. The discs are moved in reciprocal fashion with the expansion and compression of the diaphragms (they are actually bellows, but the industry refers to them as diaphragms). The illustration does not show the lever and crank arrangement by which the movement of the discs actuates the slide valves and advances the counter. In the first illustration, gas is admitted through port *E*. The pressure of the inflowing gas pushes the disc in the back chamber to the right and gas is forced out through *F*. The movement of the disc advances the slide valves, with which it is mechanically connected, until they reach the position shown in the second illustration.

At this point the right diaphragm is fully expanded, ports *E* and *F* are closed, and gas is admitted through port *D*. The process that took place in the back chamber in the first illustration is now repeated in the front section. Once the front bellows is fully expanded, the condition of the third illustration is obtained. This reverses the action in the back chamber of the first illustration, since gas is admitted to port *F* and allowed to flow out from port *E*. The disc movement reverses under this condition until ports *E* and *F* are closed, as shown in the fourth illustration, and the front section again comes into action. The continuous pulsations of discs and diaphragms and the counter driven by it thus deliver an account of the total flow of gas through the meter.

Gas meters can be equipped with recorders that give rate-of-flow readings. Since large temperature and pressure changes may produce undesirable errors in a gas meter, compensators are available. The mechanism is the same as in the pressure compensator shown in Figure 4-37. Two compensation cylinders may be connected in tandem: one compensating for temperature, the other for pressure.

CURRENT METERS

Current meters have a propeller or other rotating member that is driven by the fluid flow and geared to a counter. They measure the velocity of the fluid and convert it into flow units. Figure 4-56 illustrates a Sparling magnetic drive meter, as made by the Hersey-Sparling Meter Co., which is available for liquid flow in pipe sizes from 6 to 24 inches. This corresponds with the primary usage of such meters, which is in large pipe lines. Other types of meters are available for pipes up to 72 inches. One of the advantages of such meters is the very low pressure loss. For example, in lines of 8 inches or larger,

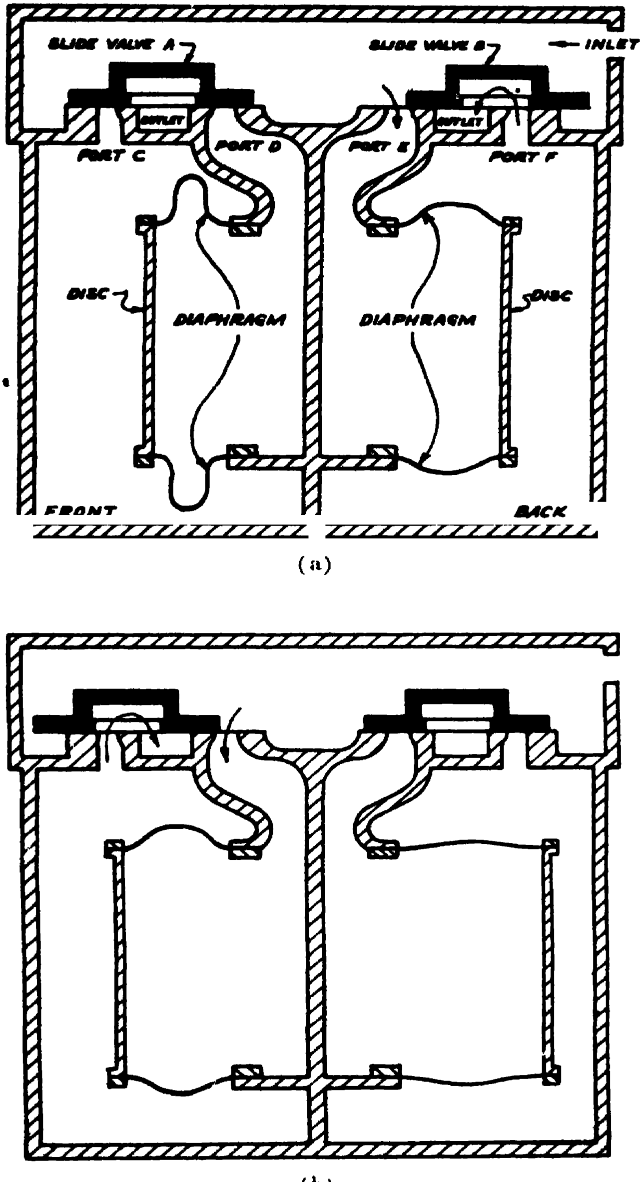
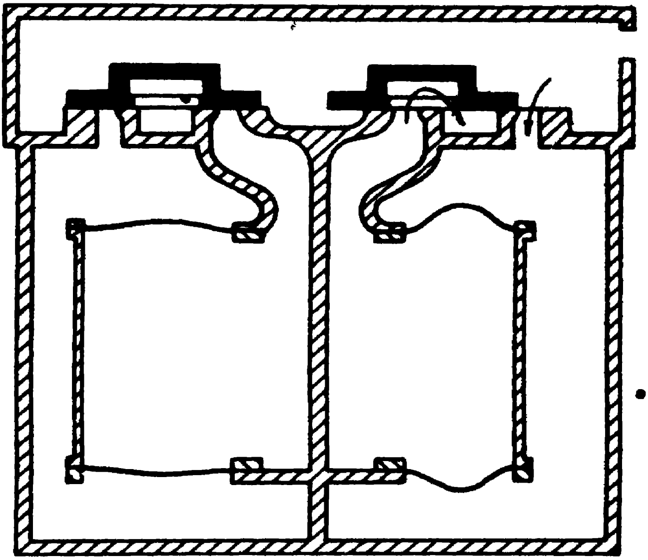
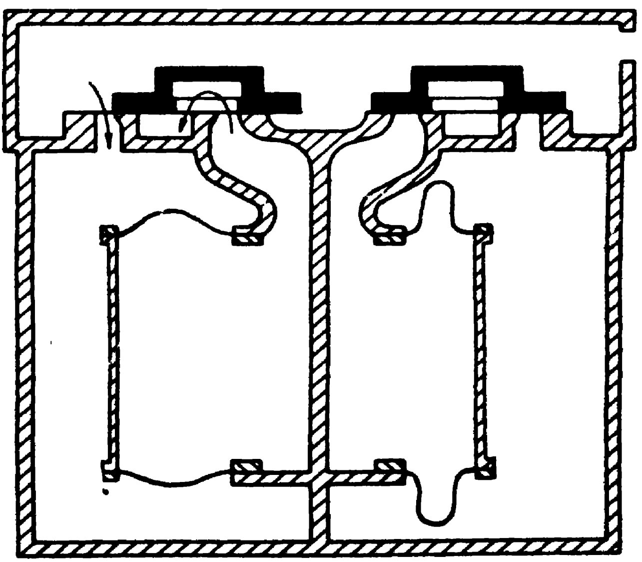


Figure 4-55. Operating principle of gas meter (*a, b, c, d*).



(c)



(d)

Figure 4-55 *cont'd.*

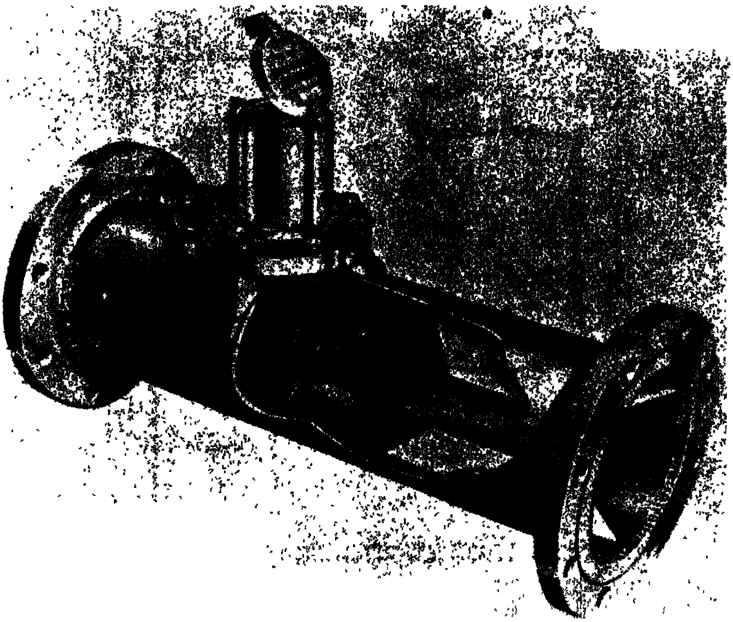


Figure 4-56. Sparling magnetic-drive meter. (*Courtesy of Hersey-Sparling Meter Co.*)

the loss is usually less than 3 inches of water at normal velocities. Generally, the propeller occupies approximately eight-tenths of the pipe diameter. Straightening vanes are provided to reduce turbulence and insure smooth flow past the propeller. A sealed housing separates the meterhead assembly from the propeller as illustrated in Figure 4-57. A magnetic ring is part of the propeller. The gear shaft of the meterhead carries a 6-pole radial magnet. Its magnetic flux lines penetrate the non-magnetic sealed housing and link with the magnetic propeller ring. Rotation of the propeller is thus transmitted from outside the seal to inside of it. The arrangement has also the advantage that, in case of trouble in the meterhead, torque from the propeller could not become excessive. The magnetic clutching action would slip before damage can be done. Thrust from the propeller is absorbed by a hardened steel ball in its nose. For temperatures up to 100°F, the propellers are of polyethylene. Accuracy is within ± 2 per cent of full scale.

The meterhead contains the indicator-totalizer directly geared to the magnetic drive which reads total flow. In addition, they can be equipped with a single pole, double throw switch which normally makes 60 contacts per minute at maximum flow. The receiving instrument converts the pulses into rate of flow and total flow readings. Other accessories provide for batch control totalizers and for taking samples of liquids after a predetermined quantity has passed through the meter.

The flow range of these meters is 10:1, *i.e.*, they read at their rated accuracy down to 10 per cent of their maximum flow rate. This flow range can be increased many times, in some cases up to 450:1, by compound meters. A

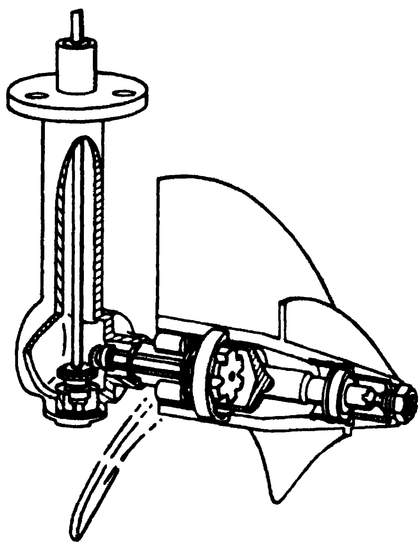


Figure 4-57. Magnetic drive of Sparling meter (*Courtesy of Hersey-Sparling Meter Co.*)

typical Sparling compound meter is illustrated in. Figure 4-58. It comprises two meters—a full-size meter and a smaller one. The primary meter tube as shown in the illustration is similar to the full-capacity meter of Figure 4-56. It is coupled with the compounding tube section which contains a differential valve and a secondary meter in a bypass channel. This secondary meter registers flow below the rated range of the primary meter. As long as the differential valve is closed, it diverts all flow through the secondary meter in the bypass channel. When the flow becomes sufficient for the primary meter to attain accurate registration, the pressure increases beneath the valve and gradually lifts it to full flow position. The totalizer registers flows of both meters through overriding clutches in one single reading.

The above described current meters are designed for the flow of liquids. A meter that will count the flow of steam, air or gas, and may also be tied in

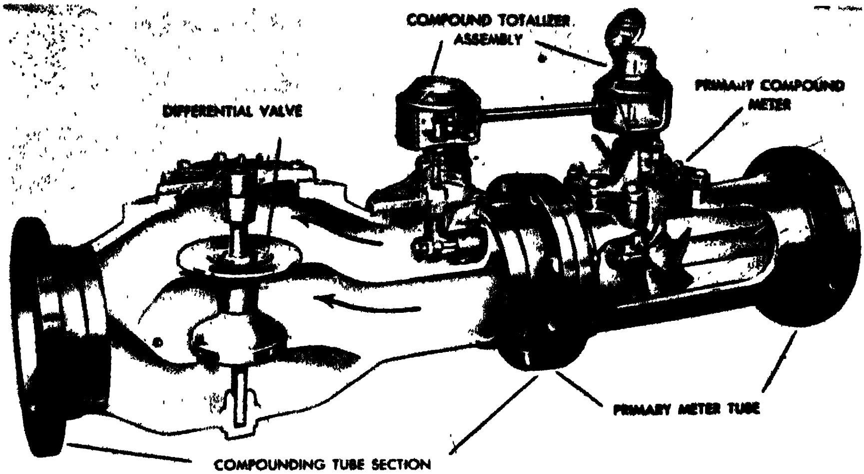


Figure 4-58. Compound meter. (*Courtesy of Hersey-Sparling Meter Co.*)

with a remote-located instrument that combines totalizer. indicator and recorder is B-I-F Industries' Shuntflo Meter (Figure 4-59). The bottom of this illustration shows the magnetic transmission from the damping chamber to the counter gear train. The driving magnet is separated from the follower magnet by a diaphragm. Stuffing boxes and shaft packings are thereby avoided. To prevent slippage in the magnetic drive because of excessive speed of the driving magnet, a reduction gear train is provided in the damping chamber which reduces the speed of the rotor to about one revolution per minute at rated capacity. The damping fan near the lower end of the fan shaft assembly is submerged in a damping fluid which fills the damping chamber as well as the cooling chamber. The blades of the damping fan are pitched at an angle to produce a downward thrust to balance the upward thrust of the rotor on top of the fan shaft assembly thereby reducing the friction in the bearings.

A pressure differential is created in the main line by means of an orifice. This causes a portion of the flow to pass upward through the nozzles and impinge on and drive the rotor. The rotor is controlled at a speed proportional to the rate of flow by the action of the damping fan which rotates in the liquid of the damping chamber. The portion of the flow which acts upon the rotor is proportional to the total flow and the speed of the main shaft is a measure of the total flow.

The damping liquid for steam meters is water which, after the initial filling before first use, is replenished by condensate from the steam. The damping liquid for air and gas meters may be water or other liquid, depending on circumstances. It must be replenished occasionally to maintain the proper liquid level in the damping chamber.

The Fischer & Porter turbine flowmeter differs from the previous types in several respects. It converts the propeller rotation directly into an electric signal, it is available for either gas or liquid service, and it is primarily intended for smaller pipe lines, generally from 1/2 to 3 inches. The turbine flowmeter for

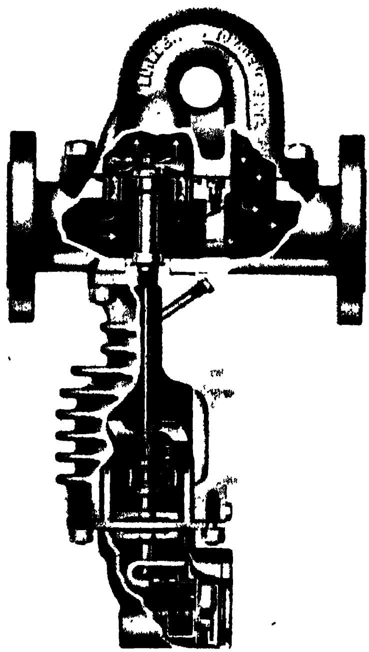


Figure 4-59. Shuntflo meter (*Courtesy of B-I-F Industries*)

liquid, as illustrated in Figure 4-60, consists essentially of a magnet rotating within a nonmagnetic housing, and an external pickup coil connected to an electric counter indicator or recorder. Liquid enters the upstream connection of the flow meter body and passes through straightening vanes to reduce turbulence caused by the upstream piping. Following the straightening vanes is a sharp-edged orifice of wide inside diameter which further reduces turbulence of the flow. This results in a flow range as wide as 15:1.

After passing through the orifice, the liquid enters the metering section. The stainless steel propeller is mounted in ball bearing races. Liquid flow past the

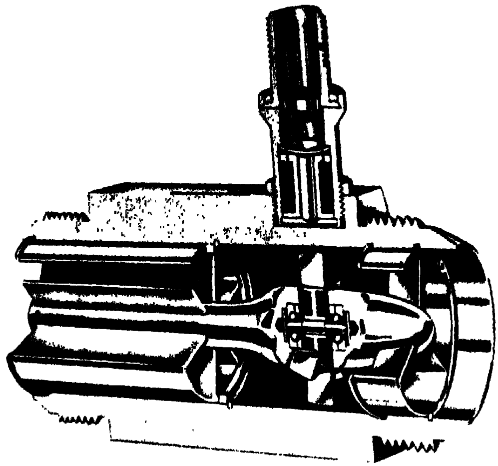


Figure 4-60. Turbine flow meter. (*Courtesy of Fischer & Porter*)

propeller causes it to turn, cutting through a magnetic field generated by a permanent magnet mounted in the pickup coil. As each propeller blade passes the magnet, the flux is disturbed and an electrical pulse is induced in the pick-up coil which surrounds the magnet. Since the propeller speed depends upon the liquid flow, the output frequency and voltage are proportional to liquid flow. After impelling the propeller, the liquid flows downstream past the rear hub and flow meter outlet. The output signal of the flow meter may be fed into a variety of instruments for reading of either total or rate of flow. The accuracy of these meters is plus or minus 1/2 per cent of instantaneous flow rates.

ELECTROMAGNETIC FLOWMETERS

The magnetic flowmeter measures the flow rate of many liquids and semi-liquids. There is no obstruction in the flow path and corrosive liquids or slurries are measured with ease. The Foxboro magnetic flowmeter, as described here, consists of the flow transmitter, connected by electric cable to a receiver which is a particular type of the Foxboro Dynalog instrument. Pneumatic or electrical control, totalizing or alarm accessories can be added to the Dynalog instrument in the usual manner.

The flow transmitter is illustrated in Figure 4-61. The liquid flows through the metering tube which is of non-magnetic metal or of "Fiberglas" composition. In the case of metal, an electrical insulating liner is applied to the inside of the tube. The magnet structure consisting of electromagnet coils and cores induces a magnetic field through the tube. Two metallic electrodes, which are essentially flush with the inside surface of the tube, contact the flowing fluid and sense the generated voltage which is proportional to flow rate.

In order for the meter to function, the minimum conductance of the flowing liquid must be about 200 micromhos* for sizes of 6 inches or less and 500 micromhos for 8 inches and larger. This compares with a conductance of 100 micromhos for most tap waters. Changing values of conductance do not affect the performance or calibration of the instrument.

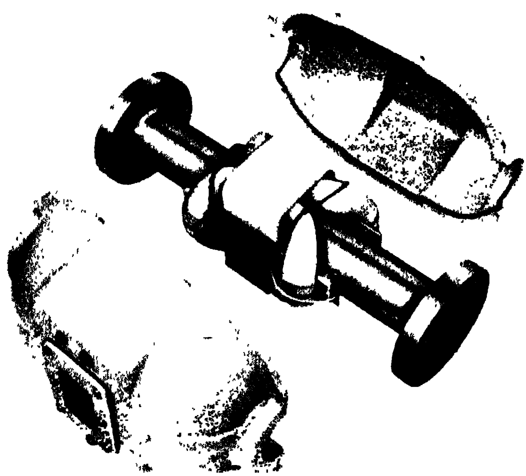


Figure 4-61. Magnetic flow transmitter (*Courtesy of Foxboro Co.*)

The output of the transmitter is linear and is directly proportional to the average velocity of the flowing liquid which is, in turn, proportional to flow rate. Turbulence does not seriously affect the transmitter. Hence straightening vanes or straight runs of pipe are unnecessary.

The operation of the transmitter is based on Faraday's law of electromagnetic induction, which states that the voltage E induced in a conductor of length D that moves through a magnetic field H is proportional to the velocity V of the conductor. The voltage is generated in a plane which is perpendicular to both the velocity of the conductor and the magnetic field.

In the magnetic flowmeter, the flowing liquid itself is the conductor moving through the magnetic field. This conductor must be visualized as a flat disc of

*Micromho is a unit for conductance. It is the reverse of resistance in ohms, multiplied by 10^6

liquid that moves between the two electrodes. The length of the conductor D becomes the distance from one electrode to the other, *i.e.,* it equals the tube diameter. When flow occurs, a steady succession of discs moves through the magnetic field past the electrodes yielding a continuous voltage.*

Figure 4-62 illustrates the operation of the transmitter in connection with the Dynalog instrument. A two-wire cable connects the electromagnetic coils to a

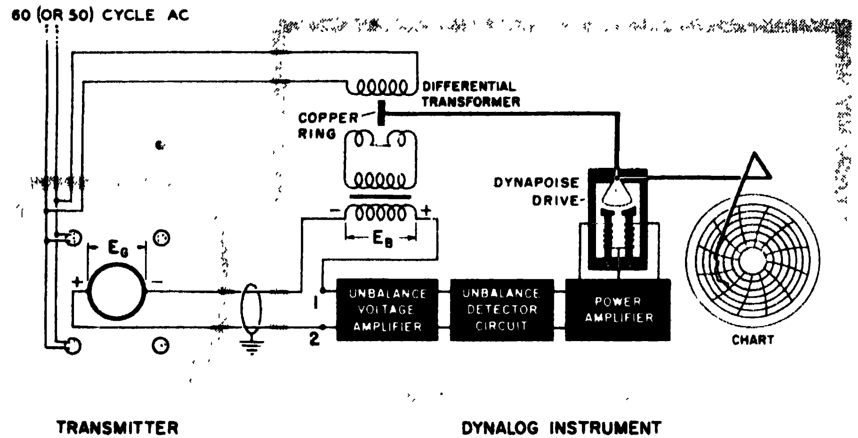


Figure 4-62. Circuit of magnetic flow meter. (*Courtesy of Foxboro Co.*)

115-volt, 60-cycle power line. This same power line is extended to the primary of a differential transformer in the Dynalog instrument. In addition, a two-wire shielded cable carries the generated voltage from the electrodes of the transmitter to the instrument. The generated voltage is connected in series opposition to the differential transformer. When a condition of null balance exists, the sum of the voltages from Point 1 around the circuit to Point 2 is zero. If a change in flow occurs, the voltage E_G generated by the transmitter will be different from voltage E_B produced by the differential transformer unit. This produces a net voltage at the amplifier input which is amplified electronically. The amplified voltage is compared in phase with the line voltage at the unbalance detector circuit to determine whether the flow has increased or decreased. The output of the unbalance detector circuit is applied to the power amplifier and from there to the windings of the Dynapoise drive, producing opposing magnetic forces which drive the rotor to a new position. This movement operates the pen and repositions the copper ring of the differential transformer to make

*In mathematical form, Faraday's law is expressed by $E = CHDV$, where C is a constant, and the other symbols as mentioned in the text. Also, flow rate Q equals tube cross-sectional area A multiplied by flow velocity V. Hence, $Q = AV$. Combining the two equations gives $Q = AE/CHD$ where A, C, H, and D can be made constants, and therefore E becomes a linear function of Q.

the balancing voltage once again equal the voltage generated by the transmitter.

Magnetic flowmeters are available for pipe sizes ranging from 0.1 to 72 inch. The standard accuracy is 1 per cent of full scale. This includes transmitter, signal cable and receiver. The flow range is practically infinite, since the rated accuracy applies even at very small flows. However, it should not be overlooked that an accuracy of 1 per cent of full scale means that, when measuring a flow rate of 1 per cent of rated capacity, the meter may read anywhere between zero and 2 per cent. Hence, there is a practical lower limit in flow even with the magnetic flowmeter, but it is by far lower than that of any other type of flowmeter.

ULTRASONIC FLOWMETERS

The flowmeter made by Gulton Industries responds to the deflection of ultrasonic waves that result from transmitting them through a flowing fluid. A transmitter which generates an ultrasonic beam is mounted to the outside of a pipe section. Two ultrasonic receivers are mounted also to the outside of the pipe, but opposite to the transmitter. One receiver is mounted at a given distance upstream from the transmitter, the other at the same distance downstream. At no-flow conditions both receivers receive equal amounts of ultrasonic energy and, hence, generate equal voltages. At flow conditions (in either direction) the ultrasonic beam is deflected and, as a result, the receivers generate unequal voltages. These voltages, when compared, indicate direction and magnitude of flow.

Similarly to the magnetic flowmeter, there is no obstruction in the process flow.

MASS FLOWMETERS

The flowmeters referred to so far measure and integrate *volume* flow rate. Changes in density of the fluid remain undetected unless additional measuring and compensating means are used. Mass flowmeters differ from other flowmeters by measuring directly the weight of the flow—not volume. The General Electric mass flowmeter, for example, measures gas or liquid flow directly in pounds and hence is independent from the effects of pressure, temperature, and density changes. This meter was developed together with Black, Sivalls and Bryson, Inc. The principles of its operation are illustrated in Figure 4-63. The completely self-contained unit includes four basic components: the flow-rate sensor, the gyro-integrating mechanism, the cyclometer register and the contact drive.

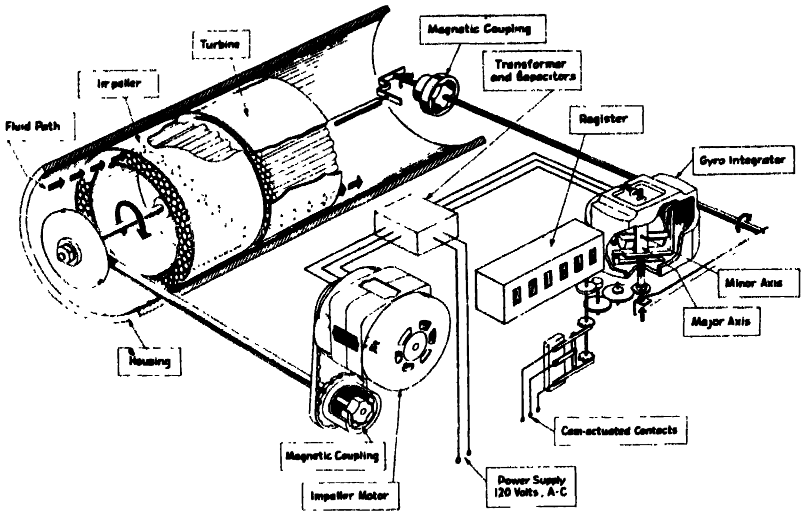


Figure 4-63. Mass flowmeter. (*Courtesy of General Electric Co.*)

The flow-rate sensor is located in the fluid stream. It consists of two cylindrical elements—the impeller and the turbine. Both elements contain channels through which the fluid flows. The impeller is driven at a constant speed by a synchronous motor through a magnetic coupling and imparts a whirling motion to the fluid. The momentum which this whirling motion adds to the fluid is proportional to the mass rate of flow. A second cylinder or turbine is placed downstream from the impeller. Its motion is spring-restrained, and the flow passing through the passages of the turbine straightens out its whirling motion. In doing so, this turbine absorbs the momentum of the whirling motion. Since the turbine is spring-restrained, the result is a torque exerted by the turbine which is proportional to the absorbed momentum and hence to the mass rate of flow.

The principle of the gyro which is used in the integrating mechanism, is illustrated in Figure 4-64. The wheel is supposed to rotate freely on the shaft *A*, so that the latter does not spin with the wheel. If the wheel would not rotate, shaft *A* would tumble from its support on top of shaft *C*. Spinning of the wheel changes this. There are two forces; *b* the gravitational force and *a* the force produced by the spinning of the wheel. The result of the two forces is a third force which causes the wheel *and* the shaft to describe horizontal circles about the pivot in direction *c*. This resulting motion is called precession. The axis about which the precession occurs is frequently called the major axis and the axis about which the gravitational force—or any other force—is applied would be called the minor axis.

In the gyro-integrating mechanism, the rotor of a small motor which forms the nucleus of the mechanism, replaces the spinning wheel. Instead of the gravitational force, a torque is now applied which has been transmitted from the turbine through the magnetic coupling to the minor axis. The rate of the resulting precession, *i.e.*, of the rotation about the major axis, is proportional to the torque and thus to the mass rate of flow.

The precession is transferred through a gear train to the cyclometer register where the mass flow of the liquid or gas is recorded in pounds. The gear train output also actuates a contact device which can be used to make and break an electric circuit. Since the rate of contact closures would be proportional to precession rate, it is proportional to mass flow rate, and can be used to actuate auxiliary equipment, such as remote indicators or batch control totalizers. Accuracy is within 1 per cent of the indicated value with a 10:1 flow range.

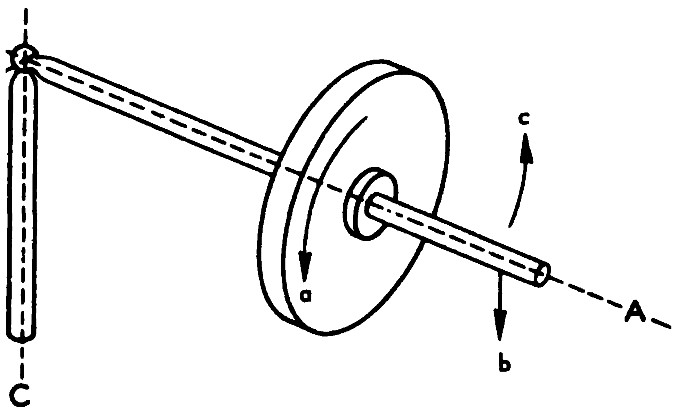


Figure 4-64. Gyro principle.

FLOW OF SOLIDS

The torque produced by radial flow acceleration has been applied to the measurement of free-flowing solids in an instrument called the Massometer, developed by Wallace & Tiernan. A schematic diagram illustrating its operation is shown in Figure 4-65. The material falls vertically on the impeller, which is driven at a constant speed by the motor. The rotation of the impeller imparts a radial acceleration to the material, which is thrown out laterally and drops through the outlet by gravity.

The radial acceleration requires a proportional torque in the motor, which depends on the quantity and density of the material involved. Therefore, measurement of this torque gives an indication of the mass rate of flow. Figure 4-66 illustrates how the motor torque is converted into an air-pressure signal that is

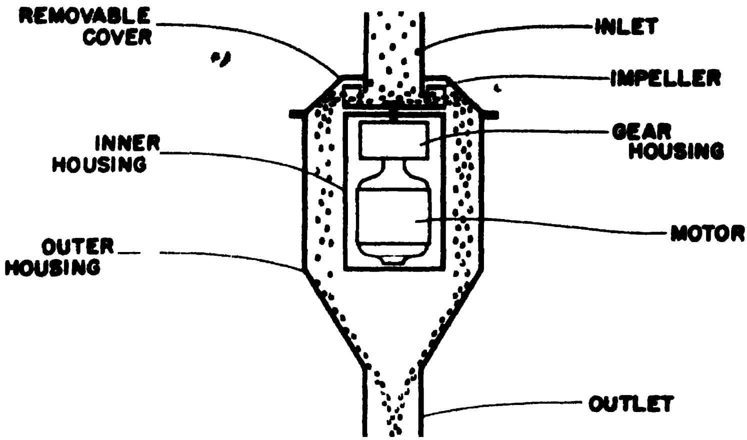


Figure 4-65. Schematic of Massometer operation. (*Courtesy of Wallace & Tiernan Co.*)

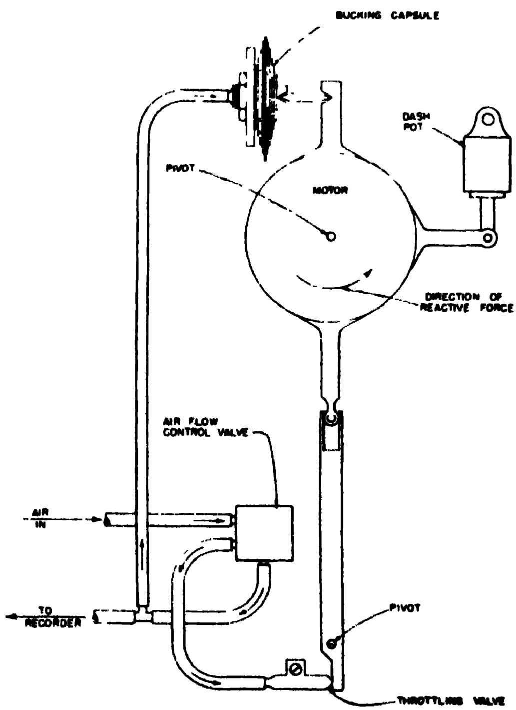


Figure 4-66. Schematic of Massometer measuring system. (*Courtesy of Wallace & Tiernan Co.*)

transmitted to a conventional instrument. The motor housing is supported in ball bearings; hence both the rotor and the stator are free to rotate about the same axis. The stator movement caused by the torque of the impeller is limited by a restraining force, due to the air pressure in a bucking capsule exerted on a lever solidly connected with the stator.

The resulting stator movement is transmitted to a flapper which operates on a nozzle or throttling valve. As the flapper is moved back and forth due to changes in the motor torque, it controls the opening of the nozzle (throttling valve) outlet. The action changes the nozzle back pressure which in turn regulates the air flow control valve, *i.e.*, a pilot valve which controls the air-pressure signal transmitted to the recorder. This pressure signal is also fed back to the bucking capsule which exerts a counter force on the torque of the motor housing. The result is a balance of forces and a definite relation for each magnitude of torque or mass rate flow.

Another method for the measurement of solids is an attachment to a conveyor system, an example of it—the Conveyoflo Meter made by B-I-F Industries, Inc.—is illustrated in Figure 4-67. This meter totalizes continuously and automatically the weight of material as it passes over a belt conveyor. The weight-sensitive section of the structure is supported at one end by the dust-tight

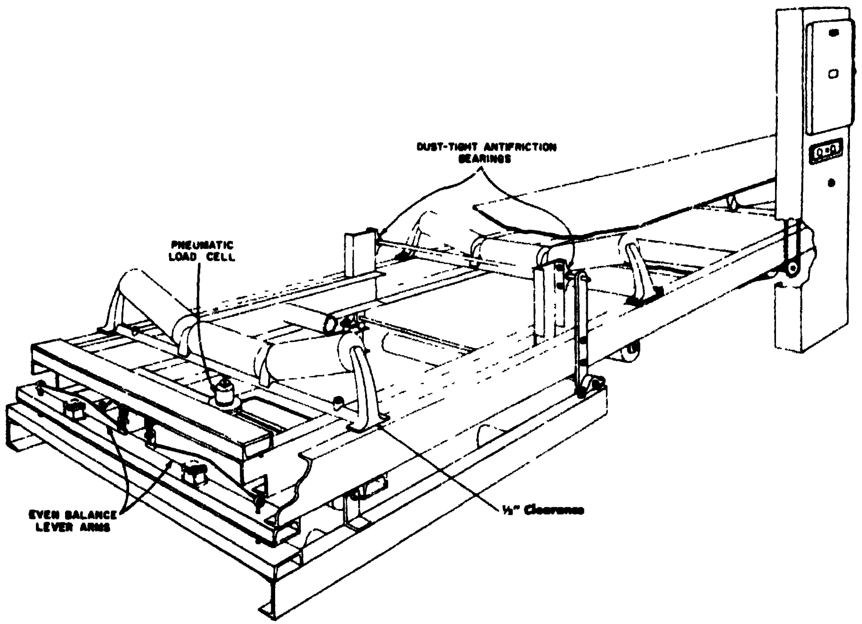


Figure 4-67. Schematic of Conveyoflo system. (*Courtesy of B-I-F Industries*)

antifriction bearings and at the other end by the even-balance lever arms and the pneumatic load cell. Actual sustained vertical movement of the diaphragm stem of the pneumatic load cell from zero to full load is less than 0.0025 inch.

The totalizer mounted on a panel at the right of the illustration receives from the load cell an air-pressure signal in proportion to the load on the belt. A belt speed pickup idler which rides the returning belt is connected by means of a sprocket-and-chain drive with the totalizer, thus measuring the length of belt passed over the weigh span. The totalizer multiplies the weight signal (weight per unit length) and the total length of belt passed to obtain total weight delivered. The mechanism for this computation is described in the following.

The air pressure from the pneumatic load cell is led to the totalizer where it is applied to a pressure-sensitive element which, through suitable linkages, positions the flapper of a flapper-and-nozzle combination. The nozzle back pressure in turn positions a pilot valve which controls the air pressure on the piston of a power cylinder. The piston moves against the pull of a return spring connected to a yoke carrying an integrating wheel. The integrating wheel and integrating disc are parts of the totalizer. The disc is driven from the conveyor belt through the belt-speed pickup and chain-and-sprocket drive and makes a definite number of revolutions for a given belt travel. The integrating wheel, whose periphery bears against the integrating disc, is rigidly mounted on a sleeve, splined to a shaft, so it is free to move longitudinally; but if it rotates it causes the shaft to rotate with it.

The yoke which carries the wheel is adjusted so that at zero weight on the weigh span the wheel rides in the center of the disc. When a load is carried onto the weigh span by the belt, the wheel moves away from the center of the disc a distance proportional to the weight on the weigh span. At other than central position of the wheel on the disc, the number of revolutions of the wheel for a given number of revolutions of the disc, *i.e.,* belt travel, depends on the distance of the wheel from the center of the disc, *i.e.,* load on the belt. Thus, the totalizer mechanism multiplies the weight per foot of belt passed by the number of feet of belt passed to obtain total weight passed.

Where the belt is moving at constant speed, a weighing cell, either of pneumatic or electric design, is applied to the conveyor belt and the output is directly fed into a conventional recorder or indicator.

5. Liquid Level

Although the first nine chapters of this book are limited mainly to those instruments that offer continuous measurement of process variables, this chapter will include a number of so-called limit controllers used to respond only to predetermined maxima or minima. These devices have become so important in industrial instrumentation that it is warranted to include the most representative types.

Pressure-gauge Method

Measurements of level that rely on the pressure exerted by the liquid head imply that the density is constant. The instrument must be calibrated for a specific density and any change in density of the liquid results in measuring errors.

The simplest method of measuring liquid level in an open tank is to connect a pressure gauge below the lowest level to be considered. This level is then the reference level and the static pressure indicated by the gauge becomes a measure of the height of the liquid column above the gauge and hence of the liquid level. The simplicity of this method should not be a reason for overlooking it. Even corrosive or highly viscous liquids or those carrying a slight amount of suspended solids may be measured by pressure gauges when seals or diaphragms are being used.

A *seal* consists of a fluid with which the measuring system is filled. The free surface of the filling liquid is in direct contact with the measured liquid. However, the two liquids must not mix nor react chemically. A *diaphragm* differs from a seal since it shuts off the liquid in the measuring system from the liquid being measured. It responds to a change in liquid level with an increase or a decrease in deflection due to the change in static pressure exerted upon it by such a change. The diaphragm communicates with the pressure element through a capillary tubing filled with an inert liquid, and the movement of the diaphragm is thus directly transmitted to the pressure element. The pressure gauge (described in detail in Chapter 3), when used for liquid level measurement, is calibrated in pressure units, in liquid level units corresponding to the specific gravity of the liquid, or in volumetric units calculated from the dimensions of the tank. It may also be calibrated from 0 to 100, which permits readings in terms of per cent of maximum level.

For the gauge to read zero when the liquid is at the minimum level, a horizontal line through the actuating element should be at about the same level as the center line of the minimum level pipe tap. Zero screw adjustments in the gauge can be used to compensate for minor inequalities.

For limit control the pressure gauge can either be a controller or can be combined with a pressure switch. Where no indication of the level is required, the pressure switch alone suffices.

Diaphragm-box Method

Figure 5-1 shows a Foxboro diaphragm box. This box is immersed in the liquid to be measured and an air-filled capillary extends from it to the instrument. The deflection of the diaphragm produced by the liquid head causes a compression of the air in the connecting capillary. The receiving instrument responds to the air from the capillary, thus indicating the liquid head exerting its pressure on the diaphragm. The box is made in two sections, inserted between which is a diaphragm of rubber or oil-resistant synthetic composition. The capillary connecting tube, which enters the top flange, is extended into the diaphragm box and bent to one side, to prevent its being sealed by the diaphragm. Where necessary to prevent contact between liquid and diaphragm, the box may be installed in a well outside the tank. The connecting piping and the well can then be filled with an inert liquid.

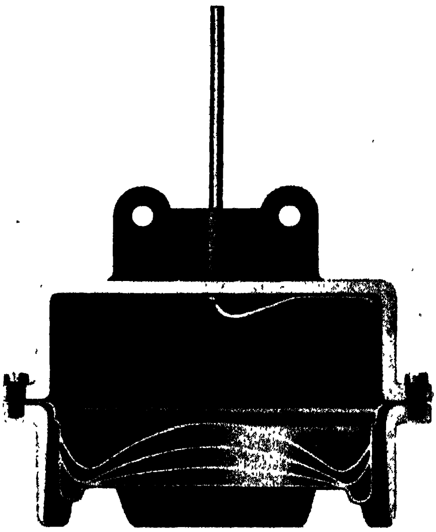


Figure 5-1. Diaphragm-box liquid level meter. (*Courtesy of Foxboro Co.*)

Air Trap Method

When a diaphragm cannot be used, a box without it may be installed. This requires that the liquid be free from solids, which might plug the capillary. The liquid rising in the box compresses the air in the capillary and the instrument responds correspondingly.

The same principle can be used for limit control. A number of diaphragm switches are available. These switches are mechanically actuated by a slack diaphragm which is exposed to the level head on one side. The whole assembly can be mounted on the upper end of an iron pipe, the lower end of which extends into the liquid. When the level rises, it compresses the air in the pipe. The increased air pressure deflects the diaphragm, operating the switch which starts the pump motor. This method prevents the switch, including the diaphragm, from contacting the liquid.

Air Pressure-balance Method

This method is usually preferred to the diaphragm box if air or liquid for purging is available, unless hand pumping is acceptable. It can be applied either from the top or from the sidewalls of the tank. It allows remote indication and has a relatively high accuracy. Frequently, it is referred to as a bubble-pipe system.

Figure 5-2 shows the Uehling Type S Tank-O-Meter. Basically, this is a manometer of well-type design. The high-pressure side is connected through line *A* with the air pressure in the 1/2-inch pipe which extends to the bottom of the tank and has a cutaway, *a*, of approximately 2 inches at the lower end. The hand pump connects with the same pressure pipe through line *B*. Ignoring line *C* for the moment, it is necessary only to actuate the hand pump a few times until the reading of the indicating column remains constant to obtain a measurement of the liquid level. What happens is that in pumping air with the hand pump, pressure is built up in the pressure pipe. As soon as this exceeds the head pressure by the slightest amount, air escapes through the liquid in bubbles. It is obvious that air pressure in the pipe can build up only until it exceeds the liquid head pressure by an infinitesimal amount. Hence the air pressure, as shown on the indicating column, is a measure of the level in the tank.

When the tank is open to atmosphere, the low-pressure side of the indicating column is left open and line *C* is superfluous. If the tank is under vacuum or pressure, it is necessary to connect the low-pressure side to the space above the liquid level through line *C*. By this means, the instrument measures the differential pressure between the level surface and the lower opening of the pressure pipe; any pressure or vacuum changes in the tank remain without influence on the instrument, which indicates true liquid level. This method

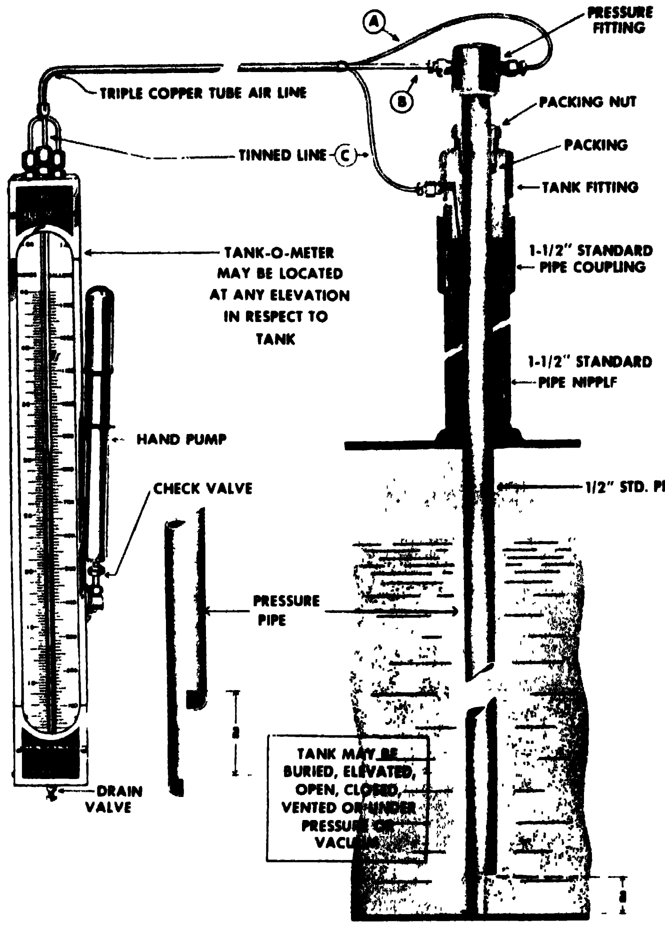


Figure 5-2. Tank-O-Meter. (*Courtesy of Uehling Instrument Co.*)

can be applied only where the liquid in the closed tank has no condensable vapors over its surface; these tend to collect in the *C* line and on top of the manometer fluid in the indicating column and produce false readings.

The hand pump can be replaced by a continuous bubble system. The amount of air should be small to avoid instrument errors due to pressure drop caused by friction of the air in the line. A needle valve combined with sight-feed bubbler or purge rotameter is practically standard equipment for this purpose, unless the bubble rates can be clearly and conveniently observed, as is occasionally the case with open tanks of relatively small size. Both sight-feed bubblers and purge rotameters are designed for indication rather than for accuracy.

The sight-feed bubbler is a small glass cup filled with oil through which the air flows in bubbles. By counting the number of bubbles per unit time it is possible to adjust the air flow to a very slow rate. The sight-feed bubbler is also a continuous visual indication of the air flow.

The purge rotameter is a simplified version of the rotameter described in the previous chapter. It serves to indicate the air flow. As an example of a number of similar devices, Figure 5-3 shows the Brooks-Mite (Brooks Instrument Company) combined with a pressure differential relay made by the Conoflow Corporation. The Brooks-Mite combines a rotameter and a needle valve. The tapered metering tube is machined directly into a clear, acrylic plastic block. The float consists of a small metal sphere. Once the

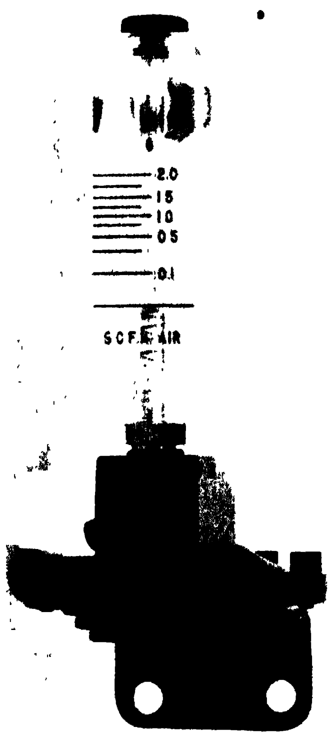


Figure 5-3. Brooks-Mite purge rotameter with differential pressure relay. (*Courtesy of Brooks Instrument Co.*)

air flow is adjusted to the desired rate by the needle valve, it will be kept constant by means of the pressure differential relay, a cross section of which is shown in Figure 5-4. The deflection of the diaphragm determines the amount of valve opening. The pressure from the outlet of the relay is applied to the bottom side of the diaphragm.

Any change in upstream pressure also produces a change at the outlet of the relay and therefore a balancing action on the diaphragm. The air flowing from the assembly is at a pressure determined by the head of the liquid in the tank. This pressure is also applied to the top side of the relay diaphragm. If, for example, the level and hence the pressure decrease, the pressure on the diaphragm also decreases, so that the relay valve throttles the

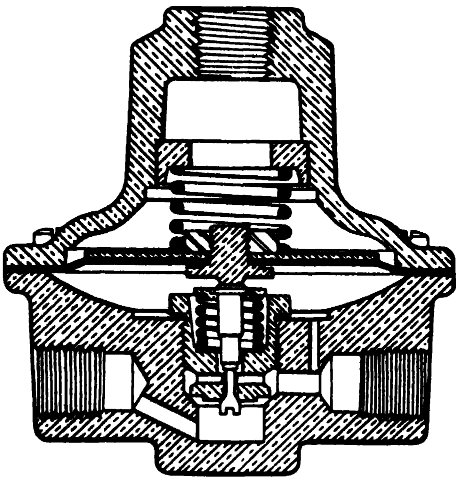


Figure 5-4. Cross section through differential pressure relay. (*Courtesy of Conoflow Corp.*)

air flow. A new valve position is obtained when the force balance between the pressure against bottom and top side of the diaphragm, *i.e.*, the original pressure differential is reestablished. The pressure differential across the rotameter is thus kept constant; hence the air flow remains constant for any setting of the needle valve.

Pressure-duplicator Method

An example of the pressure-duplicator type is the liquid level transmitter made by Taylor Instrument Companies and illustrated in Figure 5-5. It converts the pressure of the liquid head into an air signal which is transmitted to a pressure-measuring instrument as receiver. The cross-sectional view shows the transmitter in the position in which it is mounted on the bottom of a tank

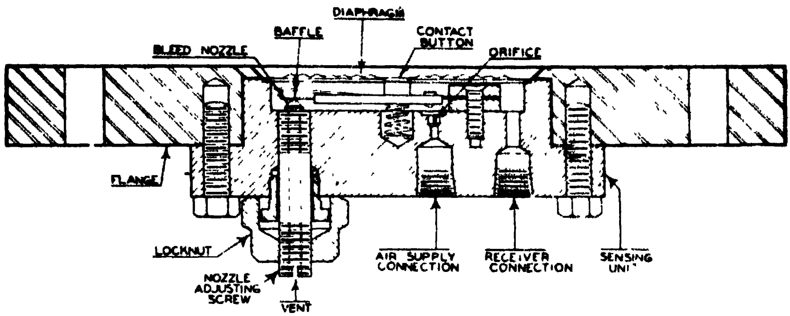


Figure 5-5 Liquid level transmitter (*Courtesy of Taylor Instrument Cos.*)

with the liquid head pushing down on the diaphragm. An air supply, usually at 3 to 5 psi above the highest pressure caused by the liquid head, is connected with the transmitter and an air line connects the transmitter with the receiver.

The downward force caused by the liquid in the tank is counteracted by an upward force due to the air pressure admitted against the lower side of the diaphragm. If the liquid level rises, it tends to deflect the diaphragm further. This motion is transmitted through the contact button to the baffle which moves closer toward the air bleed nozzle. This restricts the flow of air through the bleed nozzle to the atmosphere. and the air pressure in the diaphragm chamber consequently increases. The air pressure in the diaphragm chamber is thus equal to the pressure of the liquid head on the diaphragm, and the receiver can be calibrated in units of liquid level. The nozzle-adjusting screw which regulates the amount of air flowing through the bleed nozzle for a given baffle position permits the initial setting of instrument response versus liquid level.

It can be seen that there is considerable similarity between the pressure-duplicator type and a bubble pipe. The main difference is that the air is not allowed to escape through the liquid but passes through the bleed nozzle.

A small amount of liquid head pressure must be used to move the baffle against the coiled spring shown in the diagram. The proportion of this force compared to the total force pushing against the diaphragm increases as the liquid level falls. While the effect is unnoticeable above 20 per cent of the total range, it produces an increasing inaccuracy at levels below that figure. This, however, can be avoided by connecting a pressure differential relay, as previously described and illustrated in Figure 5-4, in such a way that it automatically adjusts the supply pressure to the transmitter, keeping it always 3 psi above the output pressure. A minimum measurable level of 5 to 6 inches of water is thus obtained.

The Taylor transmitter can also be used for closed tanks under pressure, when used with a pressure differential receiver. The high-pressure side is then connected with the bottom of the tank and the low-pressure side is connected to another transmitter mounted on top of the tank. This eliminates any possibility of condensing vapors settling in the low-pressure lines, as would happen if the low-pressure side were connected directly to the top of the tank. Under certain conditions such direct connection is possible, but as a rule it is advisable to seal off the measuring mechanism from the tank.

When tanks are measured under vacuum, the air from the diaphragm chamber cannot exhaust to the atmosphere because the pressure against the bottom of the diaphragm would be too high and balance could not be established. It is therefore necessary to bleed the diaphragm chamber to a vacuum chamber. Usually, this vacuum chamber can be the vapor space above the liquid. The air supply may be at atmospheric pressure, which means leaving the air-supply connection open to the atmosphere; if conditions require a lower than atmospheric supply pressure, a suitable source must be provided.

Differential-pressure Method

For the measurement of levels in tanks under vacuum or pressure, all those instruments described in the previous chapter for measuring flow by differential-pressure methods can be used. In applying these instruments to pressure or vacuum tanks, the only difference will be that the instrument will give a reverse reading; that is, where it read zero flow when used as a flowmeter, it will read a maximum level when used for measuring liquid level, as explained below. Provisions have to be made to obtain the corresponding response of the instrument. For example, it is possible to use compound range meters which were described under the heading "Special Meters" in the previous chapter. Since these meters are designed to allow flow in both directions, it is possible to use them for liquid level measurement and have the zero position at the inside of the chart and the pen move toward the outer edge with rising level of the liquid.

Figure 5-6 shows the liquid level installation of a typical differential meter body, such as the Barton meter body of Figure 4-26. As mentioned before, most liquids under pressure have condensable vapors over them. To prevent inaccuracies due to condensate in the line connecting the instrument to the top of the tank, a condensing reservoir or fixed level pot is installed. This arrangement subjects the high-pressure side of the instrument to a constant liquid head plus the vapor pressure and the low-pressure side to the variable head of the liquid in the tank plus the vapor pressure. The instrument now measures the difference in height between the liquid level in the tank and the fixed level in the condensing reservoir. It is obvious that the difference decreases

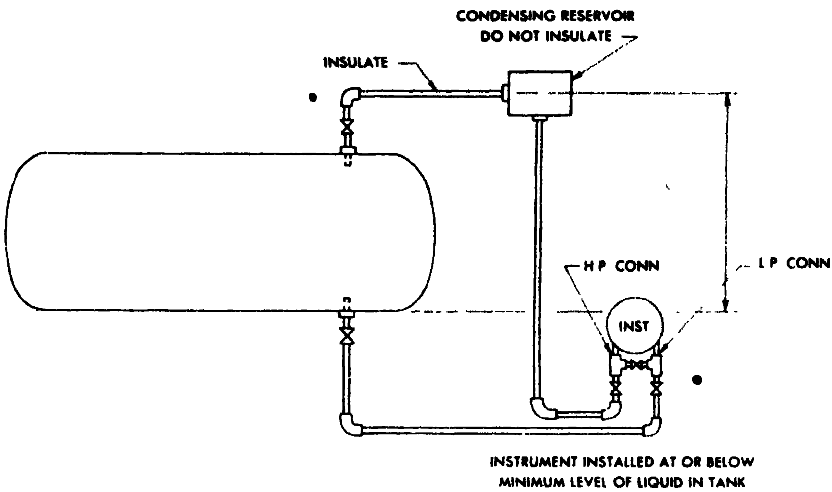


Figure 5-6. Installation of liquid level instrument.

with rising level. Thus an instrument response of increasing readings with decreasing differential is required. The maximum level is reached when the liquid level is equal to the level in the reservoir and the pressure differential sensed by the instrument is zero. An alternate method is to provide a second reservoir at the lower tank connection and then fill the measuring system up to both reservoirs with a sealing liquid.

The Yarway Indicator made by Yarnall-Waring Company is another liquid level instrument using the differential-pressure method. Its working mechanism is illustrated in Figure 5-7. The high pressure is applied on one side and the low pressure on the other side of a neoprene diaphragm (24) which is secured between housing (1) and cover (2) and is protected against distortion by a backing plate (3) and by the inside face of the cover. Movement of the diaphragm, due to a change in differential pressure, is transmitted by a pin-point contact (11) to the deflection plate (4). This plate, which is fastened to the front end of the indicator housing, has a permanent magnet (7) mounted on its free end. The poles of this magnet straddle but do not touch the outside of a non-ferrous alloy tubular well (8) screwed into and forming a part of the housing.

Inside the well, which is always at atmospheric pressure, is a spiral strip armature (17) of magnetic material, spindle-mounted on jewelled bearings. The outer end of the armature shaft carries the counterbalanced pointer. The actuating mechanism, which is under pressure, is thus completely separated from the indicating mechanism, which is always at atmospheric pressure,

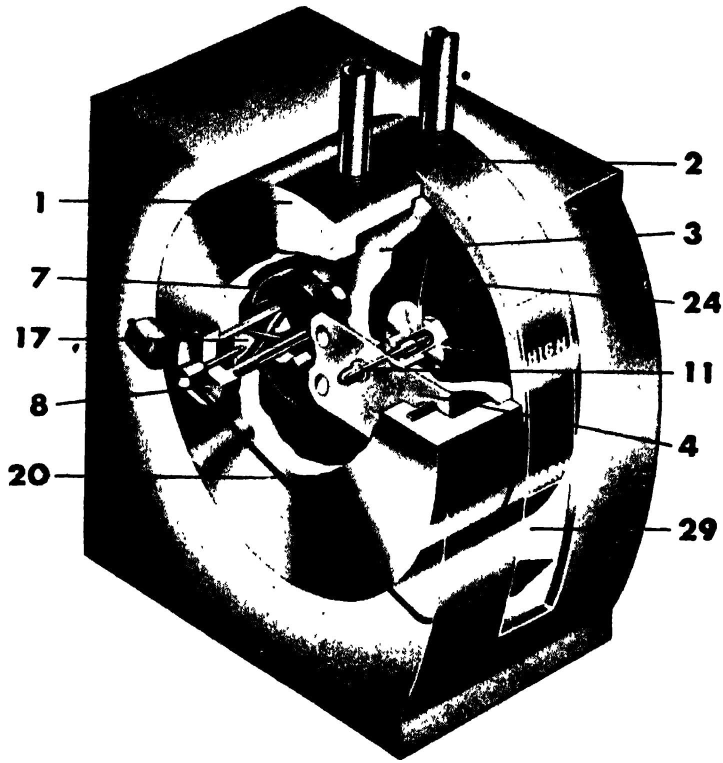


Figure 5-7. Mechanism of Yarway indicator. (*Courtesy of Yarnall-Waring Co.*)

without the use of stuffing boxes. The Yarway Indicator was primarily designed for boiler applications where it is used to show the normal operating boiler level, with red marks for high and low levels. It can, however, also be furnished as a recorder if a continuous record of the level is desired.

The Yarway Indicator is available with a number of accessories. For example, an additional permanent magnet of small size can be attached to the indicator pointer. Two, three, or four magnetic switches are then provided on adjustable arms. The rotation of the indicator pointer caused by liquid level changes produces a corresponding rotation of the permanent magnet, actuating one or the other switch to close an electric circuit which operates high or low alarm signals.

Another modification equips the indicator pointer with the movable core of a differential transformer. An electrical transmitter is then obtained, the circuit of which is illustrated in Figure 5-8.

The output of the differential transformer V_1 located in the transmitter is balanced by an output of equal magnitude but opposite polarity of differential transformer V_2. The latter is located in the receiver. If a change in level moves the core of transformer V_1, the electromagnetic coupling between primary and secondary is affected, and a change in secondary voltage is hence produced. This produces a voltage signal across the amplifier terminals. The result is an amplifier output which by means of the solenoid motor positions the indicator pointer of the receiver. The differential transformer core attached to the pointer changes the secondary voltage of V_2 balancing that of V_1. This means that the indicator pointer of the receiver moves until it reaches the pointer position of the transmitter. The two fixed output coils

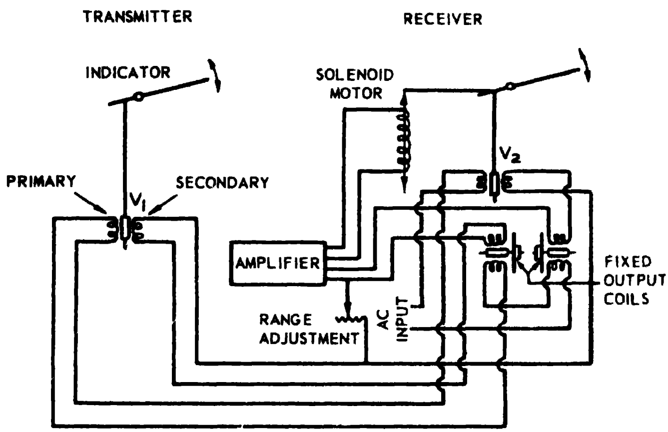


Figure 5-8. Circuit of Yarway transmitter and receiver

are adjustable to provide electrical zeroing. A variable resistor bypasses part of the signal current to provide indicator range adjustment.

One particular use of a differential-pressure method is the Bristol Mercury Counterpoise liquid-level gauge. This arrangement is used to measure water levels in elevated tanks where the instrument is to be located at ground elevation and where it is desired to eliminate the effect of the water pressure in the standpipe below the tank bottom on the instrument response. The range tube of the manometer-type instrument is offset so that it is below the float chamber and the column of mercury in the pipe connecting the float chamber to the lower range tube balances the water head in the standpipe. Each inch of mercury in the pipe counterpoises 13.57 inches of water. A reservoir is provided above the high-pressure side of the manometer to prevent loss of mercury when the standpipe is drained or the manometer disconnected.

Buoyant-float Method

Instruments using the buoyancy of floats do not depend on static pressure to measure the liquid level as do the instruments previously described. Static pressure may become a factor only insofar as a hollow float has to be protected from collapsing. One of the most important application of these instruments is in tank farms where it is frequently desired to feed all readings into one central station.

The float is suspended from a tape which is under slight tension. As the float moves up and down, riding on the liquid of which the level changes, it pulls the tape with it. This tape as shown in Figure 5-9 rotates a sprocket

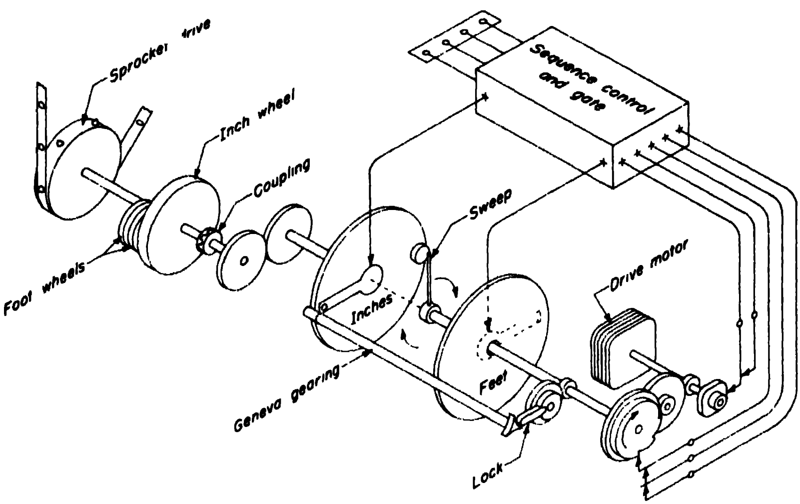


Figure 5-9. Schematic of liquid level transmitter. (*Courtesy of Shand & Jurs*)

drive. The diagram illustrates a Shand & Jurs liquid level transmitter which converts the float position into electrical impulses. The pulses, representing level information, are transmitted to remote control stations for readout.

The circumference of the sprocket wheel is 12 inches. Each revolution of the sprocket wheel represents one foot of change in liquid level within the tank. The foot wheels and inch wheels are the wheels in a counter for local readings at the transmitter. They are geared to each other and carry numbers on their periphery, so that the counter window exposes the correct level reading at any time. The transmitter wheels are connected through a coupling to the sprocket drive shaft. The first index wheel of the transmitter—marked "inches"—makes one complete revolution for each foot of float travel. A Geneva mechanism advances the second index wheel—marked "feet"—two teeth for each foot of level. The sweep mechanism is set to measure the angular displacement of each index wheel in turn from a fixed zero position and indicate that displacement by pulses on the transmission line. In order to read the position of the two index wheels, the sweep arm which is carried between these two wheels must make two complete revolutions. In addition to reading displacement of the two index wheels, the transmitter also generates a code signal to identify itself. Selection can thus be automatically confirmed at the central station each time a gage reading is taken.

On demand, the transmitter sweeper determines the position of its index wheels, and simultaneously sends pulses which correspond to float position. During the gauging cycle, a mechanical latch locks the index wheels into register, preventing errors to rapidly changing level. The transmitter completes a gauging cycle and returns to standby conditions in slightly less than 15 seconds.

A different method of sensing the movement of the float is used in the Levelrator made by Fischer & Porter. Referring to Figure 5-10, a float-guide tube is inserted downward into the vessel and is mounted with flange and gasket to the top of the tank. The lower end of the tube is closed and the inside of the tube is therefore completely sealed off from the tank. A magnet is suspended in this tube by a nylon-covered glass-fiber cable. Located around the outside of the tube is a doughnut-shaped hollow float in which a set of magnets is imbedded. Concentricity of float to tube is maintained by guide surfaces to assure vertical motion and proper magnetic relationship between primary and secondary magnets. The follower magnet inside the tube seeks a position corresponding to that of the float, thus moving the cable. The cable winds on a drum located in an instrument case which is mounted directly at the top end of the float guide tube.

The cable in this arrangement is kept taut by a so-called Neg'ator spring which is made by the Hunter Spring Company. The Neg'ator is a spiral-wound spring. It is a strip of flat material which has been given a curvature by continuous heavy forming at a constant radius so that, in its relaxed or unstressed condition, the Neg'ator remains a tightly wound spiral. This is different from the conventional spiral spring which snaps open when not restrained. If the Neg'ator is mounted for free rotation with its inner end fastened to a stud and the outer end attached to the cable, it will exert a pull of constant force on the cable in any position of the float; in this respect it acts like a counterweight. The Neg'ator has the advantage that it does not require the space for the vertical movement of the counterweight but fits directly into the instrument case.

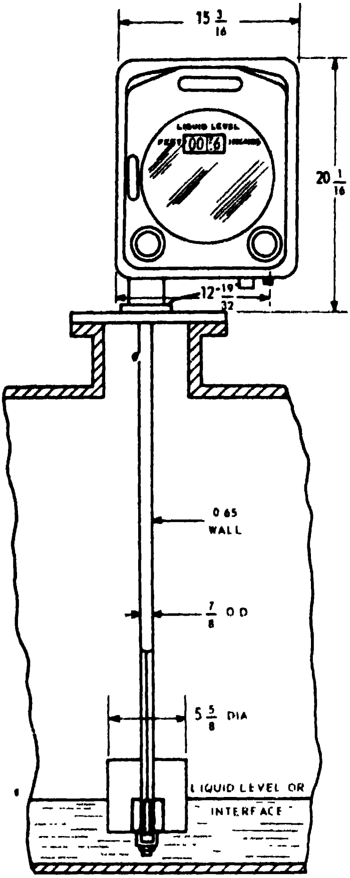


Figure 5-10 Levelrator. (*Courtesy of Fischer & Porter*)

The drum of the Levelrator drives a counter and a dial mechanism through a gear train to give direct readings of liquid level in feet, inches, and fractions of inches, or any other convenient units. The readings can also be transmitted by standard pneumatic or electric means.

There are a number of float methods that do not use a cable or tape. The Liquidometer, for example, made by the corporation of the same name, belongs to the latter class and is available in a number of models. Figure 5-11 shows the side view of one of them. Part of the gauge housing is cut away to expose the bellows seal through which the mechanical movement passes. This seals the float mechanism and the tank contents from the indicating part of the gauge and allows the instrument to be used on tanks which are under pressure. As the liquid level rises and falls the float moves with the level.

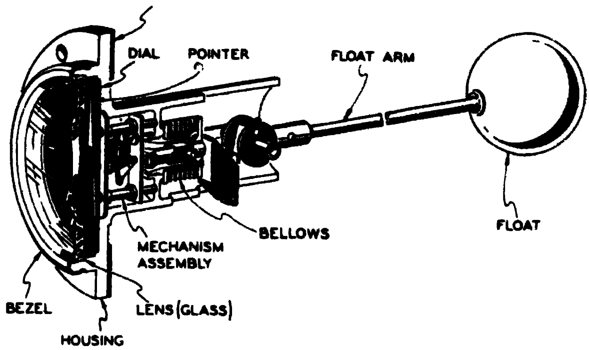


Figure 5-11. Liquidometer tank gauge. (*Courtesy of Liquidometer Corp.*)

In doing this it rotates around the pivot to which it is connected through the float arm. The float arm is part of a linkage which operates through the bellows seal to drive the indicating mechanism. The instrument is designed for installation on a tank in such a position that the face of the gauge can be conveniently seen from the side of the tank. Other models are for top and bottom mounting and for eye-level indication of liquid contents in large underground storage tanks.

For remote-reading gauges, the transmission system illustrated in Figure 5-12 is used. In this arrangement, all four bellows are fixed at their outer ends.

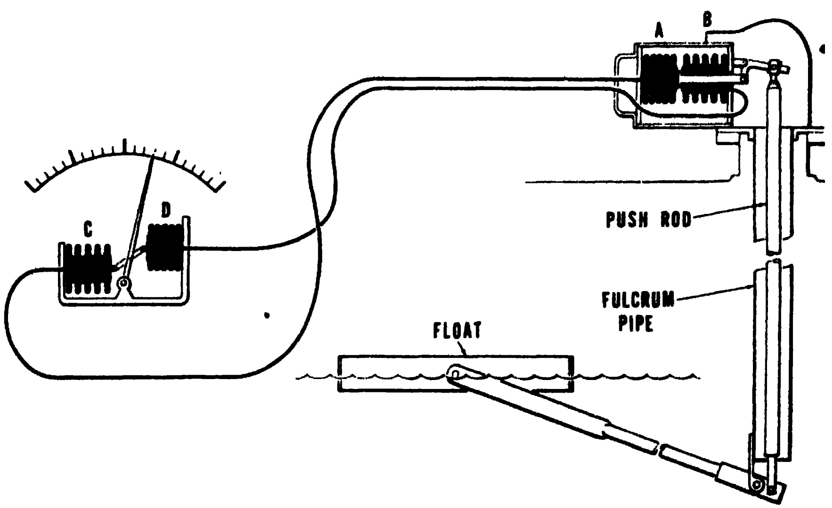


Figure 5-12. Liquidometer transmission system. (*Courtesy of Liquidometer Corp.*)

Bellows *A* and *B* are linked together and so are bellows *C* and *D*. The two circuits, *AC* and *BD*, are filled with liquid. When the float moves down, tank end bellows *B* is compressed and displaces liquid causing dial end bellows *D* to expand. Simultaneously, tank end bellows *A* expands taking in liquid which causes dial end bellows *C* to compress. When the float moves up the action is reversed. The twin hydraulic circuit in combination with the link arrangement at the dial end provides a temperature-compensated system.

While the Liquidometer uses a bellows to seal off the indicating part of the housing, the Rochester Manufacturing Company use in their Rochester Liquid Level Gauge a magnetic coupling for the same purpose. A shaft connected to the float by means of a gear-and-level arrangement carries a small permanent magnet which rotates according to the liquid level movement of the float arm. By magnetic force, this compels a similar rotation of the responsive magnet within the dial chamber, causing the pointer and dial to indicate the liquid level within the tank.

Magnetic action is also used for a liquid level limit controller made by Magnetrol. Figure 5-13 (A and B) shows the action of the controller. The float carries a magnetic sleeve on an extension rod. The magnetic sleeve moves within a nonmagnetic enclosing tube which seals the float assembly from the outside atmosphere. At normal operating level, as shown in diagram A, the magnetic sleeve is within the magnetic field of the Alnico permanent magnet. The magnet is attracted toward the sleeve and rests against the enclosing tube. In this position, the mercury switch maintains a closed electrical circuit between center and right terminals and an open circuit between center and left terminals.

As the liquid level recedes, the float is drawn down with it. When a prede-

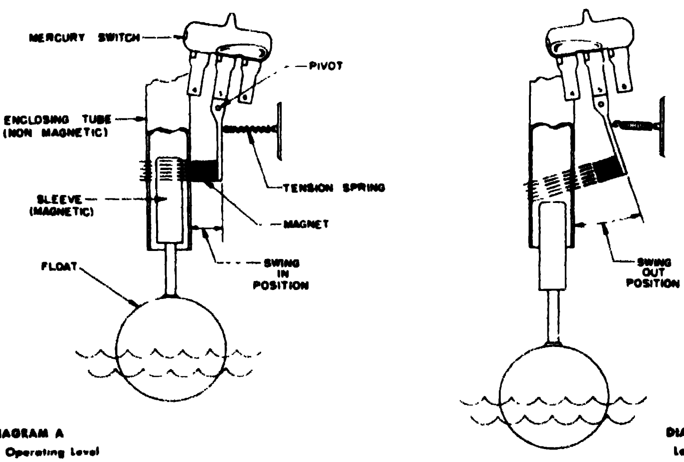


Figure 5-13. Operating principle of Magnetrol. (*Courtesy of Magnetrol, Inc.*)

termined low position is reached, as shown in diagram B, the magnetic sleeve is no longer in the field of the permanent magnet. This releases the magnet to swing outward and away from the enclosing tube. This movement which is accomplished by gravity assisted by the tension of a coiled spring results in a sudden reversal or snap-action of the switch to a position where the circuit between center and right terminals is now open and the circuit between center and left terminals is closed.

Displacement-float Method

Buoyant floats which were discussed above are lighter than the liquid in which they are partially immersed. The amount of their immersion will always be the same and they move up and down together with the fluctuations of the level. A float which is slightly heavier than the liquid and which is suspended at about the height of the liquid level will change its amount of immersion in the liquid when the level rises and falls. As the level rises, more and more of the float is surrounded by the liquid and the float loses weight. Let the float be suspended from a spring, and it is obvious that initially the spring is more expanded than it will be when the float loses weight because of the increased immersion. Since the spring contracts somewhat, the float will of course rise slightly.

Two things happen: a movement of the float that is considerably smaller than the movement of the liquid level and a change of tension on the spring that can be measured as an expression of the change in liquid level This is the basis of instruments that utilize the so-called displacement principle—the customary though not quite accurate name—because all floats displace liquid; the difference is that buoyant floats are characterized by essentially constant displacement, while the ones now being discussed operate on the principle of variable displacement. The advantage of displacement level instruments is that for the same amount of float movement, they respond to level fluctuations over a much wider range than do buoyant-float instruments. This means that, as a result of relatively small movement, better transmission methods from the float movement to the outside, like torque tubes and flexible shafts, are obtainable. It also means that because of the large range they are able to cover, they become practical not only as limit controllers, but also as indicators and recorders.

Figure 5-14 shows the torque tube unit for the transmission of the movement of the float to the outside in a Level-Trol, which is a typical displacement type instrument made by the Fisher Governor Company. Figure 5-15 shows the assembly of Figure 5-14 mounted in its housing. The arrangement consists essentially of the float, the float rod *B*, the bearing *C*, and the torque tube *E* which contains the 1/8-inch diameter rotary shaft *F* welded to the female socket *D* inside the tube. The rotary shaft *F* extends through the length of the torque

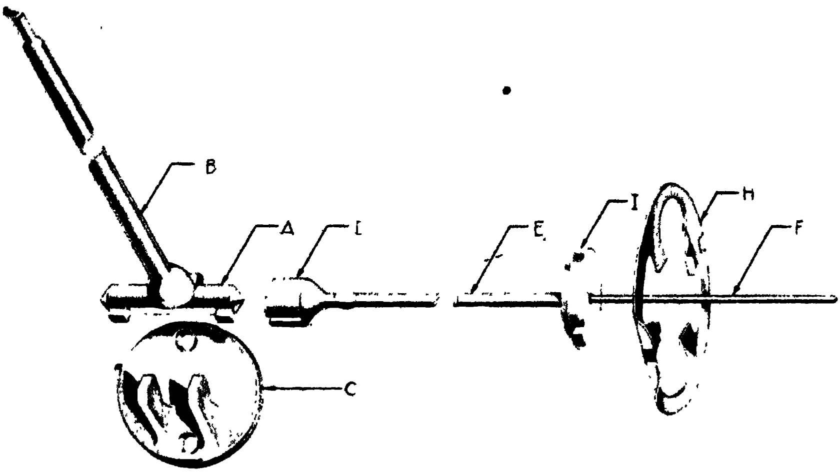


Figure 5-14. Assembly view of Level-Trol torque tube unit. (*Courtesy of Fisher Governor Co.*)

tube, through the outer tube flange *K*, and into the pilot case which is mounted on the torque tube housing member (not shown). The fitting socket *D* is firmly connected to the float rod driver *A*. The driver bearing *C* which retains the

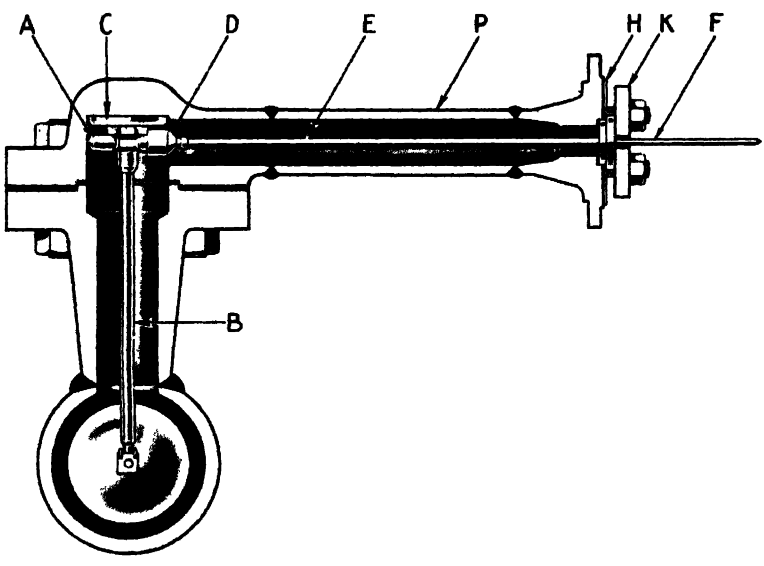


Figure 5-15. Top view of Level-Trol showing torque tube and float assembly. (*Courtesy of Fisher Governor Co.*)

float rod driver is bolted solidly to the torque tube housing. The other end of the torque tube is held firmly in position at its flanged end *I* by means of a retaining flange *K*. When the float moves up and down, the float rod rotates the rod driver, and this in turn twists the torque tube and positions the rotary shaft. The torque tube seals the float mechanism from the atmosphere.

Electrical Conductivity Method

The Republic flowmeter was discussed in the previous chapter. It utilizes the mercury rise in the low-pressure leg of the meter body to vary the resistance of an electrical circuit (Figure 4-17). Figure 5-16 shows the same principle applied

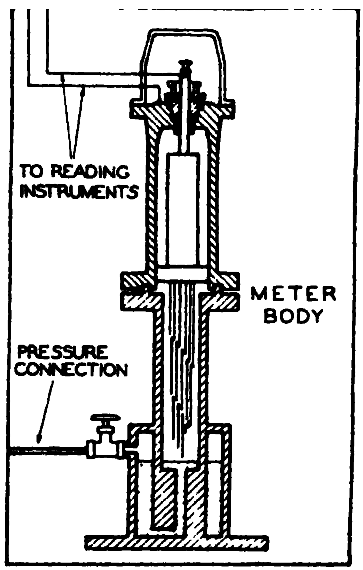


Figure 5-16. Liquid level meter. (*Courtesy of Republic Flow Meters Co.*)

by Republic to the measurement of the level in an open vessel. For measurement under pressure, a differential-pressure type is available. This meter body is used for ranges of from 0 to 15 inches to a maximum of 0 to 140 inches of water. The body can be mounted directly at the tank and be connected by two wires to the recorder.

The meter body is filled with mercury. One leg is exposed to the pressure of the liquid head from the tank under consideration while the other leg is vented to atmosphere and is free to rise and fall. A number of metal rods, ninety-one to be exact (only a few are shown in the sectional view), are exposed in sequence to the rising mercury. All are connected with an electric circuit. Between the rods are electrical resistances, so that the more rods are short-circuited by the rising mercury the less resistance remains in the circuit. The resistance is the variable in the measuring circuit to which the recorder responds.

As the level in the tank rises, the pressure due to the liquid head, which is imposed on one surface of the mercury, increases. This raises the mercury level in the contact chamber, causing the mercury to establish contact with additional rods. In this manner a change of level is transformed into an electrical signal and transmitted to the reading instrument.

If the meter body has to be installed below the tank level, it will be desirable to have the instrument read zero for zero level in spite of the head that rests on the mercury surface. Such zero suppression, as it is called, is made possible to a limited extent by using a micrometer screw adjustment which is provided to raise the contact rod unit in the chamber so that an increased amount of mercury rise is required before the first contact rod is reached.

For limit controls by the electrical conductivity method, there are a number of systems that use probes which either control the liquid at one level only (single-probe systems) or between two levels (double-probe systems). Figure 5-17 illustrates the double-probe system with a Photoswitch Level Control. Two probe rods are suspended into the tank from a standard probe fitting which has been attached to the top of the tank. The probe rods project into the tank to the level corresponding to the low point at which pumping is to start, and

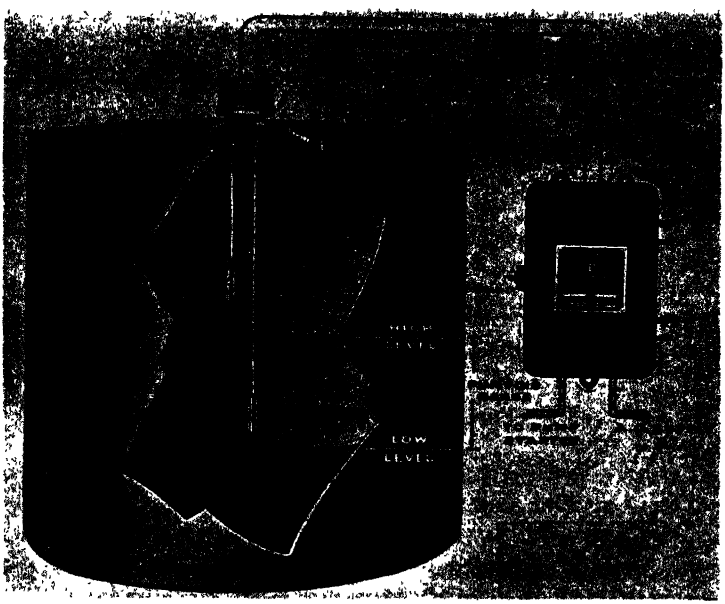


Figure 5-17. Liquid level controller. (*Courtesy of Photoswitch, Inc.*)

the high point at which pumping stops. The probes are wired to the controller When the liquid rises to the level of the upper probe, the liquid itself acts as a conductor of the minute current required for the operation of the controller. This opens the electric circuit controlling the pump, and the pumping operation stops. When the level of the liquid in the tank falls below the lower probe, the controller closes the electrical circuit controlling the pump and the tank fills. These controllers are available for resistivities of the controlled liquid from 0 to 20 megohms, which means that levels of highly conductive liquids as well as those of alcohols, refrigerants, etc. can be measured.

Capacitance Method

The Fielden Telstor operates on the basic principle of a capacitance bridge. A capacitor can be made up of two parallel plates or two concentric cylinders as electrodes with a dielectric between them. The capacitance in a given capacitor depends on the dielectric constant of the material between the electrodes. In the Telstor instrument the two concentric cylinders are simulated by a rod-type electrode located inside the walls of a vessel, the latter being equivalent to the outer cylinder of the assembly. The dielectric constant of air and most gases is approximately 1, while most liquids have dielectric constants ranging between 2 and 80. Thus, when the vessel is empty, the capacitance between probe and walls is at a low value. As the material rises and displaces the air in the vessel, the capacitance increases. It is necessary only to measure the change in capacitance to determine the total amount of a given material in the vessel.

The Telstor measuring circuit consists essentially of an inductance-capacitance bridge. The bridge circuit is supplied with a radiofrequency voltage modulated by the 60-cycle power supply. The basic bridge circuit is composed of two inductance coils and two capacitors. One of the capacitors is the vessel-probe combination; the other is part of the instrument and is used to adjust or balance the bridge to the zero level condition, as dictated by the lowest level of the material. As material rises in the vessel, increasing the capacitance of the vessel-probe combination, the bridge becomes unbalanced. A rectifier changes the alternating current, developed by the unbalance of the bridge, to direct current applied to the reading instrument.

The advantage of such a system is obviously in the ease of installation. There are no moving parts, there are no pipes that can plug up, there are no limitations when it comes to tanks under pressure. Capacitance-method instruments can be used for many granular materials as well.

Where limit control is required, the Fielden Tektor level controller finds application. An electrode or probe is located near the maximum level. The approaching material, which may be liquid or granular, conducting or nonconducting, changes the capacitance between probe and wall and makes the unit respond. In doing so, a relay with two pairs of contacts is actuated. One pair of contacts operates the signal lights on the cover of the case and the other pair is for external control of the pump motor, solenoid valve, audible alarm, etc.

Gamma-ray Method

A typical representative of this method is the Ohmart level gauging system. Its basic components are a radioactive source stack, a measuring cell stack with compensating cell, and an electrometer with preamplifier. Figure 5-18 shows the arrangement for measuring the level of hydrochloric acid which is typical of the liquids that can be handled by this system. The radioactive sources are cesium-137 or cobalt-60. These materials emit gamma rays which are meas-

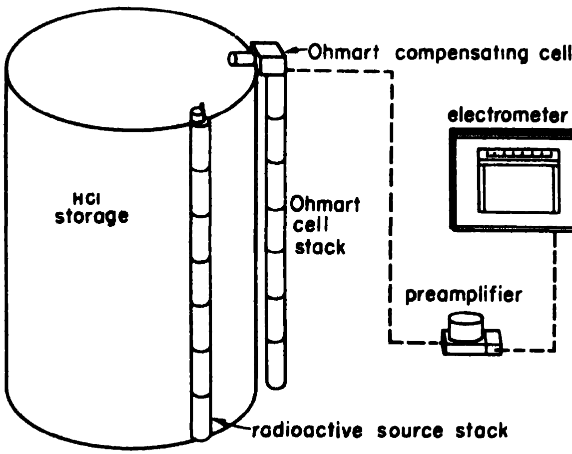


Figure 5-18. Ohmart level gauging system.

ured by the cell stack. Gamma rays are similar to ordinary light waves but of very much shorter wavelength and are comparable in this respect to the wavelength of hard x-rays. These rays are continually emitted during the spontaneous process of atomic disintegration, which is a characteristic property of all radioactive materials. Like x-rays, they penetrate solids, undergoing a loss of intensity that depends on the density and thickness of the material. Measurements of their intensity may be interpreted either in terms of variations of the density of the material, if the distance traveled is kept constant, or in terms of the distance the rays have traveled through the substance if the density remains constant.

The gamma rays from the radioactive source are projected through the tank walls and its contents and then picked up by the cell stacks. No openings in the tank are required for installation of the components.

The cell stack converts the radiation it receives from the radioactive stack into an electric signal. This cell stack contains two electrodes of different materials. They are separated by a filling gas. When gamma rays penetrate the container, the gas is ionized, and a small, continuous current flows from one electrode to the other.

Essentially linear measurements of the level of liquids or solids can be made over approximately 4 inches with a single cell 7 inches long and a radioactive source in the form of a strip the same length. A stack of three cells, which when used with a source the same length, provides continuous measurement over a height of 20 inches. Another type of cell can be made in continuous length up to 20 feet.

If the interface between two liquids—one floating upon the other—is to be measured, a compensating cell is used to provide zero suppression. It is of the same type as the measuring cell except that its polarity is reversed and that it has its own source of radioactivity which is mounted on a screw that projects into a well in the cell. Thus, the position of the source within the cell can be altered, and the output current can be adjusted to the proper value to nullify the output current from the measuring cell for any predetermined height of the interface.

The preamplifier converts the direct current from the cell stack into alternating current and amplifies it to sufficient magnitude for the electrometer which is identical with an electronic potentiometer as described in chapter I.

For a high degree of accuracy over a wide range, the Ohmart motor driven level gauge can be used. Referring to Figure 5-19, the source of gamma

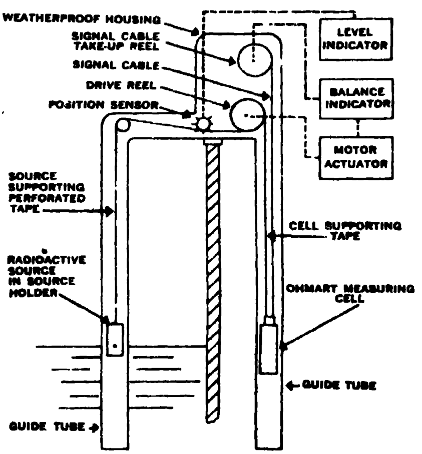


Figure 5-19. Ohmart wide-range level gauging system.

radiation and an Ohmart measuring cell are suspended from steel tapes that wrap around a motor driven drum. One of the tapes is equipped with perforations that engage the position sensor sprocket. As the drum rotates, the source and measuring cell are moved up and down together, and the position sensor rotates. The position sensor operates two potentiometers through a gear reduction mechanism. The potentiometers give output voltages that are a function of the position of the source and cell. One potentiometer is set to indicate the full range in feet; the other is set to indicate inches within that range.

A zero-suppression circuit is adjusted so that the meter on the balance indicator reads zero when the level is at the midpoint of the measuring cell and source. As the level moves up, the balance indicator reads off balance, and by means of the motor actuator, the source and cell move until the system returns to balance. The new level is then read on the level indicator.

Echo-sounding Method

The successful method of measuring the depths of oceans by echo techniques has found its application in liquid level measurement in an instrument manufactured by Bogue Electric Manufacturing Company. The sound pulse emitter of the Bogue Sonic Liquid Level Indicator is located in the bottom of the tank filled with the liquid of which the level is to be determined. The surface of the liquid serves as an acoustic reflector, and the emitter, which is called a transducer, receives the reflection of its sound pulse. The transducer is connected to a transmitter where the sound pulse originate and to a receiver into which the reflected sound, the echo, is fed. Both transmitter and receiver are connected with a time interval counter which measures the time that elapses between the emission of the sound wave and the reception of the corresponding echo. The elapsed time is converted into feet (including tenths and hundredths of a foot) of liquid level which can be read directly from the instrument. It is possible to connect a number of transducers with the same equipment and thus switch from one tank to the other and read the level of each one from the same instrument, provided that all tanks contain the same liquid at the same temperature.

The influence of temperature upon the velocity of sound in a liquid is rather pronounced. For example, a temperature change of 10°C in a 10-feet vessel filled with water could introduce an error in level of 0.2 foot. To avoid such errors, as well as those that could be produced by changing from one liquid to another, manual or automatic compensation is possible. If compensated manually, it is necessary first to calibrate the installation for various conditions, and then prepare a chart or graph according to which adjustments can be changed whenever the temperature of the liquid changes.

To obtain automatic compensation, two stillwells are required which are mounted either within the tank or outside on the tank walls. In the latter case, a number of taps are provided in the tank that connect to the stillwells. The levels in the stillwells are always the same as the level in the tank. Each stillwell is equipped with a transducer at its lowest end. One stillwell has a number of solid acoustic reflectors mounted along its inside walls which serve for calibration purposes, while the other measures the surface level. By continuously measuring the time intervals between (a) the sound pulse and the echo in the measuring stillwell, (b) the sound pulse and echo in the calibrating stillwell, and (c) the echo of the measuring and the echo of the calibrating stillwell, it is possible to maintain the calibration automatically even when temperature or other properties of the liquid change.

Ultrasonic Method

The Sonac Single-sensor System made by The Aro Equipment Corporation consists of an amplifier, the sensor with a 10-foot connecting cable, and fittings for mounting the sensor through a tank wall. The sensor is a small, hermetically sealed probe whose from face oscillates at 38,000 cycles per second. When rising liquid covers at least half the face of the sensor (if mounted horizontally) or the whole face (if mounted vertically) the oscillating action of the sensor is damped out. This automatically causes a relay in the amplifier to drop out and actuate a two-position control device. Where high-low level control is desired, a second unit can be used to produce a signal when its face is uncovered by liquid at the low level.

6. Density

The density of a liquid can be determined by the air-pressure balance method using a modification of the bubble pipe arrangement described in the previous chapter.

If the liquid in a tank is maintained at constant level, then the change in bubble pipe pressure reflects the change in density. Since these changes are usually very minute, and maintaining a constant level is frequently difficult, a single bubble pipe is not practical. Instead, two bubble pipes are used at different levels of the liquid under measurement. They are connected with a pressure-differential instrument. The pressure differential between the two bubble pipes is measured as an expression of liquid density.

The accuracy of this method can be considerably increased by means of the Foxboro liquid density measuring system illustrated in Figure 6-1. The operating principle is based on continuously comparing the hydrostatic pressure of a constant head of variable density liquid against the hydrostatic pressure of a constant head of a stable reference liquid. The changing differences in hydrostatic pressure are the actual changes in liquid density which are recorded on a chart calibrated in units of measurement.

Bubble pipe B' is connected to the high-pressure side of a differential-pressure instrument. Another bubble pipe extending into the reference chamber is connected to the low-pressure side of the same differential-pressure instrument. The vent from the reference chamber is connected to the compensating bubble pipe B. The hydrostatic pressure in the process tank is measured by the difference in elevation H between the open end of B and of B'. The dimension H is constant, therefore the hydrostatic pressure varies only with a change in density. The compensating bubble pipe B prevents the hydrostatic pressure from being affected by a variation in level in the process tank.

This system permits expanding a specific gravity* difference of only 0.050 to a 4-inch measurement scale reading. Specific gravity changes of 0.001 can be read accurately.

The most direct approach to determining the density is to weigh continuously a constant volume of the liquid. This is done in the Republic liquid-density transmitter, illustrated in Figure 6-2. A sample of the liquid flows continuously

*Specific gravity is the ratio of the density of a fluid to the density of water if it is a liquid; and to the density of air if it is a gas.

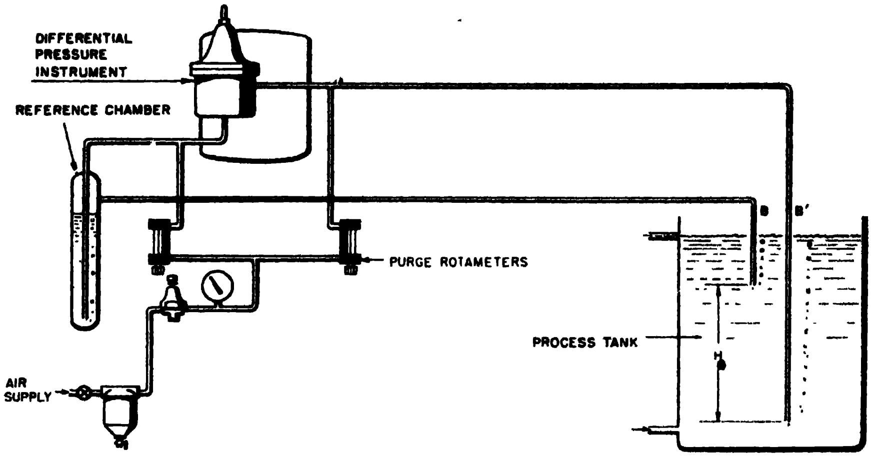


Figure 6-1. Foxboro liquid density measuring system. (*Courtesy of Foxboro Co.*)

through the meter. Entering into the center of the float chamber of the meter body, it flows through an annular space formed by a diffuser ring and leaves it through the top and bottom discharge lines. The liquid buoys up the displacer float, which is mounted rigidly on the weighbeam. The weighbeam in turn extends to the transmitting mechanism at the right. It is counterbalanced

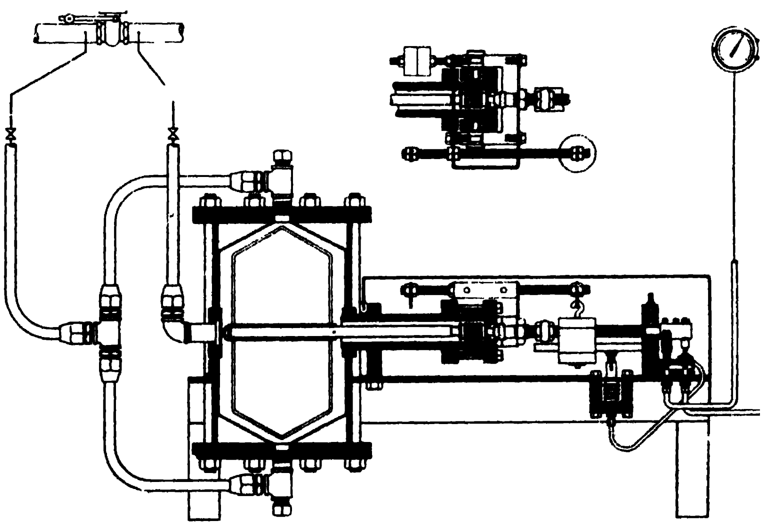


Figure 6-2. Cross section through liquid density transmitter. (*Courtesy of Republic Flow Meters Co.*)

in such a way that liquid which has the minimum density for which the transmitter is calibrated will just start to lift the displacer. As the displacer tends to rise, the throttle tip mounted on the weighbeam end approaches the nozzle through which compressed air is flowing from a supply orifice. The resulting air output is also applied to a feedback diaphragm creating a force which equals the buoyant force of the displacer. The density is thus directly expressed in air output pressure which can be transmitted to any conveniently calibrated pressure-responsive instrument.

The Arcco-Anubis Liquid Gravitometer made by the Arcco Instrument Company also employs a continuous weighing system. The liquid sample flows through the intake tube into a spherical bulb and then up through the outlet tube. The tubes act as a delicate spring balance, and allow the counterbalanced bulb and its contents to sink or rise as the gravity of the liquid increases or decreases. The motions of the bulb are directly linked to the pen mechanism or to some form of controlling or transmitting mechanism. Temperature correction is obtained through a bimetal coil enclosed in a thin tube. The coil is immersed in and surrounded by the flowing sample. The coil responds to changes in the temperature of the liquid sample and positions an arm connected to the coil through a connecting rod, which in turn acts on a floating lever actuating the pen mechanism.

The principle of the Liquidensitometer made by the Liquidometer Corporation is illustrated in Figure 6-3. A set of individually weighted and balanced floats add or remove fixed increments of electrical resistance depending upon whether they are in their buoyant or their non-buoyant positions. The specific gravities of the floats vary, one from another, by fixed increments. Immersed in a liquid of a particular density, the floats whose specific gravities are greater than that of the liquid will remain in the down position while those whose specific gravities are less than that of the liquid will become buoyant and rise to their upper positions. As they rise they close electrical switches that shunt out fixed

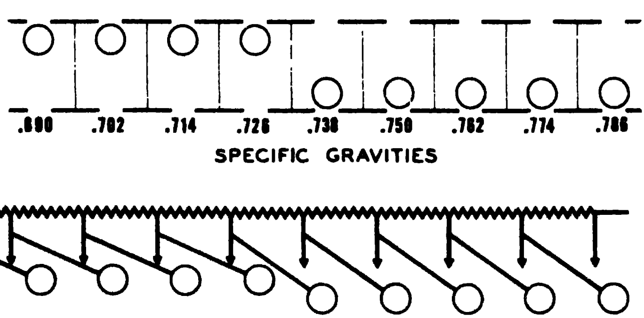


Figure 6-3. Schematic of Liquidensitometer.

electrical resistors. The total resistance is thus a function of the density of the liquid.

Where the level is subject to changes, compensation for these changes is needed. For this purpose, a level measuring instrument similar to that in Figure 5-12 is used. However, instead of actuating bellows, the push rod of the level unit positions the wiper of a potentiometer. The electric circuit combines the potentiometer of the level unit and the fixed resistances of the density unit so that the resulting signal indicates density only.

The floats of the Liquidensitometer are glass bulbs designed to withstand tank pressures of 125 psi. Glass is used because of its corrosion resistance and its ability to repel the adherence of foreign matter to insure calibration stability. The motion of the floats is transmitted to the electric switches by magnetic coupling. This permits sealing of the switches in an atmosphere of inert gas to insure trouble-free operation.

A well-known device for the measurement of density in liquids is the hydrometer. It usually consists of a hollow glass float weighted on one side to make it float upright. The amount of immersion of the glass float depends on the density of the liquid. The immersion usually can be read from a scale on the glass float which is calibrated in specific gravity, *i.e.,* the ratio between the density of the liquid under measurement to that of water.

The float position can be sensed by a photocell. In this case the top of the float is made opaque. It then serves as a light shutter for a narrow slot in the housing through which light rays are sent. The amount of light passing is measured by a photocell. Since the amount of immersion of the float determines the amount of light passed to the photocell, the density measurement can be converted into an electrical signal.

The Specific Gravity Recorder made by Leeds & Northrup utilizes a hydrometer whose center is an iron core. It floats in a hydrometer chamber which is surrounded by the windings of a differential transformer. A sample flows continuously through the hydrometer chamber and the hydrometer will rise or fall in accordance with any changes in specific gravity of the liquid. The output of the differential transformer changes with the position of the iron core. A Speedomax potentiometer is used to detect any unbalance in the circuit caused by the output from the differential transformer, and to convert this signal into a specific gravity reading.

In the Princo Densitrol made by the Precision Thermometer & Instrument Company the hydrometer principle is somewhat modified. In the conventional hydrometer, the weight of the float is constant and the volume of the immersed float changes. In the Princo Densitrol, the principle of which is illustrated in Figure 6-4, the volume is kept constant and the weight is changed. This is done by immersing the plummet completely in the liquid and fastening it, by a series of chains, to a fixed reference point. As the plummet rises due to an increase in density, chain weight is transferred from the reference point to the plummet. The plummet will then obtain an equilibrium at a new position where the added weight of chain will equal the added plummet buoyancy caused by the increase in density.

The plummet is so weighted that at the middle of its indicating range it will assume an equilibrium position where the weight of the calibrating chains is equally supported by the plummet and by the reference point. If the density rises from the midrange point, the buoyancy added to the plummet by the increase in density will cause the plummet to rise. Since the effective chain weight

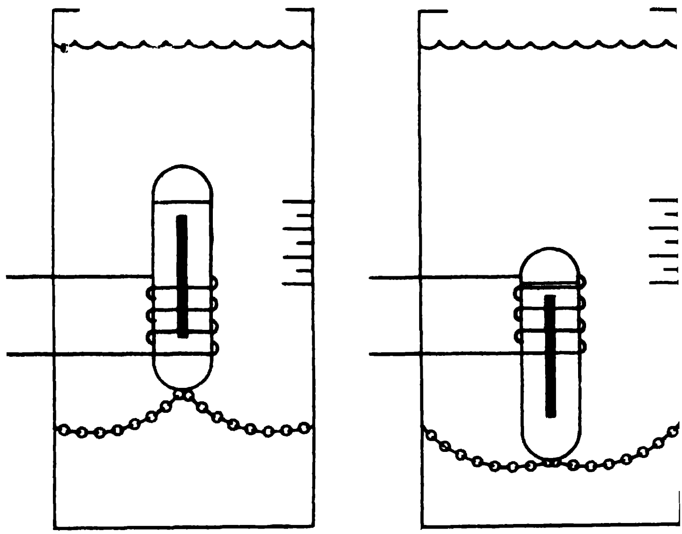


Figure 6-4. Operating principle of Princo Densitrol.

increases as the plummet rises, a new equilibrium condition is obtained. For each density within the range of the plummet-chain assembly the plummet will assume a definite equilibrium position.

The plummet core is of magnetic material and the plummet itself moves within an inductance coil. This converts the plummet position into an electrical signal which can be measured in terms of specific gravity or density.

Where the liquid under measurement is subject to temperature fluctuations which influence the density, it is possible to use automatic temperature compensation. This is accomplished by inserting a resistance temperature detector into the circuit in such a way that the effect of this detector is added to that of the plummet and coil. It is necessary that the relationship between density and temperature be sufficiently linear within the expected temperature changes to allow such correction.

Frequently, it is necessary to measure the specific gravity of a process or fuel gas. One method consists of drawing a continuous sample from the process and measuring the differential pressure produced by the sample when flowing across a metering orifice. In a system designed by Hagan Chemicals & Controls, a small constant volume blower draws a continuous sample from a gas header. The sample flow is drawn through a pressure reducing valve which is set for a downstream pressure of 4 inches water column. It smoothes out variations in gas supply pressure which would otherwise affect the gas sampling accuracy. The sample passes through the metering orifice and then through a second orifice to atmosphere. Between the two orifice plates the line is tapped by a recirculation line that connects back to the suction side of the blower. The atmospheric discharge is thus limited to about 30 per cent of blower capacity. The differential pressure of the constant volume flow across the metering orifice varies directly with changes in the specific gravity of the gas sample.

The Ranarex meter (Permutit Company), described in detail in Chapter 9 as an instrument for the measurement of CO_2 in a gas mixture by determining the weight of the gas, has also been developed for measuring the specific gravity of any gas or mixture. A continuous stream of gas sample is drawn into the lower measuring chamber of the instrument by an impeller, put in whirling motion and driven against the blades of a companion impulse wheel located in the same chamber. This action creates a torque on the impulse wheel which is proportional to the gas density. The torque is compared through a linkage system with the torque produced by atmospheric air in an identical upper chamber, the impeller of which rotates in the opposite direction. The difference between the opposing torques is a measure of the specific gravity; it causes movement of the indicating pointer and recording pen over the scale and chart which are direct reading in specific gravity units. Because of the high rate of sampling and the small internal volume of the measuring chamber, response to gas density changes is almost instantaneous. The instrument can be equipped with a pneumatic transmitter to convert the density measurement into an air pressure signal from 3 to 15 psig.

The principle of the Beckman Continuous Gas-density Balance is illustrated in Figure 6-5. The sensing element is a tiny dumbbell supported on a quartz fibre. The two spheres of the dumbbell are constructed in such a manner that each has different buoyancy characteristics. This is achieved by puncturing one sphere, making it completely independent of buoyancy effects, or by using spheres of slightly different volumes so that they react to the sample with unequal buoyancies.

Two fixed electrodes create an electrostatic field around one sphere. By applying a variable electric potential to this sphere—which is coated with rhodium

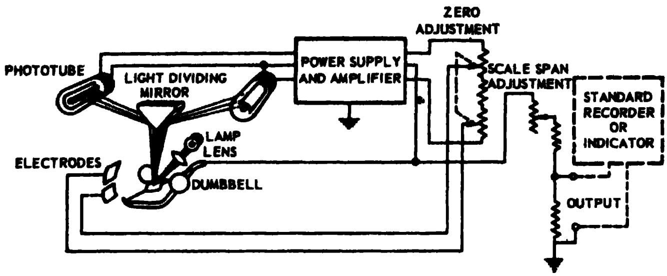


Figure 6-5. Beckman Continuous Gas Density Balance.

to make it conductive—the dumbbell can be balanced in the electrostatic field. A mirror fixed to the axis of the dumbbell reflects a beam to a dividing mirror which splits the beam equally between two dumbbells. If the dumbbell tends to rotate the light beam becomes unevenly divided and the photocells produce unequal signals. This difference signal is amplified and becomes the balancing potential applied to rebalance the dumbbell.

A continuous flow of the sample gas enters the cell, causing the spheres to react because of their unequal buoyancy. This results in a torque which causes an unbalance between the phototube signals. The amplified difference signal, applied to the electrodes, returns the dumbbell to its balanced position. Measuring the electrical potential required to keep the dumbbell balanced, gives a directly linear indication of the torque created by the differential buoyancies. This, in turn, is directly proportional to changes in sample density.

The Gow-Mac Instrument Company makes a gas density detector under a licensing agreement with Standard Oil Company (Indiana) which is illustrated in Figure 6-6. The flow circuit is a fluid bridge and mounted in the vertical plane. A reference gas enters at *A* where it splits into two branches. It leaves the bridge arrangement at *D*. Two detector elements are installed at B_1 and B_2. These elements are either thermistors or hot wires, depending upon the desired operating temperature of the device. They are wired into an electrical

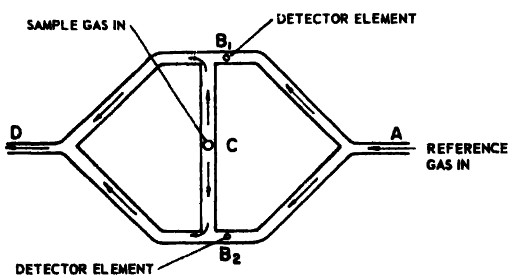


Figure 6-6. Gow-Mac Gas Density Detector.

Wheatstone bridge. When the flow is balanced, the detector elements are equally cooled and the bridge is balanced.

A sample of the gas, the density of which is to be measured, enters at C and splits into two branches. Both branches leave at D. If the sample gas is of the same density as the reference, there is no unbalance of the reference stream and, consequently, of the detector elements. However, if the density of the sample gas exceeds even slightly the density of the reference gas, there will be a tendency of sinking of at least part of the sample gas into the lower branch of the vertically located fluid bridge. This obstructs the flow A-B_2-D, causing a rise in temperature of detector element B_2 and unbalancing the electrical Wheatstone bridge. An unbalance in the opposite direction occurs, when the sample gas is lighter than the reference gas. It will then tend to rise and obstruct the flow A-B_1-D. Thus the unbalance of the electrical Wheatstone bridge becomes a measurement of the density of the sample gas.

The Qualicon series of liquid density gauges made by Nuclear-Chicago Corporation measures the density of a solution or slurry directly in a process pipe without contacting the material. The principle is illustrated in Figure 6-7. The

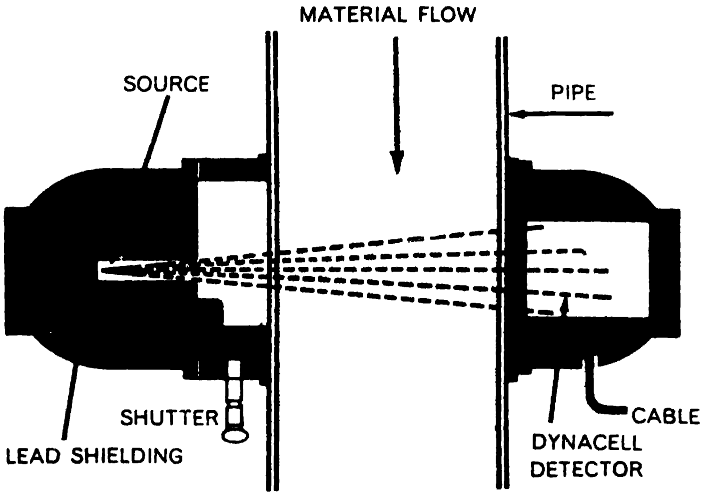


Figure 6-7. Qualicon Liquid Density Gauge. (*Courtesy of Nuclear-Chicago Corp.*)

source consists of cesium-137 which emits gamma rays. They pass through the material flow at a rate that is inversely related to its density. The gamma rays which pass through the material are detected by the Dynacell radiation chamber and are converted into the measurement signal. Measurements accurate to within 0.0001 specific gravity are attainable with the Qualicon measurement system.

7. Viscosity

Viscosity can be defined as the internal friction of a fluid. It is a measurement of the fluidity. When the fluid passes between two parallel plates of unit area and unit distance apart and the plates are moved in opposite directions at a given rate (rate of shear), a certain force must be applied to overcome the shearing stress of the fluid. The ratio of shearing stress to the rate of shear is an expression of the viscosity. In a so-called Newtonian fluid this ratio is a constant; in non-Newtonian fluids it is not. This produces special problems in the measurement of non-Newtonian as compared with Newtonian fluids. A common method of measuring non-Newtonian fluids is to determine their so-called apparent viscosity or consistency, which corresponds to the shearing stress measured by a viscosity instrument with a constant rate of shear.

A factor of considerable influence in measuring viscosity is its dependence on temperature. A change of 1°F may produce as much as 10 per cent change in viscosity. Temperature compensators are available, but they require a linear relationship between viscosity and temperature. As a general rule, it can be stated that the temperature should be kept constant, if necessary by controlled heating or cooling. Temperature compensation in the viscosity instrument should be used to correct for remaining minute temperature deviations.

There are a number of different approaches to the continuous measurement of viscosity in production processes. One, used in the Fischer & Porter Viscorator, stems from the fact that rotameter floats were originally sensitive not only to flow but also to viscosity. This required the development of floats shaped in such a way that they were relatively unaffected by viscosity changes. With two types of floats, one sensitive to flow and viscosity and the other to flow only, it is now possible to use two floats and note the difference between their responses to determine viscosity. A modification of this method would be to keep the flow constant and use only one float.

Figure 7-1 illustrates the Viscorator. It is installed in a bypass to a main flow line. A throttling valve or orifice plate in the main line creates a pressure differential which insures a reasonable flow through the instrument. To obtain a reading, manual adjustment of the flow-rate index-setting valve is required. By manipulating this valve, the flow through the bypass is adjusted until the upper float is opposite the index flow-setting graduation on the capacity scale.

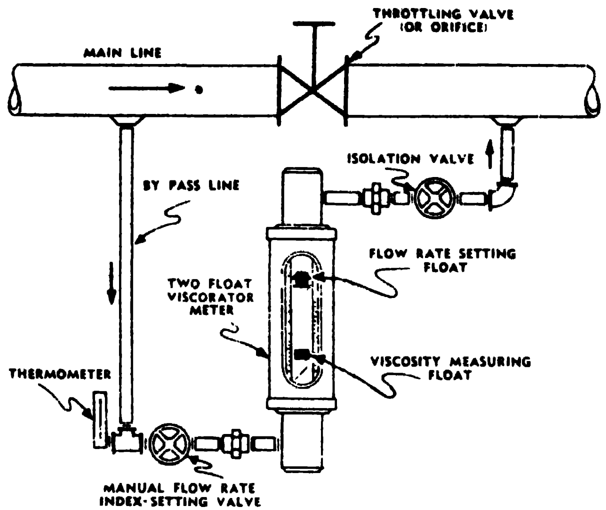


Figure 7-1. Two-float Viscorator. (*Courtesy of Fischer & Porter Co.*)

Viscosity is then read by noting the position of the lower float with respect to the viscosity graduations on the lower part of the scale.

If the bypass is equipped with a positive displacement pump driven by a synchronous motor at constant speed, the manual adjustment is no longer required, nor is the flow restriction in the main line used. In this case, the Viscorator contains a single float which indicates continuously the viscosity of the fluid. Where only a common industrial circulating pump is available, the Viscorator can be equipped with a constant-differential pressure regulator to keep the flow through the instrument constant. The movement of the float can be transmitted by methods described in Chapter 4.

The Norcross Recording Viscometer consists of two main assemblies: the measuring element and the recorder. The measuring element is installed in a vertical position, with the lower end of the measuring tube immersed in the liquid whose viscosity is to be measured. A piston is periodically raised by an air or electric motor-operated lifting mechanism. Clearance is provided between the piston and the inside of the tube to form an annular orifice. This permits a liquid sample to flow into the space which is formed below the piston as it is raised. The piston is then allowed to fall by gravity, expelling the liquid sample through the same path by which it entered. The time required for the piston to drop is a measure of viscosity. As long as the piston is falling by its own gravity an electrical contact is closed. The contact is in a circuit that energizes an electric motor in the recorder. The motor movement is linked to the pen. When the piston reaches its lowest point, the motor stops and the pen returns to zero. Since the piston goes through its cycle usually once every three minutes, the pen will be deflected from its zero position at equal intervals. The maximum positions of the pen indicate the viscosity of the liquid. The contour of these maximum positions on the chart shows the change of viscosity.

The DeZurik Regulator was developed especially for consistency control of pulp and paper stock but has found wide applications in other fields, particularly in the food industry. The regulator illustrated in Figure 7-2 consists mainly of an agitator wheel suspended in a suitable flow box and driven by an electric motor. With a slight change in the consistency of the stock, there is a corresponding change in the torque required to rotate the agitator. This torque is transmitted to a flapper and nozzle arrangement which converts it into an air pressure signal. The speed of the agitator wheel, *i.e.,* the rate of shear, is constant.

The same principle is used in the Brookfield Viscometron. This instrument measures the torque produced by a cylinder which is rotated at constant speed

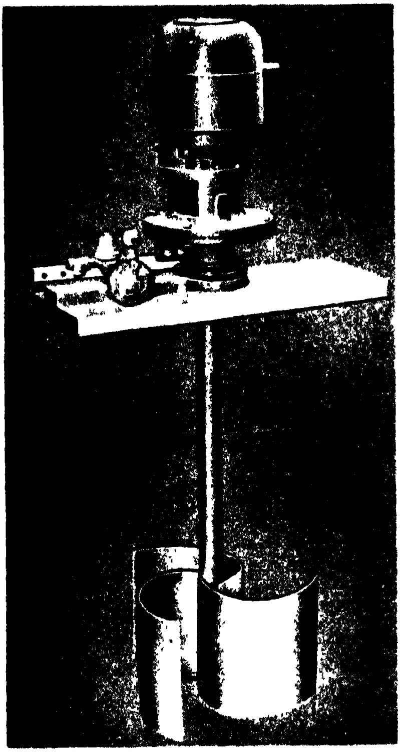


Figure 7-2. Viscosity instrument. (*Courtesy of DeZurik Shower Co.*)

in the viscous material. The torque is converted into an electric signal. This is accomplished by connecting a motor-driven shaft with the cylinder through a spiral spring. Due to the viscous drag of the fluid under measurement, the motor shaft winds up the spiral spring by an amount proportional to the viscosity. Having wound up the spring, the driving shaft and the cylinder rotate at the same speed but with a definite angular relationship to each other, which is proportional to the torque on the spring.

The principal method of converting this angular relationship into an electrical signal is by variable capacitance. One plate of a capacitor is attached to the driving shaft, the other to the cylinder. The magnitude of capacitance depends on the air space between them, *i.e.*, on the angular displacement between shaft and cylinder. The plates are connected through slip rings to outside terminals. The measuring instrument, likewise connected to these terminals, measures the capacitance and expresses the values in terms of viscosity.

Another means of signal conversion is by variable resistance. A potentiometer rotates with the driving shaft and its rotor is connected to the cylinder. The angular relationship between driving shaft and cylinder is in this case expressed by the angular position of the rotor. Connection by slip rings to the rotating parts is provided as before. The measurement circuit in this case is quite similar to that of a resistance thermometer, with the resistance temperature detector replaced by the potentiometer.

The speed for the rotating agitator wheel or cylinder must be relatively slow. Generally, it is about 50 rpm. A gear train is hence required to reduce the speed of the electrical motor.

The Vickers viscosity measuring system uses a hydraulic motor to drive the stirrer. A hydraulic pump drives oil at a constant rate through the hydraulic motor. The result is a constant motor speed with an oil supply pressure changing in direct proportion to the torque, hence to viscosity. Since these units come in practically any power rating, they may be used either to drive a sample stirrer or to drive the agitator of a process mixer and measure viscosity simultaneously, as illustrated in Figure 7-3. This method has certain advantages. One is the inherent explosion-proof nature of the hydraulic motor. Another is the great simplicity: a pressure gauge suffices to measure viscosity. The hydraulic viscosity meter can stand any amount of overloading. When the load exceeds the rating the fluid motor stalls. But the moment that the load returns to normal it resumes normal operation. What happens is that under overload the hydraulic pump discharges over a relief valve without damage to any part until normal conditions are restored.

The model shown in the illustration provides adjustment of speed by changing pump displacement. Thus the system can be adjusted for the desired speed and will then maintain it. The absence of gear trains adds to over-all simplicity.

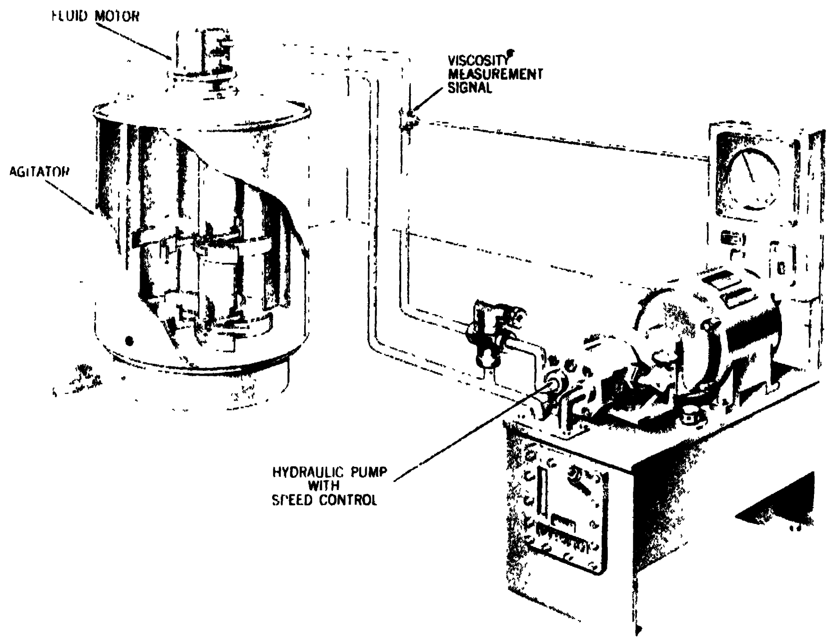


Figure 7-3. Hydraulic viscometer. (*Courtesy of Vickers, Inc.*)

Another method measures the power input to an electric mixer motor and thus determines the viscosity. An appropriate device is, for example, the Bristol Thermoverter. This is a transducer which first converts a.c. electric power into heat, and then converts this heat into a d.c. millivoltage by means of a thermocouple arrangement. A potentiometer or millivoltmeter indicates or records this d.c. millivoltage which is an indicator of power input, *i.e.,* of viscosity.

Ultrasonic shear waves are measured by the Ultra-Viscoson to determine viscosity. This instrument is made by Bendix Aviation Corporation. A thin alloy steel blade on the end of a probe is excited with a short electric pulse. This produces ultrasonic shear waves in the material surrounding the blade, causing layers of the material to slip back and forth. An electronic computer converts the energy required to produce the sliding motion into viscosity measurements on the dial of the computer or on any other suitable instrument connected with the system.

The Bendix Viscomparator is a modification of the Ultra-Viscoson. It measures and controls viscosity by continuously comparing the process fluid with a reference sample of the desired product. This sample is inserted in a well in the process line and is thereby maintained at the process temperature. This largely eliminates the error caused by viscosity changes due to temperature. The process fluid and the reference fluid are both exposed to the same temperature change, hence the difference between the two viscosities remains largely the same. If, however, the viscosity in the process fluid changes without being caused by temperature variations, then control action will be initiated.

The pressure drop of a fluid flowing at constant rate and without turbulence will change with its viscosity. This fact is utilized in Fischer & Porter's Plastometer, illustrated in Figure 7-4. The Plastometer is used primarily for measuring the consistency of fibrous or pulpy slurries. A sample of the slurry is pumped at a constant rate through the flow bridge. The different lengths and diameters of passageways will produce different pressure drops so that a differential pressure results between high-pressure tap and low-pressure tap. The differential pressure increases with the consistency of the slurry. It is converted into a pneumatic signal by the differential pressure transmitter, and, as shown, a control valve can be positioned from the controller in response to the signal of

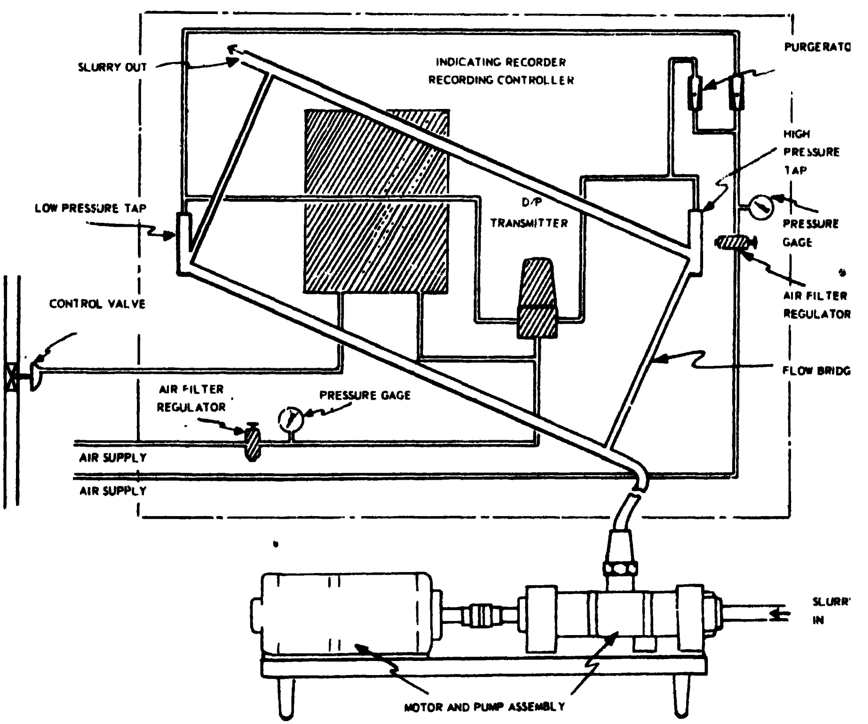


Figure 7-4. Plastometer. (*Courtesy of Fischer & Porter Co.*)

the transmitter. Air purges are provided at both the high-pressure and the low-pressure taps to prevent the slurry from entering the measuring lines and plugging them up.

The Hallikainen Viscometer was developed by the Shell Development Company to continuously measure and record the viscosity of lubricating oils and other petroleum products. It contains a capillary tube through which the process liquid is forced at a constant velocity and constant temperature. One end of the capillary is open to atmosphere. Thus, the pressure of the process liquid at the entrance to the capillary varies with viscosity. A pneumatic pressure transmitter measures this pressure and converts it into a 3 to 15 psig pneumatic signal. The choice of capillary permits measurement to be made over a wide viscosity range.

8. Speed

Speed as a variable in industrial processes usually refers to the revolutions per minute of some piece of rotary equipment. The most frequently used device in the measurement of revolutions per minute is probably the magneto. It is connected to the shaft under measurement either directly or by some suitable type of transmission, and consists of an electric generator with an emf output proportional to its angular velocity. The output is either direct or alternating current. Where a d.c. output is used the magneto is equipped with commutator and brushes which require a certain amount of maintenance. The a.c. magneto is simpler in this respect; on the other hand, the d.c. magneto is usually more accurate.

General Electric makes two types of a.c. magnetos, one a low-speed and the other a general-purpose model. The low-speed range goes up to 500 rpm and the maximum range of the general-purpose type is 0 to 3600 rpm. The magnetos are totally enclosed, ball-bearing inductor alternators equipped with permanent magnets. The accuracy is ± 4 per cent of full scale.

Barber-Colman makes a.c. and d.c. tachometer generators. The a.c. model is actually a reversible, shaded pole motor which fulfills the requirements of a low cost and rugged tachometer. With rated a.c. voltage applied to the main winding, a voltage is generated in the shading windings which is proportional to the speed at which the rotor is driven. This voltage is accurate within about 2.5 to 4 per cent in the range of 1000 to 3000 rpm. At speeds outside these limits the non-linearities increase. Such accuracy figures are predicated on a regulated power source since the generated voltage is also proportional to the exciting voltage.

The Esterline-Angus tachometer is of the d.c. type. It is calibrated to develop an open circuit emf of 25 volts at 1000 rpm. The armature rotates in a magnetic field produced by an Alnico V magnet. This armature is of the slotted iron-core type and is made up of laminations. The accuracy can be calibrated to within 3 per cent. A speed range of 50 to 5000 rpm can be covered.

The Metron tachometer (Metron Instrument Company) employs a rotary switch to sense speed. This switch charges and discharges a capacitor to produce impulses proportional to speed. These impulses register as steady readings on a d.c. indicator or recorder. Metron tachometers are inherently accurate to within one per cent of full scale. By adding simple circuits, such as bridges, and calibrating the output, accuracies to within 0.25 per cent of the measured speed can be obtained. Typical speed ranges are 5 to 100 rpm, 100 to 5000 rpm, and 5000 to 30,000 rpm.

The turbine flow meter (*cf.* Figure 4-60), which was discussed in chapter 4, measures speed of a propeller by electromagnetic impulses. The same principle is used in the magnetic type Rotopulser made by the Dynapar Corporation. It uses a rotor with individual teeth. Pulses are produced as the shaft rotates the teeth through a magnetic field. The pulses per unit time are counted by suitable electronic circuits and displayed as speed in corresponding readouts. Speed ranges from 10 to 20,000 rpm are available. One miniature high-speed unit can be used with speeds up to 60,000.

A photoelectric model of the Rotopulser by the same manufacturer is also available. It rotates a pulse disc between a light source and a silicon photocell. As the disc rotates, the beam is periodically interrupted, thus feeding pulses to a controller, indicator or recorder. Speeds up to 20,000 rpm can be accommodated.

Taylor developed a pneumatic speed transmitter which converts revolutions per minute into an air pressure signal of 3 to 15 psig which is transmitted to a receiver. A square root scale or chart is used in the receiver, since the output air pressure of the transmitter varies as the square of the shaft speed. Flyweights are connected to a rotating table which is secured to a drive shaft. The flyweights thus rotate at the same rate as the shaft. The centrifugal force exerted by the flyweights is converted into an upward motion of a non-rotating vertical spindle, and this motion is transmitted to a rocker arm. The rocker arm operates a pilot valve which determines the output pressure of the speed transmitter. This output pressure is also applied to a feedback bellows which in turn exerts a downward force on the vertical spindle. The resulting balanced position of the vertical spindle and with it the position of the pilot valve is thus proportional to the centrifugal force exerted by the flyweights.

In operation, a very small change in the radial position of the flyweights will produce full movement of the air pilot valve. Since the radius is essentially constant, the centrifugal force of the flyweights increases as the square of the speed. Hence, the air pressure to the bellows, which is also the output air pressure varies as the square of the speed. Maximum flyweight speeds from 600 to 1500 rpm are available. Where the shaft speeds are below or above this range, suitable gear transmissions are used.

The Foxboro pneumatic speed transmitter is illustrated in Figure 8-1. It measures rotational speed of machinery from zero to 6500 rpm and converts the speed into a proportional pneumatic signal of 3 to 15 psi. The input shaft, *A*, carries an eight-pole permanent magnet *B*. Disc *C* is fastened to flexure pivots *D* to which force bar *F* is also attached. Deflection of the disc and force bar is restrained by spring *J*. Magnetic flux lines link the magnet with disc *C*. Clockwise rotation of the magnet produces a torque on the spring-restrained disc. The torque then positions the force bar *F* in relation to nozzle *G* and thus increases the nozzle back pressure. This back pressure, amplified by relay *H*, produces an output pressure which is the transmitted 3 to 15 psi air signal.

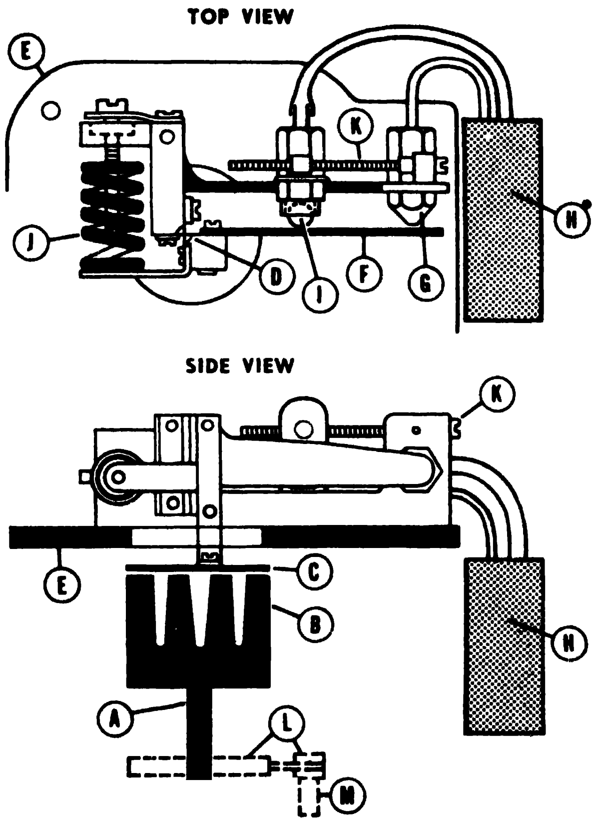


Figure 8-1. Pneumatic speed transmitter. (*Courtesy of Foxboro Co.*)

The output pressure is also connected to the ball feedback unit, *I*, which rides against the force bar. The feedback unit is a small open-ended cylinder in which a ball acts as a free floating piston. The force produced by the ball on the force bar balances the torque on the disc produced by the rotating magnet. Since this torque is proportional to the speed of rotation of the magnet, the output pressure is also proportional to this speed. The zero spring, *J*, is adjusted to produce the desired output pressure at zero rpm. The relation of the ball feedback unit to the axis of the disc is determined by a fine-range adjustment screw, *K*. Greater changes in range may be made by a series of fixed ratio drives, *L*, between the input shaft, *A*, and the integral speed changer input shaft, *M*.

9. Analysis

Analytical instruments described in this chapter are those most frequently found in process industries. Before describing details, the principal methods and applications are surveyed.

Heat of combustion is measured to detect combustible gases including carbon monoxide and oxygen. Air or hydrogen is added to the gas sample which is then burned off by a hot filament. The temperature of the filament is measured either by determining its resistance change or by using a thermocouple.

Thermal conductivity of a mixture can be measured by determining the cooling effect on a heated wire in a chamber into which sample gas is admitted. The resistance change of the wire is the measured variable. The technique can be applied to carbon dioxide, helium, hydrogen and other gases with thermal conductivities that differ sufficiently from background gases.

Chromatography is used for detecting butane, carbon monoxide, carbon dioxide, methane, and other substances. A carrier gas is usually added. The sample is vaporized. Thermal conductivity is then measured or, occasionally, the ionization potential is measured after mixing sample, carrier gas and hydrogen and burning the mixture. The sample is analyzed for several substances by first filtering the mixture through a porous medium. The migration rate changes from substance to substance, each one emerging subsequently from the filtering process.

Paramagnetism is measured to determine primarily the concentration of oxygen which is highly paramagnetic. The technique consists in having the sample pass by a chamber with a magnetic field. The chamber contains a heated wire. Heat loss from the wire depends on the amount of oxygen drawn into the magnetic field. The oxygen loses its paramagnetism when heated and flows on.

Colorimetry is a measurement of visible light that is either transmitted through or reflected by a sample. The detector is generally a photocell. It is used with dyestuffs and pigments and in determining turbidity in many liquids. By mixing the sample with a reagent, analysis of the concentration of specific chemicals such as dissolved oxygen, hydrazine, hydrogen sulfide, nitric oxide, phenol and phosphate is made possible. Water hardness is also measured by colorimetry.

Ultraviolet analysis is applicable to aromatic and other double-bonded organic materials, such as acetone, benzene, carbon disulfide, chlorine, halogenated hydrocarbons, nitrogen dioxide, and ozone. An ultraviolet light is used. The light intensity is measured generally by a photocell after passing the light through the sample. The absorption of ultraviolet radiation is thus determined.

Infrared analysis can be applied to most any fluid, except to diatomic gases such as oxygen, hydrogen, nitrogen, etc. The absorption of infrared radiation by the sample is measured by directing infrared light through it and measure its heat effect after passing through the sample.

Refraction techniques can be applied to transparent solutions, such as acids, bases, alcohol, ether, phenol, sugars, fruit juices and oils. The diffraction of a light beam is measured by means of a photocell after the light is passed through the sample.

Change of volume is a technique applied to carbon dioxide analysis. A measurement is made of the volume of the sample before and after the carbon dioxide has been absorbed by a selective agent.

Density is measured by the comparative torque exerted by the drag of gases of different density. This method is primarily used to measure carbon dioxide.

Electrolytic conductivity of a solution can be measured. This may either be the process fluid or in case of gases, it may be a liquid in which the sample gas has been dissolved. The technique may be used to determine the concentration of carbon dioxide, chlorine, hydrogen sulfide, sulfur dioxide, and other chemicals.

Amperometry determines the electrical conductivity by applying a current to the solution after adding a reagent to the sample. It is generally used for chlorine.

pH is measured by the magnitude of an electric potential across a glass-electrode membrane. It determines the acidity or alkalinity of solutions.

Oxidation-reduction potential is the oxidizing or reducing power of solutions. It is measured by the same method as pH is measured.

The dielectric constant is determined by measuring the capacity of the sample. It is used to detect water in organics and different grades of petroleum production in pipelines.

Electrochemical reaction is used for oxygen measurement. Since the output of a galvanic cell increases with the extent of depolarization caused by the oxygen in the sample, it becomes an indication of oxygen concentration.

Flash point control is used with distillate fuels. It determines the temperature at which a sample ignites.

HEAT OF COMBUSTION

Figure 9-1 shows a Bailey combustion analyzer which records the per cent oxygen and the per cent combustibles in a gaseous mixture. These are impor-

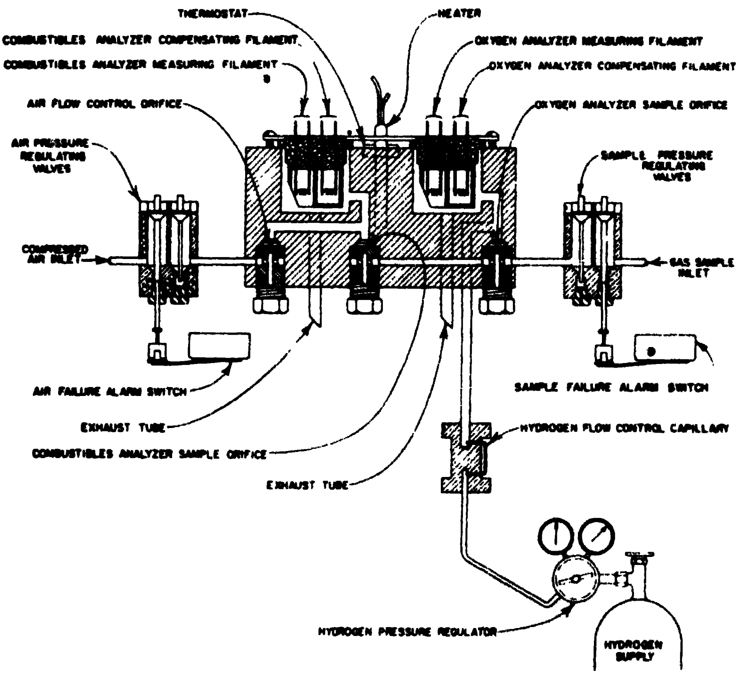


Figure 9-1. Schematic of O_2 or combustibles analyzer. (*Courtesy of Bailey Meter Co.*)

tant measurements in combustion because the oxygen content of the stack gases is an indication of excess air admitted to the combustion while the content of combustibles is a guide to the fuel-air mixing performance. The gas to be analyzed is tapped and a sample is continuously drawn into the analyzer. Pressure regulating valves keep the rate of flow of the gas sample to the analyzer constant. Regulated amounts of air and hydrogen are added to the combustibles and to the oxygen units, respectively. The temperature of the gas sample is maintained at approximately 160°F by the heater in the analyzer block. Each analyzing cell contains two identical noble-metal catalyst filaments mounted on a common base. The measuring filament is completely exposed to the gas mixture entering the cell while the compensating filament chamber is closed on all sides, except for an access hole which allows a small amount of gas sample to enter. Since the physical properties of the gas such as thermal conductivity and specific heat have the same effect on both filaments, their effects are balanced out.

Figure 9-2 is a schematic diagram of either the oxygen or the combustibles analyzer, since their circuits are identical, showing the connection of the filaments with the instrument circuit. It is evident that they form two legs of a

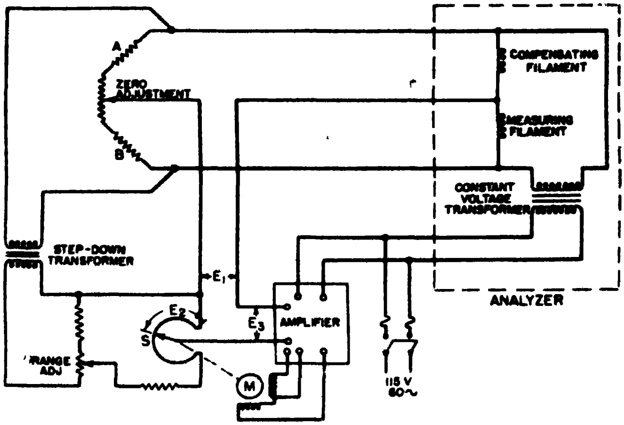


Figure 9-2. Schematic of O_2 or combustibles recorder circuit (*Courtesy of Bailey Meter Co.*)

Wheatstone bridge. As the air-gas sample mixture passes over the red hot "combustibles" filament, it burns off whatever combustible components are present. As the hydrogen-gas sample passes over the red hot "oxygen" filament, the hydrogen will burn if there is oxygen present to support combustion. In the "combustibles" part of the analyzer the heat liberated by the combustion, or rise in filament temperature, is proportional to the combustibles content of the sample. In the "oxygen" part the rise in filament temperature is proportional to the oxygen content of the sample.

The rise in filament temperature increases its electrical resistance. Hence by measuring the electrical resistance, the percentages of oxygen and combustibles in the gaseous mixture can be determined.

Figure 9-2 shows that a constant-voltage transformer supplies power for the measuring bridge which is composed of the measuring filament, the compensating filament, fixed resistors A and B and the zero adjustment potentiometer. The constant-voltage transformer also feeds a step-down transformer which supplies voltage to the measuring slidewire S. Range adjustment is supplied by a potentiometer installed in parallel with the slide-wire.

The measuring bridge is adjusted by means of the zero adjustment to have zero output voltage E_1, when no oxygen or combustibles, depending on which is being measured, are present in the gas sample and the recording pen is on zero. This balances a zero output voltage E_2 from the measuring slide-wire. As the filament temperature increases because of an increase in oxygen, or combustibles, in the gas sample the bridge output voltage E_1 increases. This imposes a voltage on the amplifier, causing it to operate the slide-wire drive motor until the measuring slide-wire voltage E_2 balances the measuring bridge output voltage E_1. As this balance is reached, the input voltage E_3 to the amplifier drops to zero and the system is in equilibrium with the instrument pen recording the per cent oxygen, or combustibles, present in the gas sample.

Oxygen analyzers and combustibles analyzers are available separately or in a single unit. In the Davis thermocouple-type analyzer for combustible gases, the filament is not part of the measuring instrument, but a thermocouple is tied to the filament and used to measure the temperature of the filament under the combustion atmosphere of the gas or vapor-air mixtures. A second thermocouple is exposed to a similar filament contained in an air-filled sealed capsule. The difference between the emf output of the two thermocouples is measured and the instrument is calibrated in per cent of combustible gases. The double filament arrangement compensates for changes in supply voltage as well as in ambient temperature.

This instrument permits scanning and recording continuously up to eight different points. A commutating valve driven by a small synchronous motor continuously tours the sampling points, and a rotary vane air pump directs the flow of gas or vapor from each sampling point through the analyzing cell. Between each sampling, air is pumped through the cell to prevent signal carry-overs from one point to another. The commutating valve is designed to dwell 30 seconds, including purge time, on each sampling point. This means that in a four-point system a measurement of one particular point is taken every two minutes, and in an eight-point system every four minutes. In the recording system the valve and recorder are connected electrically in such a manner as to insure synchronization between chart record and sampling point.

THERMAL CONDUCTIVITY

The amount of heat per unit time that travels through a body of given thickness when a given temperature difference exists across it depends upon the thermal conductivity of the body. For example, the thermal conductivity of air is about 1.36 times greater than that of carbon dioxide, which means that 1.36 more heat units will travel through a given volume of air than would travel through carbon dioxide under the same conditions. Even a small percentage, say 1 per cent, of CO_2 in a gas mixture will decrease its thermal conductivity to a measurable degree. If a heated filament is in an atmosphere of the gas under measurement, its temperature will depend on heat conducted away by the cooling effect of the surrounding gas. The cooling effect is thus a function of the thermal conductivity which in turn is a function of the constituents of the gas.

Figure 9-3 shows a typical electrical circuit as would be used, for example, with a Gow-Mac cell. This cell contains 4 filaments of which two, *A* and *B* in Figure 9-3, are exposed to the gas being analyzed. The other two filaments, *C* and *D*, are sealed in a capsule containing air or some other gas as reference.

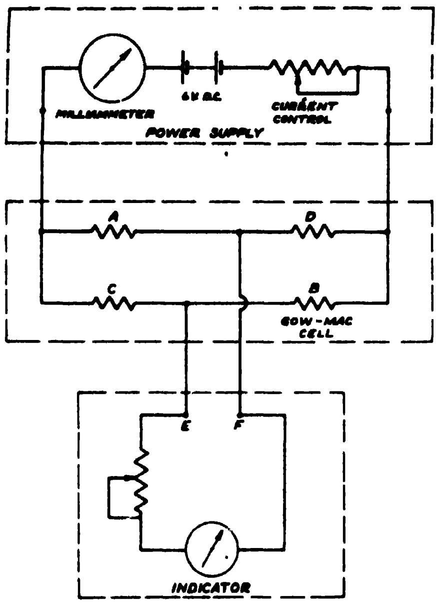


Figure 9-3. Schematic of Gow-Mac System.

The indicator reads zero as long as filaments *A* and *B* are also exposed to air. All four filaments dissipate a certain amount of heat because of the current flowing through them. If a slight amount of CO_2 is added to the air to which *A* and *B* are exposed, the temperature of *A* and *B* will increase because the thermal conductivity of the surrounding atmosphere decreases. The consequence is a change in electrical resistance of *A* and *B* as a function of the change in temperature. This causes an unbalance in the bridge which is shown by the indicator.

The wire filaments can be replaced by thermistors. Their larger change in resistance per degree Fahrenheit at low temperatures makes them desirable where high sensitivity is needed. They are used particularly where gases at room temperature or below are analyzed. In thermistor networks, resistances *A* and *C* are replaced by thermistors and exposed to the analyzed gas, while resistances *B* and *D* are exposed to the reference gas and continue as wire-wound resistors.

The temperature of the cell block must be held within ± 0.1°C or better to avoid temperature effects.

If a gas mixture is composed of more than two components, or if thermal conductivities of the gases are nearly equal, concentration of one component cannot be measured by the thermal conductivity effect alone. In this case the M-S-A Thermatron (Mine Safety Appliances Co.) can be used. It measures thermal conduction as well as thermal convection. Heat transferred by the convection flow of a gas along a heated filament depends on density, specific heat, viscosity and other factors. Combining the principle that each gas has its characteristic thermal convection loss with the principles of thermal conductivity, sensitive selective measurement of one component in a complex gas mixture is possible.

The Thermatron cell consists of two pairs of filaments. One pair for the reference gas, the other for the sample gas to be analyzed. Each pair has two filaments. One in the conduction well, the other in a convection well. The difference between the two wells consists in making the space between filament and heat-conducting wall as small as possible in the conduction well, and as large as possible in the convection well. The small interspace limits convection current and most of the heat from the filament through the gas to the wall is carried by conduction. The large interspace encourages convection currents of the gas along the filament and the heat loss is mainly through convection. All four filaments are connected in a Wheatstone bridge.

CHROMATOGRAPHY

Analytical methods for gases and liquids with boiling points of up to 450°C have more and more been taken over by gas chromatography. These instruments are relatively low in cost and simple in operation. The Perkin-Elmer Vapor Fractometer, for example, is based on the principle of gas chromatography. This technique consists of passing a vaporized mixture through a packed column by means of a carrier gas. The rates at which individual components move through the column depend on their respective affinities for the column material. Therefore, the different components emerge from the column in a sequence which depends on the relative affinity of these components for the particular column packing. As each component exits separately from the column, it is measured by a sensitive detector. The diagram of Figure 9-4 illustrates the typical cycle. The carrier gas, supplied from an external gas bottle, is maintained at a constant flow rate by a conventional pressure regulator. Carrier gas passes through a flow meter and by the reference side of the detector before it reaches the point where the sample to be analyzed is introduced. At the sample injection point, a small flash heater is provided to vaporize the sample immediately. Carrier gas and sample vapor then pass through the column into the sensing side of the detector. The reference and sensing sides of the detector are similar to the thermal conductivity cells already described. They are part of a Wheatstone bridge. When a thermal conductivity difference

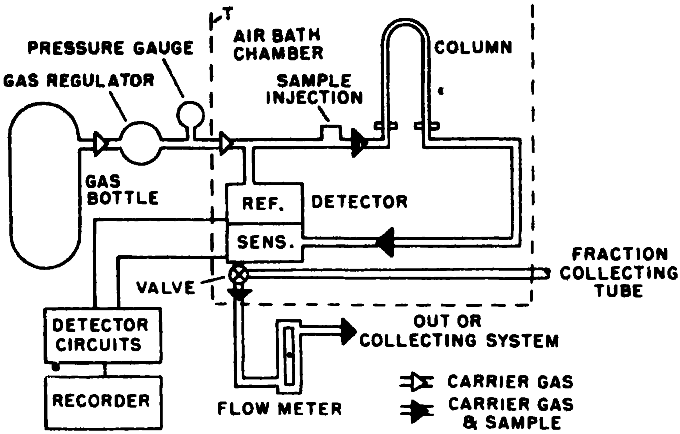


Figure 9-4. Diagram of gas chromatograph. (*Courtesy of Perkin-Elmer Corp.*)

occurs between the two sides of the detector, the resulting bridge unbalance provides a voltage which drives a standard strip-chart recorder. The carrier gas and sample then pass out to the atmosphere or to a collecting system.

A particular application of this analyzer is the Perkin-Elmer Furnace Atmosphere Analyzer. Every 10 minutes, a programmer automatically initiates a 4-component analytical cycle. Usually the materials analyzed are oxygen, carbon dioxide, carbon monoxide, and methane. The concentration of each component in per cent of total volume is directly recorded in bar graph form on the recorder. The operator can then make adjustments necessary to maintain proper atmosphere composition.

Thermal conductivity cells are the most common detectors. Other methods are occasionally used. For example, Beckman provides a hydrogen flame detector for cases where extreme sensitivity is required, such as detection of the presence of minute traces of organic compounds. The carrier gas sweeps the sample flow into the burner assembly where it is mixed with hydrogen gas. The mixture is ignited by a platinum wire and burns in a combustion atmosphere of air or oxygen that is diffused around the burner from the flow control system. The temperature of the hydrogen flame causes ionization. The result is a measurable electrical potential between the burner and an electrode located above the burner. Measurement of this potential provides a signal which is proportional to the number of carbon atoms passing through the flame.

PARAMAGNETISM

Oxygen is unique among common gases in that it is highly paramagnetic, *i.e.*, it tends to move into a magnetic field. Most common gases are slightly diamagnetic, *i.e.*, repelled from a magnetic field. The only gases in addition to oxygen which are paramagnetic are some of the oxides of nitrogen; nitrogen dioxide, for example, has about 45 per cent of the magnetic deflection of oxygen at standard conditions.

This paramagnetic property of oxygen, combined with the fact that it loses its magnetism in proportion to the square of its temperature increase, has been used in the Magno-Therm oxygen recorder made by the Hays Corporation. Its operation is illustrated in Figure 9-5. The complete analyzing assembly consists of a gas passage block, a gas diffusion block and a cell block. The cell block is constructed of non-magnetic metal with tapered plugs of magnetic metal inserted through opposite walls of the measuring cell. A strong Alnico magnet embraces the measuring cell with its pole faces in contact with the magnetic plugs. In this way a concentrated magnetic field is made to pass through the measuring cell.

Electrical resistance heaters are inserted into both the measuring and the comparison cells. These resistance heaters are connected with a Wheatstone bridge. The bridge compares the flow of current in the resistor in the comparison cell with the flow of current in the resistor located in the magnetic field of the measuring cell.

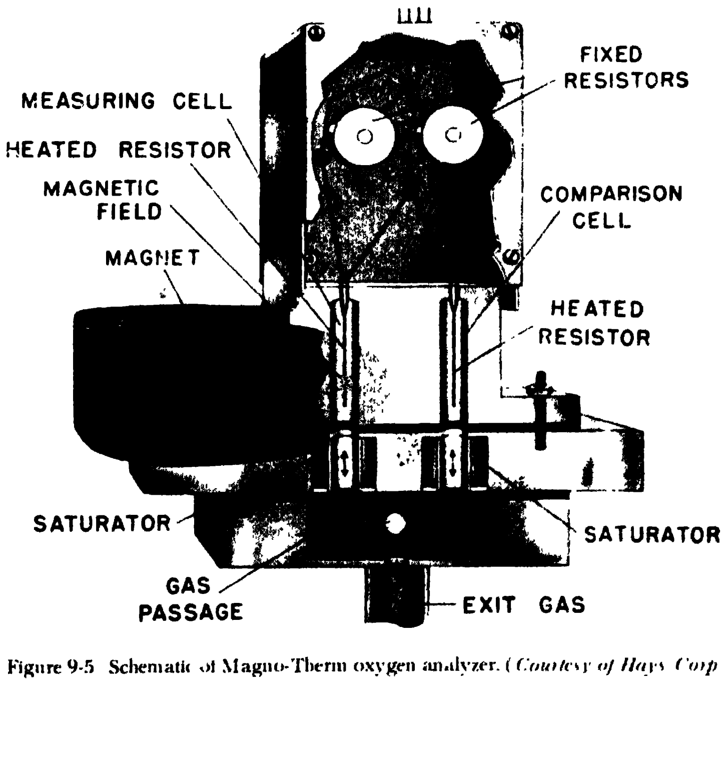


Figure 9-5 Schematic of Magno-Therm oxygen analyzer. (*Courtesy of Hays Corp.*)

A sample of the gas to be analyzed flows through the gas passage block. A portion of this sample diffuses upward through the diffusion block to the lower part of both the measuring and comparison cell. Gas diffuses into both cells and cools the heated resistors because of thermal conduction of the gas. As the oxygen-bearing gas is attracted into the magnetic field it cools the heated resistor in the measuring cell and in doing so increases its own temperature. As a consequence of the temperature rise, the oxygen loses its magnetism very rapidly. The heated, de-magnetized gas is moved out of the magnetic field and upward along the resistor by cooler, more magnetic oxygen bearing gas from below. The moving gas continues to absorb heat from the resistor and, in its downward path along the walls, releases heat to the cell block. Continuous flow of the gas sample is thus magnetically induced, causing a flow rate and cooling effect in definite relation to the magnetism of the gas entering the measuring cell.

The cooling of both the measuring cell and comparison cell resistors cause their electrical resistance to be reduced. The Wheatstone bridge measures the relative cooling of the measuring cell as compared with the comparison cell which indicates the oxygen content of the gas.

The cell block is in a glass wool-insulated metal case. The case temperature is held constant by a heater controlled by a thermostat. This temperature control reduces errors that would otherwise be caused by variable ambient temperatures.

Automatic compensation for atmospheric pressure variations is incorporated into the analyzer so that the reading is on a true per cent volume basis. The compensator consists essentially of a resistance that changes its value in proportion to the absolute pressure of the gas sample. The resistance is connected with the circuit of the instrument to correct the reading for the variation in gas sample pressure.

This analyzer is made in ranges from 0–5 per cent to 0–25 per cent. For smaller ranges, such as 0–1 per cent to 0–3 per cent, a low-range oxygen analyzer is available from the same manufacturer. It is illustrated in Figure 9-6. Two resistance heaters, $3a$ and $3b$, are again part of a Wheatstone bridge. These heaters are wound on the outside of a glass tube, 1, which is mounted horizontally in the ring-type gas passage block 2. Winding $3a$ is between the poles, 4, of a permanent magnet.

Sample gas flows through the gas passage block from 5 to 6. The oxygen, because of its paramagnetism is attracted into the glass tube by the magnetic field between the permanent magnet poles. This gas is heated by winding $3a$, decreasing the magnetic susceptibility of the gas. Cooler gas entering the tube pushes the heated gas at winding $3a$ out of the magnetic field, producing a continuous gas flow from $3a$ to $3b$. This cools winding $3a$ and heats winding

3*b*. The resulting temperature difference changes the resistance of windings 3*a* and 3*b*, unbalancing the Wheatstone bridge circuit. This unbalance is proportional to the amount of paramagnetic gas present in the sample gas. The unbalance is readily measured as a voltage, amplified and transmitted to an indicator or recorder.

The above methods for measuring oxygen content of gases are also used to analyze and continuously record dissolved oxygen in surface waters. According to the so-called Henry's Law, the partial pressure of oxygen above a water surface—at equilibrium—is a direct measure of the amount of oxygen dissolved in the water. Operation is as follows:

The sample inlet is immersed in the water to be analyzed. Sample water is pumped through a pressure regulator into an aspirator where the water is

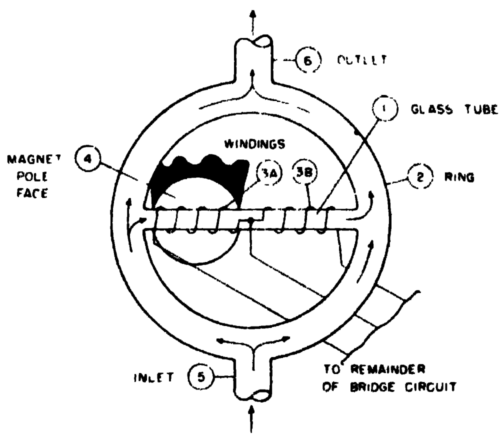


Figure 9-6. Schematic of low-range oxygen analyzer. (*Courtesy of Hays Corp.*)

thoroughly mixed with nitrogen gas. The water and gas mixture is then forced into a separator where the gas is centrifugally separated from the water. At this point, the water is discharged from the separator while the gas flows through the magnetic oxygen analyzer where its oxygen content is measured. This content is measured as a proportionality to the amount of oxygen dissolved in the water.

COLORIMETRY

Colorimetry determines primarily the color imparted to process streams by the presence of colored substances as well as colors that result from adding a reagent to the product. In a modified version—turbidimetry—it is concerned with the clarity of a sample, *e.g.*, the detection of particles, bubbles, immiscible droplets, or other opalescent matter.

The Beckman Turbidimeter-Colorimeter performs either type of service. The instrument consists basically of two units—the control unit and the analyzer unit. The control unit consists of an amplifier, an indicating meter, and the standardization controls. The analyzer unit, as illustrated in Figure 9-7, contains the light source, a sample cell, and a photocell detector. The sample flows continuously through the sample cell which is located between the light source and the detector. Collimated light passes into the sample compartment where it is absorbed, or scattered by the sample. The amount of light passing through the sample to the detector diminishes as the intensity of color or the concentration of solids in the sample stream increases. A phototube in the de-

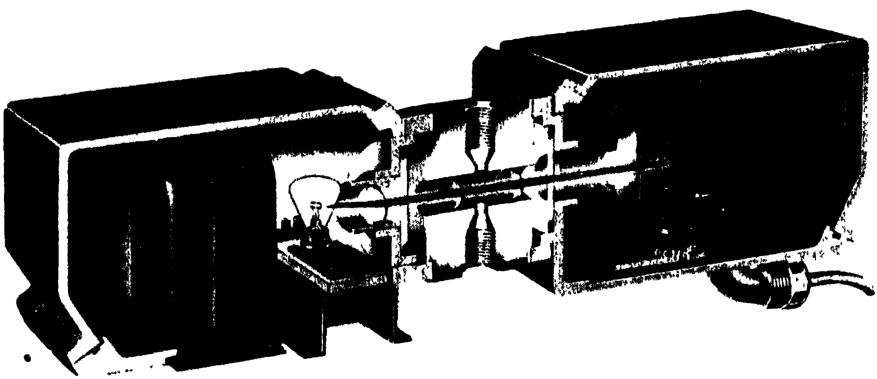


Figure 9-7 Beckman turbidimeter-colorimeter. (*Courtesy of Beckman Instrument, Inc.*)

tector measures the amount of transmitted light and generates a signal which is amplified in the control unit to drive the meter and, if desired, a conventional potentiometer-type recorder, or an alarm circuit. Proper choice of interference filters, phototube, and sample cell length make the instrument adaptable to a specific application. For example, filtering the light from the sample to minimize the effects of turbidity makes it sensitive to a particular wavelength band for accurate, reproducible colorimetric determinations. In a similar manner, filtering the light path to eliminate the effects of specific colors increases the accuracy of turbidity measurements.

The sensitivity of the Beckman instrument can be further increased by measuring the signal ratio from two phototubes. As the light emerges from the sample, a beam splitter divides it into two portions. One portion is detected by a reference phototube. The other portion is filtered to screen all but the wave-length being measured, and is detected by the measuring phototube. The two measurements are electronically compared as a ratio. This method makes the instrument respond to a particular color and automatically compensates for window dirt, turbidity, and light source variations that affect equally both the reference light and the measuring light.

The Rubicon H_2S Analyzer made by Minneapolis-Honeywell Regulator measures hydrogen sulfide concentration. It is used in the natural gas industry, in catalytic chemical processes, in monitoring stack gases from metallurgical operations or effluent gases from chemical processes prior to discharge to the atmosphere. The principle is illustrated in the schematic diagram of Figure 9-8. Gas is admitted from a sample line at approximately 2 psig, and passes

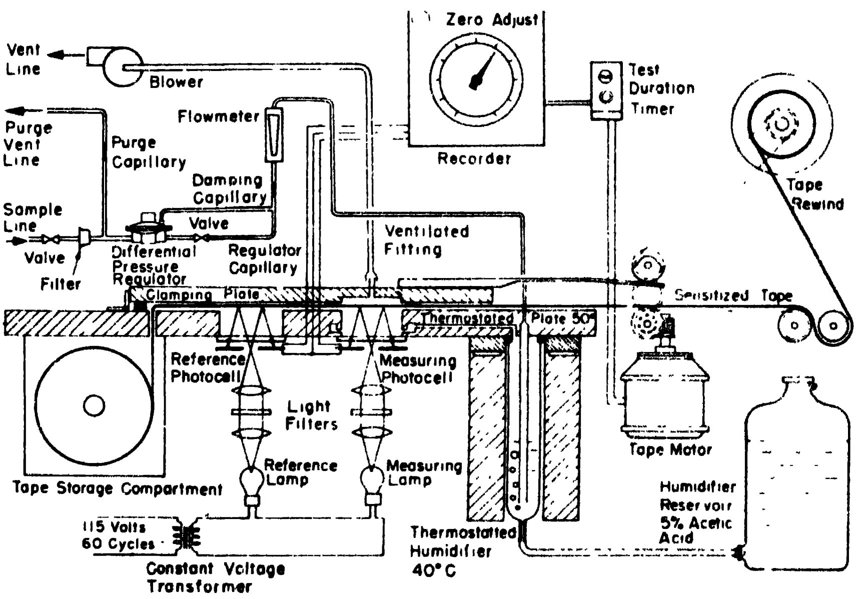


Figure 9-8. Simplified schematic diagram of Rubicon H_2S analyzer. (*Courtesy of Minneapolis Honeywell Regulator Co.*)

through filter, differential pressure regulator, and a flow meter, to the thermo-statted humidifier. Capillaries dampen out any sudden fluctuation which may otherwise pass the differential pressure regulator. In the temperature-controlled humidifier, the sample gas is made to bubble through a 5 per cent solution of acetic acid, and then flows through a passage in an aluminum plate thermo-statically controlled at 50°C. The sample then flows to the measuring cell, through the sensitized tape that crosses the cell, and finally into a vent line into which it is sucked by the blower.

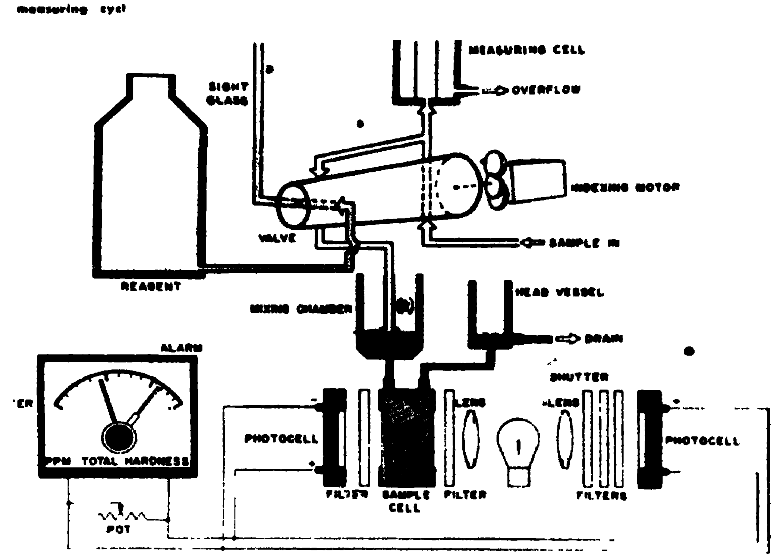
The sensitized tape is impregnated with lead acetate. It converts the hydrogen sulfide in the gas sample, regardless of concentration, to brown lead sulfide. The reflectance of the tape area subjected to the gas flow is compared by photocells to the reflectance of the clean tape. Two 6-volt lamps, optical filters, and the photocells produce a difference signal which is read by the recorder. The photocells are connected in a balanced bridge circuit.

A test duration timer is provided to control the interval during which the tape is exposed to the gas sample. By suitable prolongation of this interval (up to two hours) hydrogen sulfide concentrations of 1/10 part per million can be determined. Where the concentration is larger, the exposure time can be correspondingly reduced.

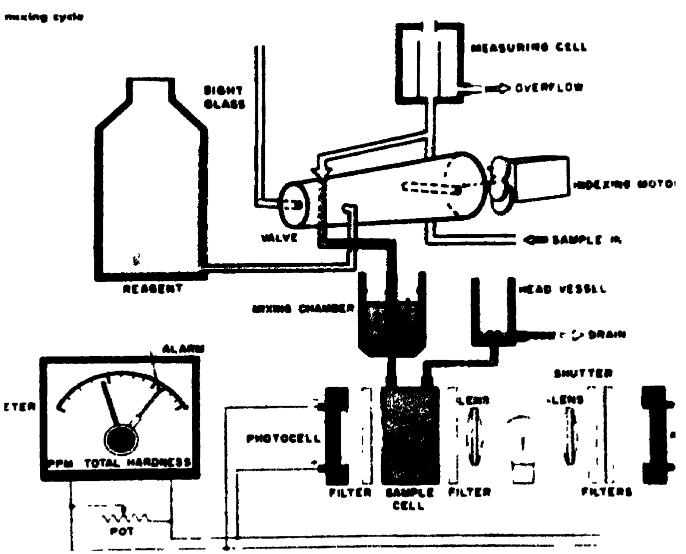
The chart record is a saw-tooth type, starting at zero for each test, gradually rising to the value representing the hydrogen sulfide concentration and returning to zero when the test is concluded.

The Milton Roy Company makes the Quantichem and the Chemalyzer, both colorimetric analyzers which use the color change of samples when reagents are added. The Quantichem is the more elaborate of the two models. It measures concentrations in parts per billion ranges with accuracies of 2 per cent of full scale. Typical determinations include soluble silica, dissolved oxygen, phenol, chromate and others requiring up to four chemical reagents.

The Chemalyzer is designed for simpler colorimetric analyses, such as water hardness, residual chlorine and phosphates. Figures 9-9 *a* and *b* show the principle of operation. Sample and reagent feed are controlled by a double-ported "Teflon" plug valve, driven by a small indexing motor through an arc of 90 degrees, first in one direction and then in the reverse direction. In the measuring cycle shown in Figure 9-9 *a*, the sample flows into the sample measuring cell and excess sample drains through the overflow. The reagent flows through the second port of the double-ported plug valve and seeks its own level in the reagent sight glass. As the motor-driven valve rotates, a measured quantity of reagent is trapped in the bore of the plug valve until the valve reaches the position shown in Figure 9-9 *b*. In this position, the sample measuring chamber connects to the reagent bore and both the measured sample and the reagent drain into the mixing chamber. From the mixing chamber, the reagent and sample flow to the optical sample cell where a color develops and interferes with the monochromatic light passing through the sample cell to one of the two photocells. The other photocell is exposed to the same light source but without the interference of the sample cell. The difference in light intensity impinging on the two photocells is then indicated in terms of the concentration of the unknown material such as water hardness. An adjustable



(a)



(b)

Figure 9-9. Operating principle of Chemalyzer. (*Courtesy of Milton Roy Co.*)

alarm contact is available with the indicator to close a relay when the measurement reaches a certain maximum.

The AutoAnalyzer made by Technicon Controls uses the color resulting from chemical reactions between different fluids. The sample is mixed with other specified chemicals, it may then be sent through a time delay coil to permit the reaction to take place, it may be filtered through a semi-permeable membrane in a so-called Dialyzer and the purified reagented sample may finally pass through a glass coil immersed in a controlled temperature bath. The different steps in the preparation depend on the material to be analyzed and the specific procedures worked out by Technicon Controls for every step. The fully prepared sample then passes through a colorimeter. A single light source is split into two beams. One beam passes through the sample to a photocell, the other passes to an identical reference photocell directly. To focus on a specific color, a filter is generally used between sample and light source. The ratio difference between the two cells is continuously measured. The result is a ratio comparison signal which is amplified and sent to a recorder.

ULTRAVIOLET ANALYSIS

Ultraviolet analysis measures the degree of light absorption as it occurs in a gas or liquid sample. Since it operates within a different band of wavelengths, it is mainly the nature of the sample that determines which method is used. In general, ethylene and carbonyl structures, molecules which include the benzene ring in their structure, such as benzene, toluene, and xylene, all absorb in the ultraviolet region.

Ultraviolet analysis is not as specific in determining the components as is infrared analysis, but it is a more sensitive technique. Also, aqueous samples can be analyzed by ultraviolet methods; while infrared analysis is limited since water absorbs in the infrared region and since the materials generally used for sample cell windows in infrared instruments are water-soluble.

The Hallikainen Ultraviolet Analyzer, which was designed by the Shell Development Company, is available for either gas or liquid analysis. Organic compounds such as aromatics, diolefins, ketones and aldehydes may be determined from a few parts per millions to high percentages. Inorganic gases and vapors such as ozone, chlorine, and mercury vapor may also be measured. The two major components of the analyzer are the optical unit and the electronic unit. In addition to these main units there are the test switch, test meter, and—generally—a constant voltage transformer. All components are enclosed in explosion-proof housings. Any standard millivolt recorder with a millivolts range of 0 to 10 may be used with the analyzer. Ultraviolet radiation from a single source is divided into a measuring beam and a reference beam. The measuring beam passes through the sample cell and falls on one phototube and the reference beam passes through a similar aperture and falls on a second phototube. When the concentration of an ultraviolet-absorbing compound in the sample cell changes, the ultraviolet transmission through the cell also changes, resulting in a corresponding change in current in the measuring phototube. The difference between the two phototube currents is displayed on the recorder, which is coupled to the phototubes through a simple differential cathode follower amplifier.

The phototubes are conventional ultraviolet-phototubes. The standard ultraviolet source is a mercury vapor lamp radiating primarily at 2537 angstrom. This source is useful in most applications but other sources are available. A cylindrical shutter surrounds the source and facilitates checking and adjustment of zero and span in plant service. An electrical heater controlled by thermostat provides a constant temperature environment for the source to ensure stability.

INFRARED ANALYSIS

Infrared analyzers, similar to ultraviolet and other analyzers, are primarily instruments that analyze a sample for all or at least a number of its constituents. However, when used for continuous measurement of a plant stream rather than for laboratory purposes, such analyzers concentrate on only *one* constituent.

When infrared light passes through certain gases or liquids a portion of the infrared spectrum will be absorbed. Carbon monoxide, carbon dioxide, ethylene, isobutane and many other substances have infrared absorption characteristics. Excluded are elemental diatomic gases, like oxygen, hydrogen, nitrogen, chlorine, etc.

Within the acceptable substances the concentration of any component in a mixture can be determined by the specific absorption pattern that is unique for each component.

The Mine Safety Appliances Company is the producer of the LIRA infrared gas and liquid analyzer. The principles of this analyzer were developed by Luft, and the trade name LIRA stands for Luft-type Infra-Red Analyzer.

Figure 9-10 shows the components and operation. Two similar "Nichrome" filaments are used as sources of infrared radiation. Beams from the filaments

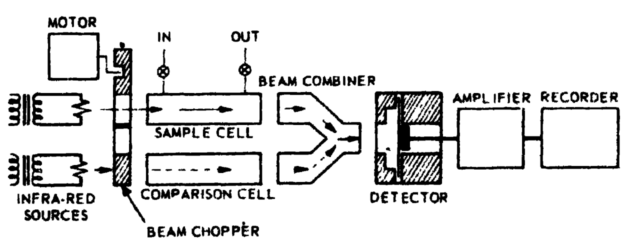


Figure 9-10. Schematic of LIRA infrared analyzer (*Courtesy of Mine Safety Appliances Co.*)

travel through parallel stainless steel cells. One beam traverses the sample cell and the other the comparison cell. The emergent radiation is converged into the single detector cell by a beam combiner which consists of two cylinders in the form of a *V.* As the gas in the detector absorbs radiation its temperature and pressure increases. The expansion of the detector gas causes a microphone membrane, which forms one plate of an air capacitor to deflect and hence to change the capacitance.

Between the source and the cells, a reciprocating metal slider alternately blocks the radiation to the sample cell and to the comparison cell. When the beams are equal, an equal amount of radiation enters the detector from each beam. The amplifier is tuned so that only variations in light intensity occurring at the alternating frequency produce an output signal. Therefore, since the beams are equal, the output is zero.

When the gas to be analyzed is introduced into the sample cell, it absorbs and thus reduces the radiation reaching the detector from the sample beam. As a result the beams become unequal and the radiation entering the detector flickers as the beams are alternated. The detector gas expands and contracts in accordance with the flicker. The expansion and contraction of the gas causes the membrane to move in response, changing the capacitance in the electronic circuit. The variation in capacitance generates an electric signal which is proportional to the difference between the two radiation beams. The signal is then amplified and fed to a recorder or indicator.

When the detector chamber is filled with gas it becomes sensitive only to those spectral regions in which that gas absorbs. Thus, other components are not measured unless they are substances which have absorption regions overlapping those of the gas in the detector cell.

Where measurement of one component of a mixture which also contains interfering gases is desired, the beam combiner is filled with the interfering products. This cell then acts as a filter and absorbs those regions of the infrared spectrum which are common, allowing the rest of the regions to be absorbed in the detector. Since the absorption in the beam combiner acts equally upon the radiation through the sample and through the compensator tube, the instrument maintains its selectivity.

REFRACTION

Refractive index is the ratio of the sine of the angle of incidence of a light ray to the sine of the angle of refraction. Some liquids have widely different refractive indexes. For example, the index of water is 1.33299, while that of benzene is 1.501 (at 20°C). Mixtures of substances of different refractive indexes can be frequently controlled because the resulting index informs about the relative quantities of constituents in the mixture.

The diagram of Figure 9-11 illustrates the operation of the refractometer made by Waters Associates. The instrument measures the amount a light beam is bent when the refractive index of a liquid sample changes. A light beam from an incandescent lamp is directed through a slit, mask and lens to the sample cell through which the liquid sample is flowing The beam passes through the sample liquid, the reference standard and the sample liquid again to a mirror mounted behind the sample cell. The mirror reflects the beam back through the cell for a second traversal of the sample liquid and the reference standard.

At this point, the location of the light beam depends upon the relative refractive indexes of the sample and the reference standard. The beam is then divided by a beam splitter mirror. Each half of the beam falls on a photocell.

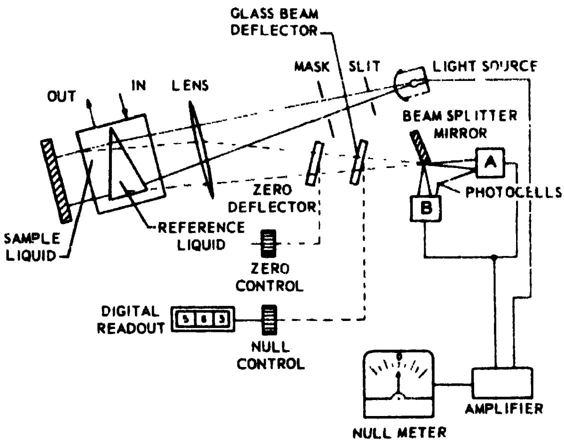


Figure 9-11. Diagram of digital refractometer. (*Courtesy of Waters Associates*)

Initially the reference standard and sample may have equal or different refractive indexes. The recorder is set to the proper zero reading by adjusting the mirror, the manual zero adjustment and the zero control knob. When this is done the amount of light falling on each photocell is equal. Any change in the refractive index of the sample liquid causes the beam to shift, and more of the light falls on one photocell than on the other. The photocell detector circuit becomes unbalanced and a signal is impressed on the amplifier. The amplified signal excites the recorder motor, and it drives the beam deflector in a direction that equalizes the light falling on the two photocells.

The more the refractive index of the sample deviates from the reference the greater the unbalance in the detector circuit and the more the deflector must turn to rebalance the split beam. The position of the deflector, therefore, is a measure of the refractive index of the sample. Since this is directly coupled to the recorder pen the recorder indicates differences in refractive index directly. The entire assembly of the Waters differential refractometer is mounted within a conventional strip chart recorder case.

The same company makes a refractometer which can be attached directly to the wall of a pipeline or tank. It dispenses with sample lines and reference liquid and is primarily designed for dark, extremely viscous liquids, or those that contain large amounts of solids. The light is beamed directly through a lens to a prism in contact with the process fluid. The beam is refracted at the prism-fluid interface and directed back to a deflector and photocell detector system similar to the one described above.

CHANGE OF VOLUME

The Orsat apparatus has been the accepted standard of flue gas analysis for many years. Its principle is to draw a certain amount of flue gas, usually 100 cc, into a graduated burette, then to pass it through a solution of potassium hydroxide or caustic potash which absorbs the CO_2 gas, and have it return to the graduated burette where it will then occupy a smaller volume because the CO_2 has been removed. The difference between the initial and the final volume is a measure of CO_2.

The Hays Combustion Meter operates on exactly the same Orsat principle of chemical absorption and volumetric measurement. The schematic of Figure 9-12 illustrates its operation. It is actuated entirely by water. Cardisorber is used instead of a potash or other solution to absorb the CO_2 gas. Each analysis cycle uses about one gallon of water. Incoming water passes through a filter, cooling coil *K*, and to aspirator *A*. Water flow continues through the aspirator into the overflow tank and enters the standpipe through orifice *X*. The aspirator continuously draws flue gas from the furnace. When the standpipe is drained, gas is drawn through the measuring chamber *B*. But when it refills over level *V*, gas is drawn through the bubbler, *D*, and aspirated at *A*. Bubbling through the shorter of the two tattler jar tubes is therefore normal, except when a sample is being drawn by the analyzer.

At the beginning of an analysis cycle, gas is drawn through tube 1 into the measuring chamber, *B*, and tubes 3 and 2. As water rises in the standpipe to level *V* a quantity of gas is trapped. Water continues to rise and pressure is equalized through tube 3. When water level is at *W*, measuring chamber *B* will contain a specific amount of gas at atmospheric pressure.

Water continuing to rise, pushes the gas sample from the measuring chamber through tube 4 into the absorption chamber *S*. Chamber *S* is packed with steel wool and filled with Cardisorber which instantly and completely absorbs CO_2. Some of the solution—depending upon the amount of CO_2 absorbed—is displaced into the main Cardisorber tank causing the solution to rise in the

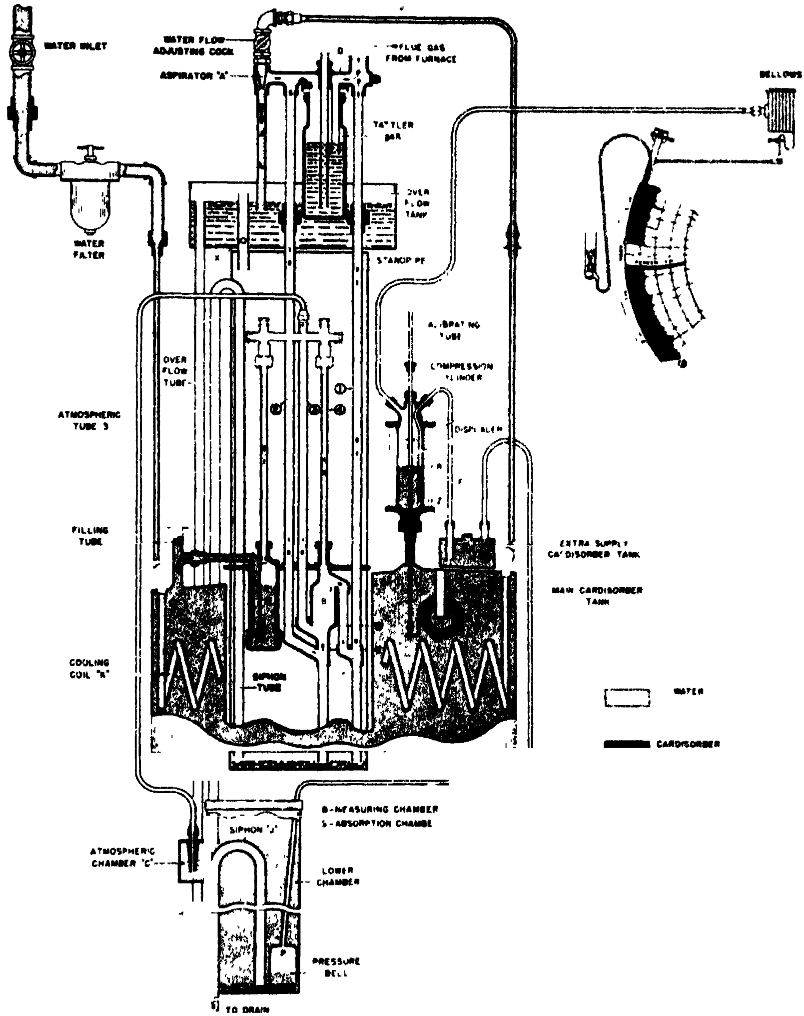


Figure 9-12. Diagram of Hays combustion meter (*Courtesy of Hays Corp.*)

compression cylinder. When Cardisorber reaches level *R* the calibration tube seals and air is trapped in the cylinder. Any further rise of the solution causes trapped air to expand the bellows. Pen movement follows bellows expansion to record the per cent of CO_2.

In the meantime, the water has filled up the standpipe to the point where the syphon is primed and now starts emptying the water from the standpipe at a rate that exceeds the inflow. The syphoning action continues until the water reaches the level that breaks the suction. The unabsorbed part of the gas sample is pushed back into the measuring chamber *B* to be discharged and the analyzing cycle begins again. Incoming gas purges the measuring chamber before another sample is trapped. As the standpipe water is siphoned it empties into the lower chamber. This creates a pressure in bell *P* and forces Cardisorber into the compression chamber from tank *E*. When siphon *J* operates, the pressure in bell *P* is relieved and the compression cylinder siphon, *F*, returns any excess Cardisorber to tank *E*. This action returns Cardisorber to level *Z* after each analysis.

The bimetallic helix *H* compensates for changes in temperature of the Cardisorber due to seasonal water temperature changes. The helix moves a displacer in the compression cylinder as its movement responds to temperature changes.

DENSITY

Another CO_2 instrument for flue gas analysis is the Ranarex instrument made by the Permutit Company. Figure 9-13 is a schematic of the instrument. Its application for gas density measurement was mentioned in Chapter 6. The following discussion describes the instrument as used for CO_2 measurement. The design is based on the fact that the specific weight of flue gas increases in proportion to its CO_2 content, since CO_2 is about 50 per cent heavier than the other constituents of the flue gas.

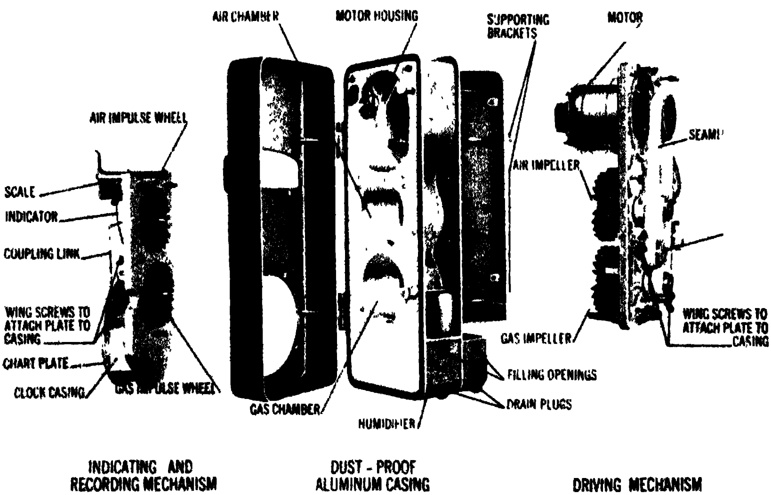


Figure 9-13. Assembly view of Ranarex. (*Courtesy of Permutit Co.*)

The lower impeller draws in a sample of the gas being tested. In the gas chamber, it imparts a whirling motion on the gas. This motion tends to rotate the impulse wheel in the *gas* chamber. However, the impulse wheel is restrained from rotating by the link which connects it with the impulse wheel in the *air* chamber. Both wheels exert a torque on each other, each trying to rotate in an opposite direction. The result is a net motion which depends on the difference in torques between the two impulse wheels and which positions the indicator needle.

The impulse wheel in the air chamber is provided to compensate for changes in fan speed, temperature, humidity and atmospheric pressure. To do this, gas sample and air are brought to the same temperature and humidity by passing them through separate compartments in the same humidifier. The air is drawn into the air chamber by the upper impeller. The resulting whirling motion tends to rotate the air impulse wheel, but the direction of rotation is the opposite of the direction of the gas impulse wheel. The torque on either wheel increases with the density of the gas. It was pointed out that the specific weight of CO_2 is so high that its presence can be detected by this characteristic. The torque on the gas impulse wheel will increase with the percentage of CO_2 and thus produce a reading on the indicator. The signal may also be transmitted to a recorder.

ELECTROLYTIC CONDUCTIVITY

Conductivity, as considered here for the purpose of measurement of a process variable, is the conductivity of an electrolyte. The electric current obtained is due to a flow of ions, and it is a definition of an electrolyte that it is a solution containing substances that ionize. There is a difference between the current flowing in a wire, which is due to a flow of free electrons, and the current flowing in an electrolyte. One of the consequences of this difference is that polarization occurs in the latter case, as described below.

Electrolytic conductivity is measured by electrodes that are placed in electrolytic solutions. A current flows from one electrode through the solution and continues through the second electrode. If this current continues in one direction ions will accumulate around an electrode and thus make it more difficult for the following ions to reach the electrode. This action is called polarization. It can produce serious errors. To reduce polarization, a.c. is used with conductivity measurement. The greater the concentration of the solution, *i.e.*, the greater the ion flow, the higher must be the frequency. For this reason, Foxboro, for example, uses 1000 cycles per second with their equipment. It is possible, however, to reduce polarization by covering the electrode surface with a spongy black platinum coating. This allows the use of 60 cycles per second for practically all applications. The platinum coating must generally be renewed after 6 months of use.

The conductance of the solution is measured and used as an expression of its concentration. The relationship between conductance and concentration is not a linear one. It is a curve which usually shows a maximum of conductance for some percentage of concentration and a nonlinear downward slope for any concentration below or above the maximum. This limits the application of conductivity measurements to small ranges, and may make it impossible near the point of maximum conductance. It also means that where the solution contains various ionizing substances, calibration of the instrument is usually impossible.

The inverse of conductance is resistance, and speaking in terms of resistance, the range of resistance that is practical to cover in industrial conductivity measurements is 50 to 100,000 ohms. Commercial ranges are generally considerably narrower, and the idea is to allow measurement of a large number of substances within the same instrument range. To do this, electrodes vary in size and spacing. Substances, for example, of high conductivity will have relatively wide spacing of electrodes and small surfaces. A correction factor is usually attached to each cell which reduces the value actually measured to the common instrument standard.

The electrodes in combination with the electrolytic substance are part of a Wheatstone bridge arrangement. One leg of the bridge can be used to compensate for temperature variations. This is frequently necessary because the relation between ionic concentration and conductivity varies with temperature. The compensation is either manual or automatic. Automatic compensation can be obtained by a resistance temperature detector or by the Bishop method. Both methods are described in the following.

The resistance temperature detector is exposed to the substance under measurement and is connected with the Wheatstone bridge in such a way that it compensates for changes in concentration reading which are due to changes in temperature. It is, however, necessary that the temperature coefficient of the resistor corresponds to the temperature coefficient of the electrolytic substance.

The Bishop method uses two cells. One cell is the measuring cell containing the electrodes which are exposed to the electrolyte. The other cell is sealed and contains a standard solution, but is likewise immersed in the electrolyte; however, the electrodes are not in physical contact with it. Each cell is connected with another bridge leg; thus the temperature changes in the sealed cell compensate for those in the measuring cell.

A typical conductivity cell, made by Industrial Instruments, Inc., is shown in Figure 9-14. The valve permits removal of the cell from a tank or pipeline without having to drain the liquid. To remove the cell, the packing gland is slightly loosened, and the cell can then be retracted to a stop. At this point

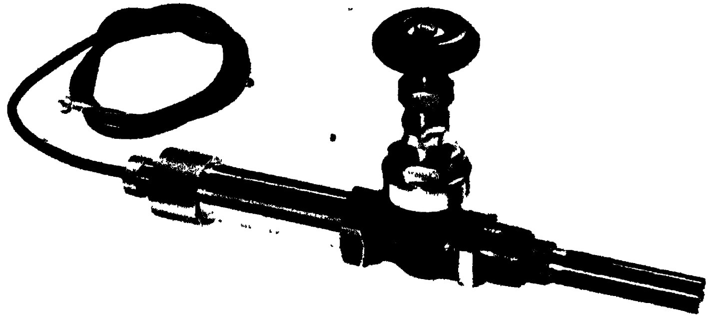


Figure 9-14. Conductivity cell (*Courtesy of Industrial Instruments, Inc.*)

the valve can be closed and, after turning the cell through a small angle, it can be removed.

Industrial Instruments, Inc. also makes a conductivity measuring system without electrodes. It can be used where fibers tend to clog conventional conductivity cells or where abrasive slurries, hot, highly conductive solutions, or extremely corrosive solutions create a problem. The cell in this case consists of a neoprene covered "Teflon" tube with threaded, stainless steel terminations, and a sealed assembly of two toroidal coils surrounding the tube through which the liquid sample flows. One of the coils is connected to a high audio-frequency voltage source. The second coil is connected to a receiver which measures the output voltage from this winding. The arrangement is equivalent to two transformers. The first has, as its primary winding, the input coil, and as its secondary winding the sample flow itself. The second transformer has as its primary the sample flow and as its secondary the output coil. With constant input voltage, the output of this system is proportional to the conductivity of the liquid sample.

In measuring *gases* by electrolytic conductivity, it is necessary to have the gas first absorbed by a liquid. One of the outstanding features of this principle of analysis is its sensitivity to extremely small quantities of various gases and vapors. On certain types of application, it has been possible to obtain full-scale travel of the recorder on less than one part per million.

A typical example is the Davis continuous electro-conductivity analyzer which was designed for the analysis of gases and vapors that will ionize either directly in water, or when decomposed by heat. The method used is to measure the difference of electrical conductivity of distilled water before and after the gas sample has been passed through it. The measurement is made by two sets of electrodes connected with a Wheatstone bridge.

If the sample concentration is relatively low or if the analyzer samples relatively pure air, a water recirculation system is utilized; the system then consists of a distilled water reservoir, ion exchange chamber, flow meters, analyzing cell, and a special pump serving to continuously draw the sample and to recirculate the water. For applications in which the sample concentrations are relatively high, a constant supply of distilled water must be provided: thus, for certain applications, this analyzer comes equipped with a water distillation system, in addition to the above components.

The sample which the pump draws at a fixed rate passes into the ion exchange chamber, which is simply a container of distilled water through which the sample is bubbled. The ionization of the gases increases the conductivity of the water. Some gases do not ionize directly in water. For these cases, a so-called pyrolizing furnace can be provided.

The distilled water circulates through the ion exchange chamber at a constant rate. Before entering, it flows through a cell where its conductivity is measured by two electrodes which are immersed in it. After the sample is bubbled through the water, increasing its conductivity, the water flows through another analyzing cell where its conductivity is again measured.

There are thus two pairs of electrodes continuously immersed in the water, one pair in the neutral water, the other in the water of increased conductivity. The water between the electrodes constitutes an electrical resistance. These resistances are connected through the electrodes with a Wheatstone bridge. Since the relative values of the resistances change with the change of conductivity of the water due to its contamination with the sample, it follows that the unbalance of the bridge will be a direct result of the composition of the sample. The instrument shows the total concentration of all ionizable gases present in the sample unless the undesired gas or vapor can be scrubbed or filtered out of the mixture.

The flowmeters are required to have a constant check on the correct rate of flow of the sample and the water. It is possible to scan continuously up to eight different points.

AMPEROMETRY

Amperometry is a measurement of current. Contrary to the electrical conductivity technique described under the preceding heading, it uses d.c. rather than a.c. for measurement. The Foxboro Residual Chlorine Analyser operates by amperometry. It automatically adds a reagent to a flowing sample of treated water. The current flow as this mixture passes between two electrodes is directly proportional to the concentration of residual chlorine. The current is recorded by a Dynalog recorder.

The measuring cell is shown schematically in Figure 9-15. The mixture of sample and reagent enters the cell and passes through a restriction into the measuring chamber. In this chamber are a copper electrode, a platinum elec-

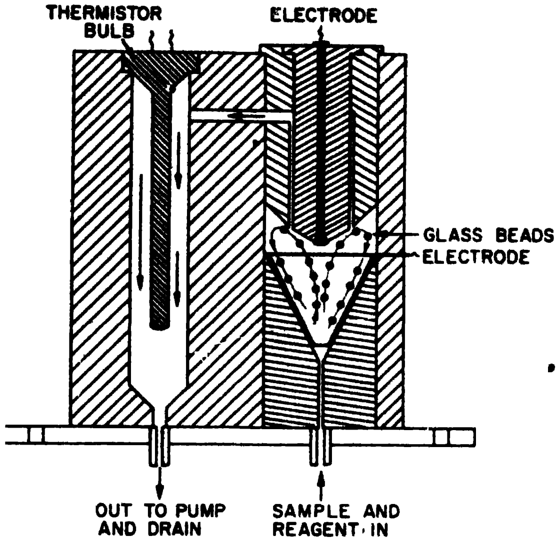


Figure 9-15. Amperometric cell. (*Courtesy of Foxboro Co.*)

trode, and colored glass beads. The strip copper electrode is cemented to the wall of the conically shaped chamber. The platinum electrode is mounted in the center of the chamber slightly downstream of the copper electrode. The velocity of the fluid agitates the beads and causes them to clean the electrode surfaces of any substances which might adhere. The clearances at the exit of the measuring chamber keep the beads from leaving the chamber. The fluid passes out of the chamber, across the top of the cell, past a thermistor bulb, and out of the cell. The cell body is made of clear plastic to permit visual inspection of the operation of the glass beads.

The thermistor bulb is part of a temperature compensating circuit. The change in resistance of the thermistor bulb compensates for the increase or decrease of electrode current caused by the changing water temperature.

pH

The effective acidity or alkalinity of a liquid is commonly expressed in pH. A pH of 7 corresponds to a neutral solution. As the numbers increase toward 14 the alkalinity increases, and as the pH approaches 1 the acidity increases. The electrochemical reaction that takes place in a liquid when an acid is added consists in an increase of hydrogen ions and a decrease of hydroxyl ions. Since the hydrogen ions are positive and the hydroxyl ions are negative, it is possible to measure the change by electrical means.

The most common method of industrial measurement is the glass electrode in combination with a calomel electrode, as illustrated in Figures 9-16 and 9-17. The glass electrode contains a buffer solution, *i.e.,* a solution that maintains a certain pH even though a limited amount of acid or basic substance be added. The standard Beckman electrode, for example, has a spherical end about ½ inch in diameter filled with the buffer solution. The wall is of very thin glass and constitutes a membrane between the buffer solution and the liquid under measurement. A platinum wire coated with silver chloride connects from the buffer to the electrode head. The potential difference between the buffer solution and the process liquid across the glass membrane is of measurable size, in spite of the high membrane resistance, which may amount to as

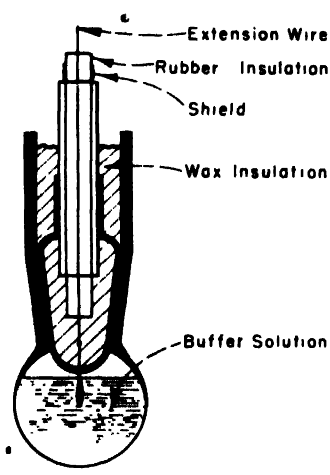


Figure 9-16. Schematic of Beckman glass electrode.

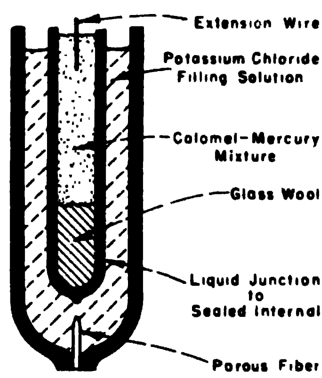


Figure 9-17 Schematic of Beckman calomel electrode.

much as 1000 megohms. The resulting voltage varies from −465 millivolt at 3 pH to −43 millivolt at 10 pH.

The circuit is completed through a calomel electrode, which serves as a reference electrode having a constant output of + 245 millivolts. A liquid junction between the process liquid and the calomel electrode is established by means of the outer chamber, which is filled with a saturated solution of potassium chloride and a porous fiber through which a minute quantity of potassium chloride diffuses into the process liquid. The inner chamber of the calomel electrode is filled with glass wool in its lower part, on top of which is placed a layer of a paste which is a mixture of calomel and mercury. A pin hole provides a liquid junction with the outer chamber and completes an electrolytic cell of constant emf.

The net output of the two electrodes is about 25 millivolts at 7 pH and changes some 59 millivolts for each pH. The current has to be kept at a very low rate (about one micro-micro-ampere or 10^{-12} ampere) to avoid polarization of the cells. By means of an electronic amplifier it is possible to increase this extremely small current sufficiently to feed it into a standard electronic potentiometer where the pH of the process liquid is recorded.

The emf output of the glass electrode changes with temperature. To correct for a measurement error due to this characteristic, the electrode assembly usually includes a resistance thermometer which is connected into the measuring circuit and compensates for changes in liquid temperature.

OXIDATION-REDUCTION POTENTIAL

The oxidation-reduction potential, sometimes called redox, is measured by the same electrodes and methods as pH. In both cases, redox and pH, measurements are concerned with positive and negative ions in solution. The loss of electrons produces positive ions, and is equivalent to oxidation, while reduction is equivalent with a gain of electrons or negative ions. There are a number of reactions in industrial processes that are known to produce a specific oxidation-reduction potential. By measuring it, the completeness of the reaction can be determined.

DIELECTRIC CONSTANT

The dielectric constant of a liquid can be measured by moving the liquid between the two plates of a capacitor. Since different liquids have different dielectric constants, the presence of one liquid in another can be measured. An example is the measurement of basic sediments and water in crude oil. The BS & W Monitor made by Instruments, Inc. is a dielectric constant chemical analyzer for this purpose. It consists of a detector unit, a power unit, and a cell unit. The cell unit is connected with the sampling line, which is tied into the process line. Changes in dielectric constant of the flow alter the impedance of one of two tuned circuits which are inductively coupled to the output of a crystal-controlled oscillator. The voltage across these tuned circuits is rectified and amplified. The output signal from the amplifier, indicating both magnitude and direction of change of the dielectric constant, drives a panel meter or recorder.

ELECTROCHEMICAL REACTION

The oxygen recorder and indicator made by Mine Safety Appliances has a detector element which is essentially a primary cell with a metallic anode and a hollow carbon cathode immersed in an electrolyte designated as "Oxylite." It is housed in a plastic container. The sample to be analyzed is passed through the hollow carbon electrode of the detector cell. Hydrogen evolved at the carbon electrode in the cell causes polarization of the cell, resulting in a decrease of the generated voltage and current. Oxygen from the sample diffuses through the wall of the carbon electrode and combines with the hydrogen thus producing a depolarization, *i.e.*, increase of generated voltage and current. Consequently, the more oxygen the sample contains, the higher is the electric current generated by the cell.

The current delivered by the detector cell is affected by variations in the cell temperature. To eliminate this effect, the cell is placed in a thermostatically controlled water jacket which is maintained at a constant temperature of approximately 30°C.

FLASH POINT CONTROL

One of the criteria in the quality of distillate fuels is flash point. A continuous flash point recorder for this purpose was developed by Standard Oil Company (Indiana) and licensed to Precision Scientific Development. It automatically determines the flash point every 5 minutes. The flowing sample stream is first cooled. After flowing through a heater where its temperature is gradually raised, the sample is mixed with air. The sample temperature is recorded electronically prior to exposure to high voltage sparks every other second. When the temperature is reached at which the sample flashes, the recording pen automatically drops and the cycle ends. After a 2-minute cooling, the cycle recommences.

10. Automatic Controller Action

The Closed Control Loop

The instruments described in the first nine chapters measure process variables. Such measurement is a prerequisite of automatic control. An automatic control system generally consists of the measuring means, the controller, and the final control element. These elements react upon each other and thus form a circle or closed loop, as illustrated in Figure 10-1.*

"Control" means either to keep a controlled variable relatively constant, or to change it as a function of some other variable. The controller, which receives the signal from the measuring means, compares it with the set point signal and responds to it with an output signal to the final control element, which produces the correction in the process. The process reacts to this correction, which is sensed by the measuring means and the controlled variable signal is modified accordingly. The different steps of which this closed control loop consists can be enumerated as follows:

(1) Detection of deviation of controlled variable from set point by measuring means;
(2) Signal from measuring means to controller, indicating the deviation;
(3) Controller action;
(4) Corrective signal from controller to final control element;
(5) Corrective action by final control element;
(6) Reaction of process and consequent modification of measured quantity of controlled variable;
(7) Detection of modification of controlled variable by measuring means;
(8) Modified signal from measuring means to controller.

If the modified signal of step (8) corresponds to the signal transmitted when the controlled variable is at the set point, then the corrective cycle terminates. However, if the deviation from the set point persists, the cycle repeats itself. Step (8) is the signal for the success or failure of the action. It is this feedback that modulates the correction.

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*While using this conventional block diagram representation, it should be born in mind that the generation of the set point signal and the means for comparing it with the controlled variable signal are in this text considered to be part of the controller.

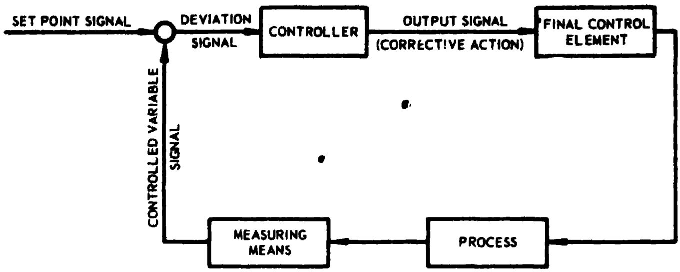

Figure 10-1. Control loop diagram.

Time Lags

In each of these steps a time element is involved. It takes some time for the measuring means to detect the deviation. It again takes time to transmit the change in the controlled variable to the controller, and so on through the eight steps. These time lags are of decisive influence in controlling a process. It is convenient to differentiate between two types of time lags: dead time and time constant.

Take a process which includes some controlled variable, such as flow, pressure, level or temperature. A sudden change in the signal to the final control element will change the controlled variable. This process response will not be an immediate change but a gradual one. It depends on the characteristics of the process. Six of the most typical process characteristics are represented in Figure 10-2. In all cases, the automatic control action was disconnected and a sudden change in the position of the final control element—a so-called step input—was introduced at time t_1. The change of the process variable, such as level or temperature was then measured and represented in the graph. Some processes have the characteristic of 10-2*A* and 10-2*B*. For example, a level in a tank with constant outflow would continue to rise at such a constant rate. Most processes, however, show characteristics similar to Figure 10-2*C* through 10-2*F*. In all these processes, the controlled variable gradually approaches a new level by its inherent self-regulation. For example, increasing the heat input in a heating system by a given amount will raise the temperature to some such new level.

To determine the time constant in cases *C* through *F*, a tangent is drawn—as a dashed line through the point of steepest rise in the response curve. A second dashed line is extended from the final level toward the left. The intersection of the two dashed lines defines the time, t_3. The time from t_1 to t_2 is called the dead time. The time from t_2 to t_3 (or from t_1 to t_3, where no t_2 is indicated) is the time constant. In case *C* times t_1 and t_2 coincide. Hence the dead time in this case is zero.

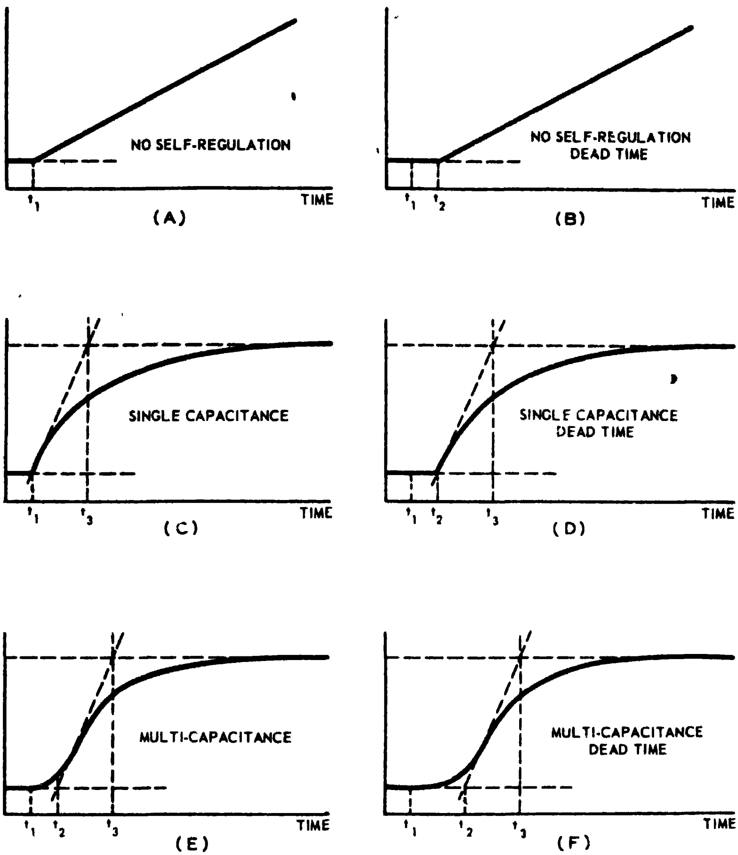

Figure 10-2. Typical process characteristics.

The time constant can be defined as the time the controlled variable requires to go through 63.2 per cent of its full change.

The time constant is infinite in cases *A* and *B*, since the controlled variable does not settle out on a new level by itself.

Dead time and time constant of a specific process determine generally which control action to use. Strictly speaking, in using the criterion of dead time and time constant, as is done in the following, it must be understood that these are not merely the time lags of the process, but of all components in the control loop, *i.e.*, process, final control element, measuring element, and controller.

Unfortunately, it is difficult and often impossible to give quantitative data for the selection of control action. The reader must therefore be satisfied with such general terms as "large" and "small." For a more thorough treatment of the subject, he is referred to the author's book on "Automatic Control."*

Table 10-1 lists the criteria used in selecting a specific control action, as will be discussed in the following paragraphs.

TABLE 10-1. HOW TO CHOOSE CONTROL ACTIONS

	Two-position	Single-speed floating	Proportional speed floating	Proportional position	Proportional plus reset	Proportional plus reset plus rate
Time constant (t_1)	Should be large	Should be small	Should be small, but may be medium	Should be medium to large	May be small	May be small
Dead time (t_2)	Should be small	Should be small	Should be small	Should be small to medium	Should be small to medium	May be large
Ratio t_1/t_2	Should be large	The smaller the better	The smaller the better	The larger the better	The larger the better	Any
Magnitude of load changes	Should be small	May be large	May be large	Should be small	May be large	May be large
Speed of load changes	Should be small	Should be very small	Should be small to medium	May be large	Should be small to medium	May be large

Two-position Control

Let a temperature controller receive a signal indicating a deviation of the controlled variable from the set point. The controller transmits a corrective signal to a valve,** which regulates a steam supply. The amount of steam admitted determines the controlled temperature in the process for some given load condition. If the temperature drops below the set point the valve is fully open; if the temperature rises above the set point, the controller shuts off the steam flow. As there are no intermediate valve positions, the temperature cycles continuously around the set point. The amplitude of these cycles must be within limits that are compatible with the process requirements.

Every time the valve opens, steam flows at its maximum rate. If the time constant is small, considerably overshooting followed by undershooting results, producing cycles of large amplitude. Therefore, the time constant must be large in order to obtain control within reasonable limits.

*W. G. Holzbock, "Automatic Control: Principles and Practice," New York, Reinhold Publishing Corp., 1958.

**Since the valve is a frequently used final control element, this text will often refer to a valve where some other final control element may as well be used.

On the other hand, the presence of dead time in which the process response is small or zero results in excessive correction which must be avoided. Hence the requirement for small dead time.

If a large load change occurs, it will take a relatively long time for the correction to compensate for the change. The same is true when the load change is small but fast. The result is that in both cases excessive temperature variations will result. Speed and extent of load change should therefore be small.

While many processes have small and slow load changes during operation, they require start-up periods, for example, in a heat-treating furnace, where the temperature has to be brought up through a considerable span as quickly as possible. This means both large and fast load changes. While direct on-off control would not be applicable, multiposition controls take care of the start-up period and then switch over to on-off control during the operating period.

Proportional-position Control Action

The essential difference between two-position and proportional-position action is that proportional-position action tends to obtain a middle position which it can maintain, while two-position action is based on continuous cycling.

A controller with proportional-position action increases or decreases the deviation signal by a certain factor. This factor is called the gain. To determine the gain of a controller, the change of output signal is expressed in terms of per cent of rated output signal span. Thus, a pneumatic controller which has a span from 3 to 15 psi, *i.e.*, a span of 12 psi, will change its output signal by 25 per cent, if it increases this signal from, say, 8 psi to 11 psi. Similarly, the deviation signal is expressed in terms of measuring range. If a temperature instrument has a range of 200°F, then a deviation of 20°F from the set point, means a 10 per cent deviation signal. The gain of a proportional-position controller is defined as the ratio of change in output signal to the change of deviation signal. Hence, in the preceding example, the gain is $25/10 = 2.5$. The greater the gain is, the greater will be the corrective action of the final control element for a given deviation signal.

"Proportional band" is a term frequently used instead of gain. To convert gain into proportional band, the inverse value of gain is multiplied by 100. For example, a gain of 2.5 equals $\frac{1}{2.5} \times 100 = 40$ per cent proportional band.

The term "gain" (or proportional band) applies to any controller which contains proportional-position action. This includes proportional plus reset and proportional plus reset plus rate controllers. However, it always refers to the gain of proportional-position action only, assuming any other control actions to be nonexistent or inactive.

The band width of a controller is equal to its measuring range divided by the gain. In the preceding example, the measuring range is 200°F and the gain is 2.5; hence the band width is 200/2.5 = 80°F. The band width expresses the change in controlled variable signal that produces maximum change of output signal.

Excessive gain produces over-correction of the controlled variable beyond the set point. It is the characteristic of overshooting that it reverses once it has reached its maximum and is followed by undershooting which means passing the set point because of its inherent inertia—a phenomenon equivalent to the inertia of a moving body retained by a spring. The resulting movement is an oscillation around the set point. Magnitude of response can be reduced by reducing the gain to such a degree that no cycling occurs. This results in a sluggish response which is undesirable in a process where quick correction is required. The necessary compromise for optimum control is a gain that results in a few, rapidly subsiding cycles around the set point. The gain necessary for this condition depends on the speed and magnitude of the load change and the time required by the control system to correct for the deviation. If the process response is fast, small gain is chosen, and vice versa.

Proportional-position action, in the ideal case, maintains a linear relationship between the controlled variable and the valve position. If load changes occur that require a different valve opening to maintain the controlled variable at the set point, proportional-position action cannot produce it because of the following reasons. The load change produces a deviation. This results in corrective action and the valve assumes a new position. As the process responds to the correction, the controlled variable again approaches the set point and the valve automatically returns to its original position, although it should remain in a different position to compensate for the load change. This condition results in a compromise which leaves a certain amount of deviation without correction. This offset may be hardly noticeable where high-gain settings can be used, but the smaller the gain is, the more objectionable it becomes.

High gain makes the control very sensitive, and as pointed out before, overshooting followed by cycling will result if the process response is too fast. This condition will increase considerably if dead time is present, as it will take longer to correct for overshooting. Although load changes with proportional-position control should be small to not more than medium, they can be fast, since the corrective action with the intermediate positions of proportional-position control reduces cycling that would be caused in two-position control by fast load changes.

Proportioning Control Action

Proportioning control action is used in electric controllers to determine the duration of an electrical impulse. Thus a proportioning controller is a duration-adjusting device, whereas a proportional-position controller is a position-adjusting device. Proportioning action consists in chopping an output signal into on-and-off cycles.

Consider an electric heater for a temperature-controlled furnace. Let the total duration of each on-off cycle be 60 seconds. When the temperature is below the proportioning band, the "heat on" period is continuous. As it enters the proportioning band, the "heat on" period becomes an increasingly smaller fraction of the total cycle. At a certain point the heat will be on for only 50 seconds, then off for 10 seconds, then on again for 50 seconds, etc. At the set point it will be on for 30 seconds out of 60, and when it reaches the upper end of the proportioning band the heat is off all the time.

The criteria which determine the choice of a specific control action are essentially the same for proportioning and proportional-position action.

Single-speed Floating Control Action

This action is frequently used in simple electric controllers. It consists in moving a valve or other final control element between its open and closed position, so that when the controlled variable rises above the set point the valve position changes in one direction, and when it drops below the set point it changes in the other direction. There is generally a neutral zone, *i.e.,* a small range above and below the set point, in which the valve will not move. No fixed relation between magnitude of deviation and valve position exists as is the case with proportional-position action, but the valve position changes the more the longer the deviation persists. Once the controlled variable returns to the desired value, the valve remains in the position it has reached at that moment. This action has the advantage over proportional-position action that the valve can assume *any* position to maintain the controlled variable at the set point, or at least in the neutral zone, while for proportional-position action the only position of the valve at the set point is the *midway* position.

When the controlled variable changes sufficiently to start the corrective action it is desirable that the floating speed be (a) sufficient to overcome the rate of change of the controlled variable and (b) slow enough to prevent overshooting. Both these conditions can be fulfilled only if the rate of change of the controlled variable is not constant. This is true when the process is self-regulating, *i.e.,* when it absorbs a certain amount of internal changes, as in the case of a controlled temperature process where a drop in temperature may decrease the temperature loss, thus helping to produce a new balance of conditions.

To prevent cycling, it is further necessary that the gradual corrective action finds a small time constant and a small dead time. Otherwise the valve movement will have advanced too far before the primary element senses the results of the correction. Since the valve can change the flow of the control agent only gradually, the load changes must be slow to permit satisfactory control.

However, the magnitude of load changes has little effect on the controlling ability of single-speed floating action.

Proportional-speed Floating Control Action

This action—also known as integral action—differs from single-speed floating action insofar as its speed changes in proportion to the amount of deviation of the controlled variable from the set point. A neutral zone is not necessary in this kind of action. Since its rate of correction increases with the size of load change, it is able to operate well with faster load changes than can be tolerated with single-speed floating action. For the same reason, the amount of self-regulation can be considerably less.

Proportional plus Reset Control Action

If proportional-position action is combined with proportional-speed floating action it is possible to compensate for offset by the continued movement of the final control element, which persists as long as the process variable is not at the set point and is due to the integrating action. The proportional speed of the floating action adds the further advantage that correction will be faster, the greater the deviation. Proportional-speed floating action combined with proportional-position control is called proportional plus reset action. Another term is "proportional plus integral" action.

The effect of reset action is to add corrective action to the process as long as the deviation exists. This is the same as shifting the set point gradually and thus forcing the controller to follow until the original set point has again been reached. When a deviation occurs, there is an immediate response from the proportional-position action of the controller. This response is increased at a fixed rate by the reset action. The number of times per minute, that the initial proportional-position action is increased by the reset action is commonly expressed in repeats per minute. Once the reset adjustment of a controller is made, the magnitude of reset action is proportional to the magnitude of deviation and the time it lasts. This causes prolonged cycling when load changes occur too rapidly. Hence, load changes must be slow to medium for this kind of response.

For proportional-position control only, the gain must be high, to avoid objectionable offset. Since the addition of reset action eliminates offset, the gain can be less. It follows from the previous discussion about gain that proportional plus reset action is suitable for processes with fast response.

Proportional plus Rate Control Action

This action is designed to overcome the limitation of speed in corrective action even more than is possible with straight proportional-position control. A description was given in Chapter 1 of how the Taylor Transaire temperature transmitter compensates for lag in the temperature-measuring thermal system by adding to the transmitted air pressure an increment of magnitude proportional to the rate of pressure change exerted by the thermal system on the transmitter mechanism. This same principle applied to a controller is rate action; either the controlled variable signal or the output signal to the final control element is increased in proportion to the rate of change of the signal. The effect is the same as if the gain was temporarily increased. The result is that even a sluggish corrective action becomes sufficiently rapid to furnish satisfactory control. Derivative action is another term for rate action.

Rate action produces a faster corrective action than proportional-position action alone. The time in minutes which the final control element requires to change from one position to another because of proportional-position action only, minus the time it would require if rate action is added, defines the rate time, which is generally expressed in minutes.

The acceleration of a changing signal which is inherent in rate action makes it valuable for long time constants with initially small responses as in Figures 10-2*E* and *F*. However, rate action does not eliminate offset as does reset action. Since processes with short time constants require low gain, offset is the result. Consequently, rate action is particularly helpful under conditions which require reset action to overcome offset. Therefore, proportional plus rate action is usually combined with reset action as described immediately below.

Proportional plus Reset plus Rate Control Action

This triple combination overcomes limitations to a greater extent than any other type of control. It contains the compensation for large time constants with slow initial response of the rate action. It also combines the favorable response of proportional-position controllers to fast though small load changes with the applicability of proportional plus reset control to slow though large load changes; hence load changes may be relatively large and fast.

It might be concluded that proportional plus reset plus rate action should be used for all applications, where a choice between two-position, proportional-position, proportional plus reset, proportional plus rate, and proportional plus reset plus rate action is involved. This would not be good practice for two reasons: (1) the use of two-position control may mean the choice of a solenoid valve instead of a pneumatic final control element, which may occasionally result in a more economical control arrangement, and (2) there are price differences between the various types of controller. Pneumatic controllers of different control action may exceed the cost of a two-position controller by the following percentages:

Proportional-position controller	30 per cent
Proportional plus reset, and proportional plus rate controller	50 per cent
Proportional plus reset plus rate controller	70 per cent

Off-band Control

Load changes can be divided into those that produce a temporary deviation of the controlled variable within the band width of the controller and those that move it beyond this band. The latter usually occurs only when a process is started or when the set point is changed to a new level. Suppose a controller with a temperature range of 400°F operates with a gain of 10 at a set point of 300°F. This means that, reset action excluded, it controls between 280 and 320°F.

Let the instrument be a proportional plus reset plus rate controller. Reset action has been compared with a shifting of the set point so that the controller is able to increase the corrective action gradually until the controlled variable returns to the original set point. If the process temperature is below the band width, the shift will proceed until the band finally corresponds to the instrument range between 300 and 340°F. The effect is the same as if the set point was changed to 320°F. The result is that up to 300°F—the original set point—the *maximum* corrective action is applied to the final control element. As a result there is considerable overshooting of the 300°F set point, and oscillations occur before stable conditions are again established.

Rate action can either be added to the proportional signal of a controller before it is mixed with the reset signal, or it can be added to the combined proportional plus reset signal. In the latter case, the rate response is affected by the band shift produced by the reset action. It takes effect only when the temperature in the above example crosses the 300°F set point. Its only advantage in this case is that it damps the resulting oscillation faster than would be the case without rate action. However, adding the rate action before the reset action results in rate action which is not affected by the band shift due to reset action. It produces effective damping as soon as the temperature crosses the lower end of the non-shifted band width, *i.e.,* at 280°F. This improves the controller action considerably in off-band action.

Some pneumatic controllers, like the Taylor Tri-Act and most electronic controllers, are constructed in such a way that rate action takes place before reset action. They are described in the next two chapters.

Inverse-derivative Control Action

Rate or derivative action is an increase of controller sensitivity that takes place upon a deviation of the controlled variable and gradually subsides as corrective action takes place. Sometimes conditions demand just the reverse: the corrective action takes place so quickly that the controller gain has to be reduced considerably to avoid excessive cycling in response to every deviation produced by a process upset. The larger the deviation, the more should the gain be reduced. This is particularly true of certain pressure and flow applications. It may happen that the gain of such a controller must be reduced to a degree that makes control difficult, although it is required because otherwise the controller would start cycling with each deviation. A controller that automatically reduces the gain when the controlled variable deviates from the set point and increases it again as corrective action takes place would overcome this difficulty. This is the opposite of derivative (rate) action. It is called "inverse derivative action," a term formulated by C. B. Moore in 1948.

11. Electric Controllers

Two-position and Multi-position Controllers

The most common two-position controller is the household thermostat. Opening and closure of its contacts actuates a relay system which in turn controls the heating system.

Contacts which are provided in instruments for two-position control action may also be used as alarm contacts to release visible or audible alarm signals. In producing such signals, the human operator becomes an element of the control loop. His response is caused by the alarm signal and he provides the corrective action.

The Foxboro Dynalog, described in Chapter 1, records the measurement of up to six different points on a common chart, and may be provided with Rotax contacts which will actuate a common or selective alarm, or will operate multiple two-position or three-position control relays. A common alarm is an alarm common to all of the six records, and is actuated when any of these records exceeds the common set point. The alarm relay is locked in until released by an external push button. A selective alarm consists of one to six latching relays actuated by the corresponding number of measurements, if and when any of the measurements exceeds either a common set point or its individual set point. Each relay may be released externally by push buttons. If used as a two-position controller, the operation is identical with that of the selective alarm, except that the relays return automatically to their original condition as the corresponding measurement recrosses its set point.

For control of one to three records, three-position control may be included. To describe the action, suppose a temperature-controlled furnace is heated by electric heaters, whose power is controlled by switches in the instrument. The full power is used to bring the process up to somewhat below the operating temperature (lower set point); then the system is switched to the medium position until the operating temperature is reached. When the temperature exceeds this point the power is cut off. The furnace is thus heated at an accelerated rate up to the lower set point and at a decelerated rate to the upper set point. This action effectively reduces the time required to bring the furnace to its operating temperature and reduces cycling when this temperature is reached.

Another arrangement of three-position control is "high-and-low" control, where one contact is actuated somewhere below the set point and the other above the set point, with a neutral zone as interval.

When a controller is set for, say, 72°F, the control contact will open at 72°F as the temperature increases, but it may require a 2°F drop before the control contact closes again. This difference of 2°F is commonly called differential gap or the neutral zone, and the more sensitive an instrument is the smaller is the differential gap. Oscillator-type controls are probably the most sensitive.

The Brown Electr-O-Vane control unit is of the oscillator type. It is illustrated in Figure 11-1. This unit is part of an indicator or recorder and can control any load within the contact capacity of its relay. It is available with Class II, Class III, and Class V thermal systems in filled-system temperature instruments, and can also be applied to pressure instruments. The vane,

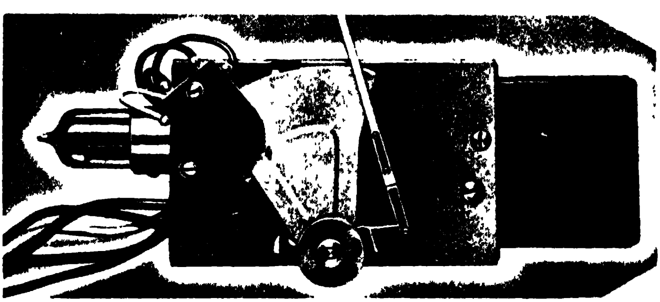

Figure 11-1. Electr-O-Vane control unit. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

which is positioned by the actuating element of the instrument, moves gradually into the field between two oscillator coils. A vane movement of .002 inch suffices to change the oscillation in the circuit enough to energize or deenergize the relay. This makes the instrument an extremely sensitive two-position controller. The Electr-O-Vane allows operation with a differential gap of as low as 0.1 per cent of full scale, which means that, for an instrument range from 0 to 120°C, the differential gap would be 0.12°C.

The General Electric pyrometer (illustrated in Figure 1-2) includes also an oscillator-type control. The pointer carries a vane, and it can be seen that the control index on top of the scale is set at 100°C. When the indicator reaches this point, the vane will enter the field between a pair of oscillator coils. This will produce the necessary signal for the operation of the control relays.

In the Gardsman Pyrometric Controller made by the West Instrument Corporation, the control feature is a photocell arrangement. The principle of operation is illustrated in Figure 11-2. A manually operated setting arm, carrying

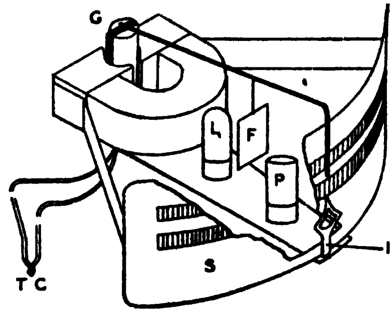

Figure 11-2. Schematic of Gardsman controller. (*Courtesy of West Instrument Corp.*)

the set-point index *I*, may be positioned at any desired point along the scale. On this arm, but behind the scale, are a small light source, *L*, and a photocell, *P*, so arranged that the light from the light source is projected upon the sensitive surface of the cell. As long as the light strikes the photocell, sufficient current flows to actuate the relay which controls the electric power. When the temperature rises to where the positions of the instrument pointer and set-point index coincide, the opaque flag *F*, carried on the instrument pointer arm, interrupts the light beam and the current flowing in the photocell decreases until the controlling relay drops out.

Some electric controls have final control elements that operate only in connection with the particular controller for which they are designed. Figure 11-3, for example, is a schematic wiring diagram for two-position control as used with a Honeywell Industrial Motor. The control instrument operates a two-po-

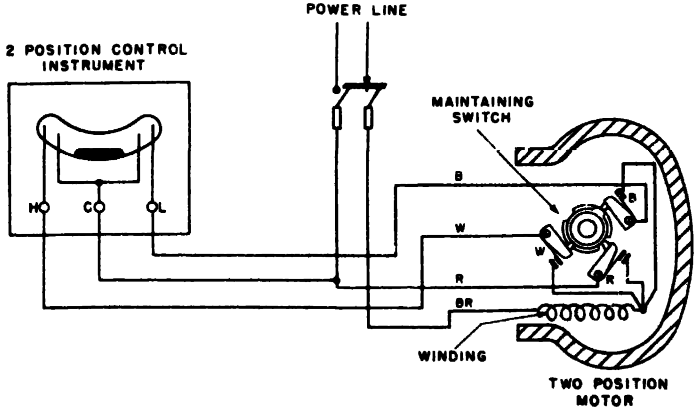

Figure 11-3. Schematic of industrial motor with two-position control. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

sition mercury switch. When the instrument tilts the switch to the right, the mercury connects *C* to *L*. Current will then flow from the power line *C* through *L* to contact *B*, through the motor winding, and back to the power line. The motor is thus energized, driving the final control element as well as the maintaining switch cam.

When the motor shaft has rotated through 30°, the mercury switch contact in the instrument can be broken because the cam shaft has closed contact *R* and opened contact *B*. A circuit is now closed from the power line through *R*, the motor winding, and back to the power line. The motor continues to run until the shaft has rotated one-half revolution, at which time contact *R* opens and contact *W* closes. If the instrument mercury switch is still closed between *C* and *L*, or in the neutral position, as illustrated, the motor will stop since contacts *B* and *R* are both open. When the instrument connects *C* to *H*, current flows through *W* to the motor field, and similar action is repeated for the second half revolution.

The motors are thus unidirectional and if they are connected to a control valve they must be geared in such a way that the valve will be closing during 180° of the rotation of the motor, and opening through the following 180°.

Proportioning Controllers

The Bristol Free-Vane electronic controller controls the length of on-periods and off-periods in a proportioning control system. The arrangement is again based on the interaction between a vane that moves with the instrument pointer and a pair of oscillator coils that are positioned with the set-point index. A variable capacitor is connected in parallel with the oscillator coils. The capacitance can be varied by rotating one set of plates of one polarity against a set of plates of opposing polarity, thus changing the active area of the capacitor. This rotation and hence change of capacitance is provided by a Telechron motor operating at a constant cycle time. Thus capacitance is periodically added to the oscillator coils. Just before the beginning of the off-period during which a relay is to be de-energized, this capacitance adds to the detuning of the oscillator circuit which, in turn, controls the relay. In other words, vane position relative to oscillator coils and a certain position of the capacitor plates to each other must coincide to produce the off-period. As the controlled variable approaches the set point, the vane covers an increasingly larger area between the coils. This increases the off-periods.

Suppose this controller is used to control temperature. It has a range of 0 to 1000°F, and the set-point index is adjusted to 750°F. Since the smallest gain, the controller can be set for, is 15, it follows that the maximum band width is about 65°F. Let the controller be adjusted for this maximum band. The band thus extends from 717.5°F to 782.5°F. Heat is being added to the process during the on-periods when the relay is energized. When the temperature is at or below 717.5°F, the relay will be closed 100 per cent of the time. When the temperature is at the set point of 750°F, the relay will be open 50 per cent of the time and closed 50 per cent of the time. When the temperature is at or above 782.5°F, the relay will be open 100 per cent of the time. When the temperature is at any other value within the band width, the percentage of on-time to off-time will be proportional to the position of the instrument pointer or pen within the band. If the band is narrowed by increasing the gain setting, this same proportional action will occur, but within the narrower range of temperatures. The time for one cycle of operation of the proportioning unit (on-time plus off-time) can be 15, 30, or 60 seconds, depending on the gears used in the unit.

Proportional plus Reset Controllers

Figure 11-4 is a schematic drawing of the arrangement for proportioning plus reset control used with Leeds & Northrup's Speedomax potentiometers. The instruments respond to a millivolt signal, and in the following a thermocouple is considered as the measuring means. A change in the emf output of the thermocouple unbalances the measuring circuit of the instrument. The amplifier, in response to the deviation of the controlled variable, operates a balancing motor, which readjusts the measuring slide-wire resistance, positions pen and pointer, and also readjusts resistance *A*. The latter produces a change in the relative magnitude of the portions *a* and *b* into which *A* is divided by the contactor.

Together with resistors *B* and *C* and the relay coil *D*, the arrangement constitutes a Wheatstone bridge. Hence, the voltage differential across the relay

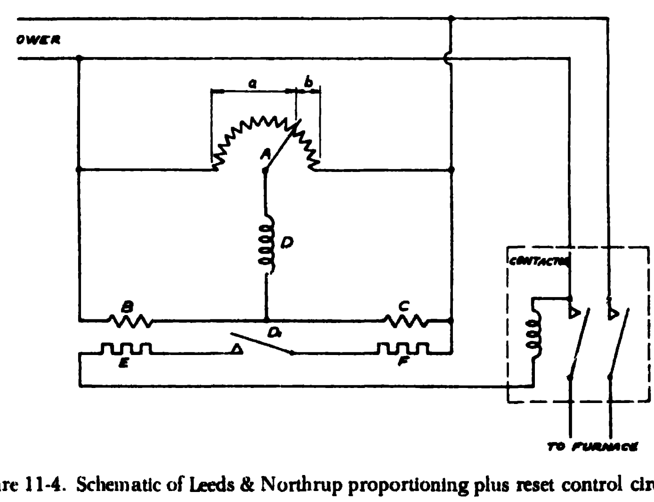

Figure 11-4. Schematic of Leeds & Northrup proportioning plus reset control circuit.

coil is zero as long as the proportions of the resistances are such that $B/C = a/b$. As the balancing motor changes the proportion a/b, a current will flow through the relay coil D due to the voltage differential that appears across it. Relay D operates contact D_1, and in so doing the contactor coil is energized, closing the contacts and supplying power to the furnace.

E and F in the diagram represent small heaters in the control unit. When contact D_1 closes, current will flow through heaters E and F. These are in close thermal contact with resistors B and C, respectively. The increase in temperature of either one changes their electrical resistance and therefore the balance of the bridge. To explain their function, let the effect of the heaters be at first disregarded so that the proportion of resistor B to resistor C is always the same. In this case the relay would close every time the temperature dropped below the set point, and would open again when the temperature returned to the set point. That would not be a proportioning action, but simply on-off control.

Introducing now heater E only, while heater F continues to be disregarded, a means is obtained of changing the proportion B/C by increasing the resistance B each time contact D_1 closes and puts heater E into action. Even when the temperature is at the set point, and the contact D_1 opens, the cooling of the resistor unbalances the circuit again, causing the relay to energize and close its contact, which in turn heats the resistor again, balancing the circuit, and so on. This alternating action feeds just enough power to the heater to hold the temperature at the set point as long as the heat demand of the process is the same.

If the controlled temperature drops because of a load change which increases the heat demand of the process, the instrument would again change the proportion a/b. Let it be assumed that a decrease in temperature means an increase of resistor a with respect to b, and vice versa. To compensate for this additional unbalance, *i.e.*, to make B/C again equal to a/b, it is necessary to increase the resistance of B, which is possible by means of the heater. Hence the heater has to apply more heat to B to raise its resistance to obtain the desired proportion, as before. It will, therefore, take more time to rebalance the circuit, and the on-time intervals for the furnace will lengthen. Conversely, if the temperature rises, because the process demands less heat, the proportion a/b would decrease: Less heat to resistor B would be required for balancing, and the on-time intervals would be consequently shortened.

Heater F is introduced to eliminate offset and produce reset action. It is in series with heater E and when contact D_1 is closed it supplies heat to resistor C. Because resistor C is built on a heavier base than resistor B, it responds more slowly to a change in temperature. It adds a gradual component to the bridge unbalance which increases with the time the temperature stays off the set point. In the case of a temperature drop this makes the on-time intervals increasingly longer. It not only reduces the time needed to bring the temperature back to the set point, but is an action which persists until the furnace has returned automatically to the desired temperature.

If, for instance, a load change drives the furnace temperature below the set point, the longer pulses cause the heavy-base resistor *C* to increase its electrical resistance slowly. This further unbalances the circuit and further lengthens the pulses. As a result, when the furnace temperature returns toward the set point, the heavy-base resistor, which is also slower in cooling than *B*, does not return to its original value, but to a new value which causes the circuit to rebalance at a new level. Because the added resistance of the heavy-base resistor *C* is just enough to compensate for the increase in heat demand, circuit rebalance is established with furnace temperature back at the set point, preserving the longer pulses as long as the increased demand exists.

To prevent excessive overshooting when the process is being started and brought up to temperature, a rate of approach adjustment is provided by which the pulses can be manually regulated.

The actual instrument connects the contactor to the output of an electronic amplifier. The amplifier in turn detects the bridge unbalance.

Single-speed Floating Controllers

An example of single-speed floating control is the Barber-Colman arrangement shown in Figure 11-5. Again, it is assumed that a temperature controller positions a valve, although different arrangements may as well be used. As

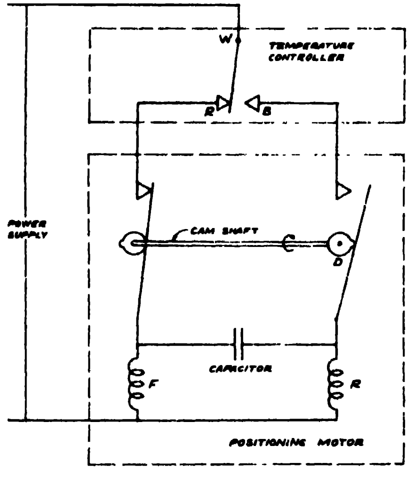

Figure 11-5. Schematic of Barber-Colman floating controller.

long as the circuit through *W, R,* and *F* is closed, the motor will run in the forward direction, opening the valve. It will stop when the movable contact *W,* which is actuated by the thermal element of the temperature controller, is between *R* and *B,* and it will turn in the opposite direction when contact is made between *W* and *B.* The cam contacts operated from a cam shaft coupled to the motor, are merely provided to open when the valve is either fully open or fully closed to prevent the motor from running beyond either of the extreme positions. To regulate the speed of the motor, a small oil pump is built into the unit which pumps the oil from a reservoir through an orifice and back into it again. The orifice is adjustable and the resistance it offers to the oil flow slows down the motor. In this manner, the motor speed can be regulated.

The Wheelco Throttltrol modifies the principle of single-speed floating action by limiting the movement of the final control element in successive steps. Figure 11-6 illustrates the operation. The control instrument with its "high" (*H*)

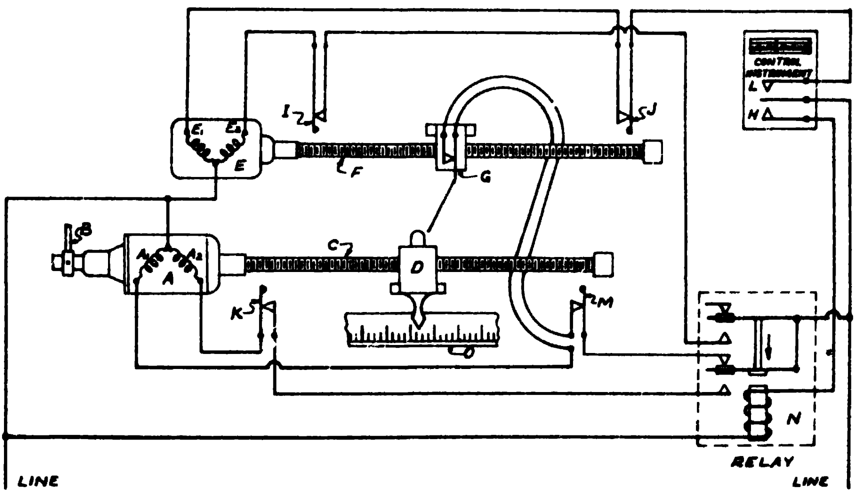

Figure 11 6. Schematic of Throttltrol operation

and "low" (*L*) contacts is shown in the upper right corner. A reversible motor *A* operates the final control element through the operating arm *B.* Motor *A* also rotates a spiral shaft *C,* which when revolving drives a rider, *D,* either up- or downscale, depending on whether either motor winding A_1 or A_2 is energized. A second reversible motor, *E* drives spiral shaft, *F,* and through it rider *G.*

When winding E_2 is energized, rider *G* moves toward the left until it hits limit switch *I,* thereby opening it. This interrupts the circuit through winding E_2 and further movement to the left is not possible. The same limitation is provided for movement toward the right when E_1 is energized by means of the limit switch *J*, which opens the circuit through E_1. Limit switches *K* and *M* fulfill the same function for rider *D*. Rider *G* carries a switch which is operated when it strikes the prong on rider *D*.

Suppose a process temperature is measured by the control instrument and operating arm *B* positions a control valve. As the temperature increases, contact *H* in the instrument closes. This energizes relay *N*, which pulls its contacts down, energizing in turn winding A_2 of motor *A*. The motor turns the valve toward its closed position. Simultaneously, it moves rider *D* toward the left until it hits limit switch *K*. This interrupts the circuit through motor winding A_2, and the motor stops with the valve in fully closed position.

When relay *N* acted, its upper contact also closed a circuit through winding E_2 of motor *E*. Both motors had started simultaneously, and rider *G* moved toward the left as well as rider *D*. However, rider *G* moved at a very much slower rate. When *D* has reached its limit switch *K*, rider *G* has only passed through a very small fraction of its travel and slowly continues to move.

Since the valve is now fully closed, the temperature will drop and contact *H* will open. Relay *N* will de-energize and its contacts will snap back to their initial position. This stops motor *E* and starts motor *A* in the opposite direction, since the winding A_1 is now energized. Consequently, the valve will begin to open and rider *D* will move toward the right. However, *D* will not be able to move all the way back from where it originally started. Rider *G* moved to the left meanwhile, and as soon as the prong of *D* hits the switch on *G*, the switch opens and the circuit through windings A_1 is interrupted. The motor stops and the valve remains in a partially open position.

It is possible, and quite probable, that the valve is now somewhat too wide open. The temperature will rise, and the procedure described before will be repeated, except that the final position of the valve is somewhat less open. Thus by a certain number of oscillations, the valve will finally arrive at a position which corresponds to the process.

Should the temperature drop and the *L* contact close, the E_1 winding of the motor *E* will energize and *G* will move toward the right. This will close the switch on *G* and the A_1 winding of the *A* motor will again become energized, thus allowing the valve to open further.

Rider *D* carries a pointer which indicates the amount of valve opening on scale *O*.

Proportional-speed Floating Controllers

Figure 11-7 illustrates GPE Controls' proportional-speed floating controller. The controller receives a comparatively high-power controlled-variable signal from a transmitter, such as was shown in Figure 4-35. It compares the transmitter signal with the set point, and when necessary sends a corrective signal

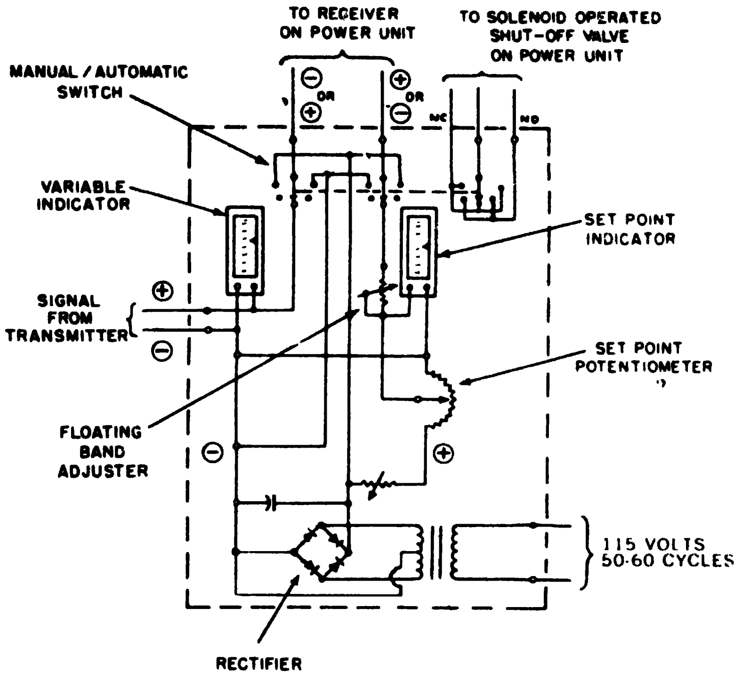

Figure 11-7. Schematic of proportional-speed floating controller. (*Courtesy of GPE Controls, Inc.*)

to the final control element. Two indicators are provided; one is to read the controlled variable, the other the set point. The constant voltage transformer through the rectifier and set point potentiometer feeds a voltage into the circuit to balance the voltage received from the transmitter. By adjusting the set point potentiometer, the level of the balancing voltage and hence of the set point is shifted.

The actuator of the final control element is designed so that it moves with a speed that is proportional to the magnitude of the corrective signal. This is further described in the chapter on "Final Control Elements." The floating band adjuster changes the magnitude of the output signal and hence the speed of the actuator for a given deviation of the controlled variable from the set point. A manual-automatic switch permits manual-to-automatic transfer. This multi-position switch has additional contacts which are wired into the actuator of the final control element. They permit manual movement of the final control element in either direction or locking it in position.

In some cases, it is possible to apply the measurement signal directly to an electrohydraulic transducer and thus obtain a very simple and compact controller. An example is GPE Controls' Rotojet which is described in Chapter 14.

Proportional-position Controllers

An example of a simple proportional electrical controller is illustrated in the circuit of Figure 11-8. This arrangement is used by Minneapolis-Honeywell Regulator Company, mainly for temperature control. The thermal system of the temperature controller actuates the wiper of potentiometer *G*. The position of contact *W* which is part of the valve positioning motor is controlled by coils *E* and *F*. If more current flows through *E* than through *F*, contact *W* will move toward *R*. Conversely, if more current flows through *F* than through *E*, contact *W* will move toward *B*. Contact between *W* and *R* causes a current flow through motor winding *F* and the motor will move in one direction. When contact between *W* and *B* is made, motor winding *R* will be energized

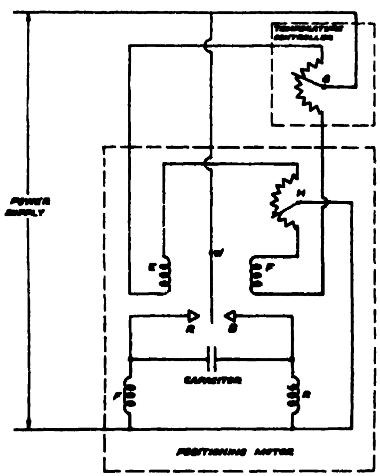

Figure 11-8. Schematic of Honeywell proportional-position controller.

and the motor will move in the opposite direction. Thus, the motor will either open or close the valve, except when the contact *W* is in the position shown in the illustration. At this position the motor stands still and the final control element maintains its position. Under such balanced conditions exactly the same amount of current flows through coils *E* and *F*. Should the temperature deviate from the set point, then potentiometer *G* will change its position.

Suppose the wiper moves upward. This increases the current through *E* and decreases it through *F*. Consequently, *W* will be attracted toward *R* and the motor will start running in the corresponding direction. The wiper of potentiometer *H* is mechanically linked to the motor movement, and as the motor runs the wiper will move downward, compensating for the unbalance caused by *G*, until the currents through *E* and *F* are again the same, bringing *W* back to its neutral center position. It follows that the amount of motor movement is proportional to the amount of temperature deviation. The relatively narrow band width is usually chosen between 3 and 6°F. It is factory-set and not adjustable.

Another method of proportional control action is exemplified by the Stepless Gardsman Controller (West Instrument Corp.). It uses basically the same photocell arrangement as the Gardsman Pyrometric Controller previously described and illustrated in Figure 11-2. An amplifier and a saturable core reactor are added. The opaque flag *F*, which blocks the light beam when the positions of millivoltmeter pointer and index pointer coincide, does so gradually as the two pointers approach each other. Consequently, the current passing through the photocell is reduced gradually until the flag reaches a point where the light beam is eclipsed completely, at which point only a very slight current flows through the cell.

The saturable reactor is a device for controlling current by means of a variable impedance. A simple saturable reactor is a coil wound around a core of magnetic material. The external load is in series with the coil. Unmagnetized, the core strongly opposes the flow of a.c. through the coil and load. By magnetizing the core, the impedance is reduced, permitting a greater percentage of the a.c. current to reach the load.

It is possible to control the degree of core magnetization and hence of a.c. impedance by adding a d.c. control current. This current is applied to a control coil wound about the same core as the a.c. coil. The a.c. current flow through a.c. coil and load is then monitored by the amount of d.c. current in the control winding. The saturable core reactor is frequently referred to as a magnetic amplifier, particularly when certain refinements are added to the basic unit.

In the Gardsman controller the current which flows through the photocell is amplified and then applied as control current to the d.c. winding of the saturable core reactor. The a.c. windings are connected to the a.c. power supply and the load, respectively. Variations in the control current thus modulate the current flowing through the a.c. windings in proportion to the variations emitted by the photocell. Hence, power supplied to the load is proportional to the demand sensed by the measuring instrument. The reactor does not consume power through heat generation; but since it is connected with the load, certain losses are unavoidable. When the controller is calling for full power, 90 per cent of maximum power will be applied; but when it is calling for no power, 3 per cent will still be applied, since the circuit through the reactor and the load is never opened. Thus the power is controlled between 3 and 90 per cent of maximum in proportion to the amount of light that the pointer flag allows to fall on the photocell while it is within the proportional band. The band width is adjustable between ½ and 4 per cent of the range.

Proportional plus Reset Controllers

The Beck Triple Function Mechanism made by the Harold Beck Company is essentially a powerful motor of a 30 pound-foot torque that includes in the unit a slide-wire for proportional-position control and a reset action feature. The motor positions the final control element. Figure 11-9 shows the principle of operation in a schematic diagram that includes the Beck Triple Function Mechanism, the Beck electronic relay detector, and a control instrument. The proportional-band (gain) potentiometer R_2 and the set-point potentiometer are manually adjusted. Control potentiometer R_7 and the mechanism potentiometer

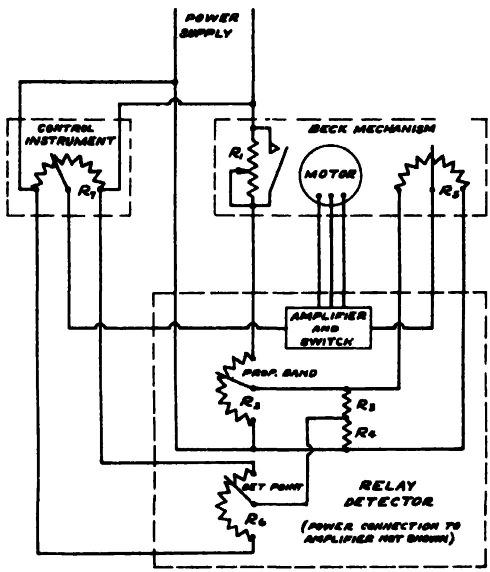

Figure 11-9. Schematic of Beck triple-function mechanism, relay detector, and control instrument.

R_5 are automatically positioned from the control instrument and Beck mechanism, respectively.

The control potentiometer spans either the entire scale of the instrument or only part thereof. It is assumed here that it covers the whole scale.

The arrangement contains two bridge circuits. The primary bridge comprises control potentiometer R_7 and set-point potentiometer R_6. The secondary bridge includes resistors R_3 and R_4 and potentiometer R_5. Resistor R_2 sets the proportional band or gain of the control system by changing the voltage that is applied to the secondary bridge, while the voltage to the primary bridge is kept constant. If the voltage to the secondary bridge is reduced, a larger amount of slider movement on mechanism potentiometer R_5 is required to balance a deviation on control potentiometer R_7 than would be the case with higher voltage. Hence, reducing the voltage on the secondary bridge by manipulating potentiometer R_2 will increase the gain, *i.e.,* narrow the proportional band.

The set point is adjusted by potentiometer R_6. Its location may be either in the relay detector, as shown in the diagram, or part of the control instrument. As long as the set point potentiometer R_6 is divided into two equal parts by the slider, the slider of R_7 must also be at the midpoint to keep the system balanced. This means that under this condition the set point of the controller is at midscale of the instrument. However, adjusting the set point potentiometer by an amount as shown in the diagram, produces an opposite balancing movement of the control potentiometer, so that the set point is shifted toward one end of the instrument scale. Set point adjustment to any point on the scale is thus possible.

Proportional-position control is obtained by this arrangement because a deviation of the controlled variable from the set point will produce a response in the control instrument which readjusts the slider of R_7. The resultant unbalance is sensed by the relay detector and converted into a corrective signal to the motor of the Beck mechanism. The rotating motor positions the slider of R_5 to rebalance the circuit. As soon as balance is obtained the motor stops.

The mechanical construction of the Beck mechanism is such that by means of a pawl-and-ratchet arrangement the slider R_5 will return along the potentiometer toward the midpoint faster than it departs, in relation to the speed of the motor. When a certain deviation of the controlled variable occurs, it will produce a corresponding movement of the motor, together with the slider of potentiometer R_5, to rebalance the control circuit. Assume this movement has increased the valve opening by a certain amount. The result will be the return of the controlled variable to the desired value. As this occurs, the control instrument moves its slider R_7 toward the initial value; as a result, the motor is re-energized, this time in the opposite direction, and returns the slider of R_5 by means of a pawl-and-ratchet mechanism. However, the slider returns faster to its initial midposition than the valve is reset to its original opening, and the system becomes balanced at a valve opening larger than before the deviation occurred.

The contact across resistor R_1 is periodically closed—usually one second per minute—during all the time the control system is in operation. When it closes it cuts out the resistor, which is in the power supply to the secondary bridge. This means an increase in voltage and, therefore, is equivalent to a decrease in gain. As long as the slider of R_5 is in its midposition, cutting in and out of R_1 is of no consequence. If, however, a deviation of the slider exists, the effect of the deviation is increased every time the contact closes. This causes renewed motion of the motor and the valve. Due to the mechanical pawl-and-ratchet arrangement the discrepancy between valve opening and slider position is increased. The result is that the valve remains in a slightly wider open position each time the circuit recovers from the transitory disturbance caused by cutting resistor R_1 in and out. The action continues until the slider of R_5 regains its midposition and this is only possible when the slider on R_7 is back to its original position, which again requires that the controlled variable is back at the set point.

Thus reset action is obtained which continues repositioning motor and valve until the controlled variable coincides with the set point and the primary bridge is again in balance.

The Hays Master Pressure Controller is another example of how in an electric controller proportional and reset action can be combined. Its principle is illustrated in Figure 11-10. It is designed as the main controlling unit of the

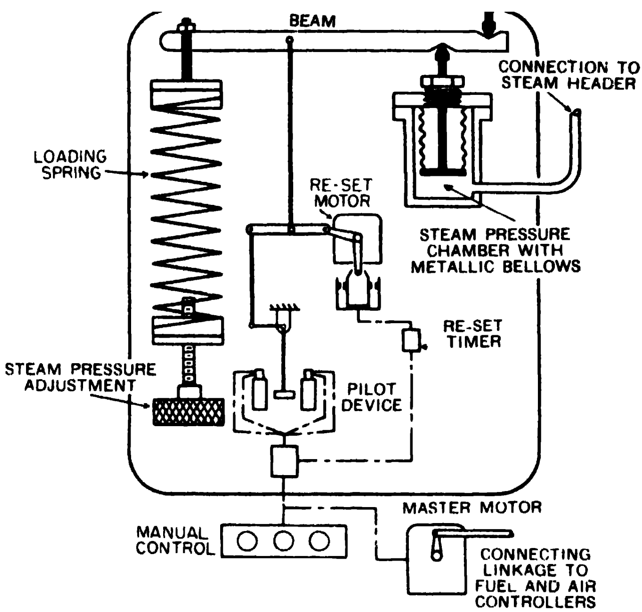

Figure 11-10. Schematic of master pressure controller (*Courtesy of Hays Corp.*)

Hays centralized combustion control system. It responds to a change in steam pressure and adjusts the rate of fuel and air supply to maintain the steam pressure practically constant.

The pilot device which is shown as part of the unit is illustrated separately in Figure 11-11. A magnet bar (3) is connected by a suitable linkage to the control mechanism and moves to the right or left depending on the controller action. Two mercury switches are used; one is mounted to the left and the

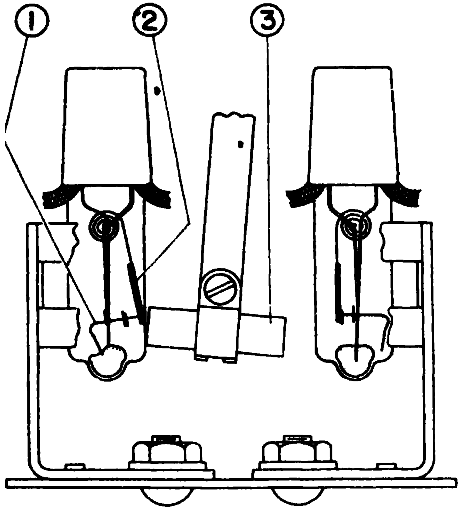

Figure 11-11. Schematic of pilot device. (*Courtesy of Hays Corp.*)

other to the right of the magnet bar. When the magnet gets sufficiently close to one of the glass tubes it attracts an iron plate (2) inside the tube. This draws a wire (1) into a globule of mercury in the bottom of the tube, closing the circuit. As soon as this circuit has caused the proper response and corrected the condition which started the movement, the magnet is drawn away from the switch and the mercury switch again breaks the circuit.

Steam header pressure is connected to the pressure chamber containing the metallic bellows, as shown in Figure 11-10. Changes in steam pressure are received by this chamber, causing a movement of the bellows. This in turn moves the beam, which acts against the loading spring. The beam movement transmitted through the follow-up linkage moves the magnet bar making contact with one of the mercury switches, and through relays starts both the master motor and the reset motor. The movement of the master motor is transmitted either by electrical means or by rigid connections to the air and fuel controllers, causing them to make changes in rate of fuel and air proportional to the change in steam pressure. The master motor continues to operate until either the beam returning to its initial position or the action of the reset motor opens the mercury switch in the pilot device.

The reset motor is a two-speed device with a motor-operated adjustable timing interrupter which governs the frequency and length of time of its operation. When the movement of the beam closes the mercury switch and starts the master motor and reset motor, the action of the latter tends to open the switch again. As long as the deviation from the steam pressure set point persists, the reset motor continues to operate through its auxiliary contacts, although at a slower rate because of the timing interrupter. The movement of the reset motor closes again the mercury switch of the pilot device and restarts the master motor to make an additional adjustment to the air and fuel controllers to return the pressure toward the set point. When the set point is reached the reset auxiliary contacts are broken, and no further action takes place until the pressure again deviates from the desired value.

Controllers for Proportional-position, Reset, and Rate Actions

Figure 11-12 is a simplified circuit diagram showing the main components of Leeds & Northrup's M-Line control unit. The controller provides proportional plus reset action, with or without rate action. A signal of 0 to 4 or 1 to 5 milliamperes d.c. is received from the transmitter of the measuring means and balanced against the set-point signal. Any deviation of the controlled variable from the set point produces a deviation signal. When the controlled variable is at the set point, transmitter current i_3 flowing through resistor R_1 is equal and opposite to set-point current i_5. The actuating voltage e_3 is zero and e_1 is equal to the potential across battery E. The amplifier measures the unbalance between e_1 and feedback voltage e_2 through a synchronous converter, a switch that alternates between the two contacts shown at the rate of 60 cycles per second. The controller increases the output current i to the value required to make e_2 equal e_1. The output current is also applied to an electropneumatic converter, or magnetic amplifier and saturable core reactor. The load indicated in the diagram would consist of a pump, a control element, or the heating elements of an electric furnace.

When the controlled variable moves off set point, the transmitter current i_3 changes, producing an unbalanced signal e_3 across R_1. The voltage e_1 then becomes equal to e_3 plus E and the amplifier detects an unbalance between e_1 and e_2 which at first is equal to e_3. This unbalance forces the output current to assume a new value such that e_2 again becomes equal to e_1. As a result, current variation is proportional to the deviation from the set point. The gain ad-

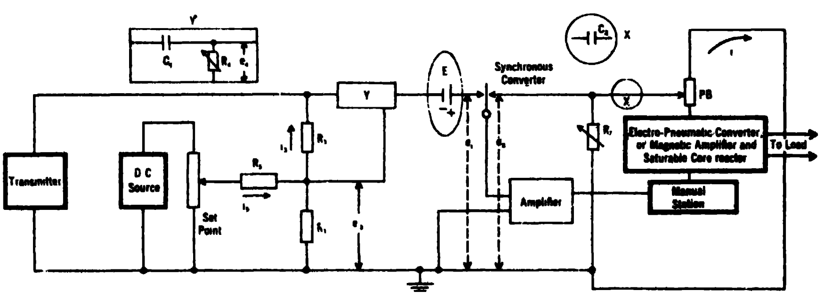

Figure 11-12. Schematic of M-line control circuit. (*Courtesy of Leeds & Northrup.*)

justing rheostat *PB* permits adjusting the percentage of transmitter range over which the output current will go from its maximum value of 5 milliamperes to its minimum value of 0 milliampere.

If the controlled variable tends to settle off the set point due to a sustained load change, proportional-position action alone would not return the controlled variable to the set point. In order to accomplish this, reset action is introduced at X by means of capacitor C_2. The reset rate is adjustable by means of variable resistor R_2. With C_2 in the circuit, battery E is not actually required and is therefore not found in the controller.

With the controlled variable lagging above or below the set point, an e_1 voltage other than zero is produced. To provide an equal e_2 voltage, a current must flow through R_2, charging capacitor C_2. As C_2 charges, this current tends to diminish. To keep the charging current flowing, the output current must continually change, producing a corresponding change in the controlled variable, until e_1 is again at zero with the controlled variable on the set point.

Rate action is introduced at insert Y. Rate time is adjustable by means of variable resistor R_4. The speed at which an upset produces a change in the variable determines the rate at which the transmitter current varies. As i_3 changes at a given rate, it produces a changing voltage across R_1 and R_3. As long as voltage across R_3 continues to change, a current flows through R_4, charging capacitor C_1. This produces rate action voltage e_4, which is added to the proportional-position voltage across R_1, and e_1 thus becomes greater than it would be with proportional-position action alone. In order to make e_2 equal to e_1, the current output must contain an added increment equivalent to that demanded by e_4, thus producing an additional change in the final control element. When assuming the voltage across insert X to equal zero, it becomes evident from the diagram that the feedback voltage produced by the output current across *PB* is identical with voltage e_2, and that the change in current is the sum of the proportional-position and the rate actions. This further adjustment of current output due to rate action is maintained as long as transmitter current i_3 is changing, but ceases when i_3 is constant.

The Foxboro Electronic Consotrol Controller is available in two models. One is a proportional plus reset controller with a gain of 0.25 to 4 (equal to a proportional band of 50 to 400 per cent) and a reset of 2 to 60 repeats per minute. This would mean that it is suitable for processes with small time constants and with dead times ranging from about 0.5 to 15 minutes. Generally, flow control systems fall into this category, and the manufacturer calls this a "Flow Controller."

The other model is called "Universal Controller" and includes rate action. Its gain is adjustable from 0.3 to 50 (proportional band: 2 to 300 per cent) resets from 0.04 to 100 repeats per minute and rate times from 0.01 to 25 minutes are available.

The Flow Controller utilizes a magnetic amplifier, while the Universal Controller uses a transistorized amplifier instead.

Figure 11-13 illustrates the front view of either controller. At the top, an indicator shows the difference between controller set point and process measurement, *i.e.*, the deviation signal. The span of this meter is considerably expanded so that, rather than 100 per cent of scale being spread across its face, the span is 10 per cent on either side of center. Thus, when the measurement is above the set point by 10 per cent of transmitter range, the pointer will deflect full scale to the right, and when 10 per cent below the set point, it will deflect full scale to the left.

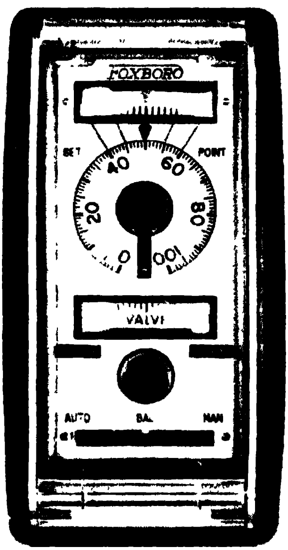

Figure 11-13. Front view of Consotrol controller. (*Courtesy of Foxboro Co.*)

In addition to showing deviation, this meter, when used with the set-point scale, indicates process measurement when the controller is on either automatic or manual operation. When the deviation pointer is centered, for example, the scribed line directly below the pointer extends the reading to the set-point scale. Since there is zero deviation, the measurement is the same as the set point. At other points on the deviation scale, a reading can be taken similarly by following the guide lines from the deviation pointer to the set-point dial. Thus, the indicating control station can be used without any auxiliary receiver. When the transfer switch is in the "Bal" position, the meter indicates the difference between controller output and manual output.

The set-point dial, seen below the deviation indicator, is available in various ranges to suit each particular process. Turning with the knob and dial is a

10-turn potentiometer which provides the set-point voltage. A Zener diode regulator (*cf.* page 15) supplies stable d.c. voltage to this potentiometer for comparison with a voltage drop in the measuring circuit from a transmitter.

Below the set-point dial is an output current meter graduated 0 to 100 per cent. The meter is always connected so that the output signal is readable at all times, whether on automatic or manual control.

The automatic-to-manual transfer switch is a four-position switch located at the bottom of the instrument. Its function will be described later.

Figure 11-14 shows a greatly simplified functional circuit of the flow controller. The measurement signal produces a voltage which is compared with a

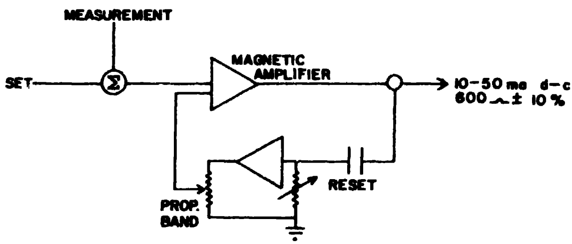

Figure 11-14. Simplified circuit of Foxboro flow controller.

set-point voltage, and their difference, the deviation signal, is fed to the input of the magnetic amplifier. The set-point voltage is adjusted by positioning a potentiometer. The resulting output of the amplifier is a 10 to 50 milliampere d.c. signal which in turn feeds an output load, such as an electrohydraulic valve actuator, of 600 ohms ± 10 per cent.

Across a resistor in the output circuit is a feedback circuit incorporating the functions for proportional band (gain) and reset action. A magnetic amplifier in this circuit amplifies the feedback signal to the desired level. The feedback signal is fed back into the input circuit of the controller where it is connected to oppose the actuating signal.

Varying the setting of the proportional-band resistor changes the relative value of the voltage which is fed back. In modifying the amplifier input, the feedback signal then has the effect of varying the amplifier gain in proportion to the actuating signal. The reset action is varied by the adjustable resistor which together with the capacitor changes the rate of change of the feedback signal.

The functional schematic diagram for the Universal Controller, Figure 11-15, is identical to that of the Flow Controller diagram of Figure 11-14, except for the addition of a derivative network in the feedback circuit which provides the desired rate action. Adjusting the derivative resistor varies the time it takes to charge the capacitor and, hence, adjusts the rate time of the controller.

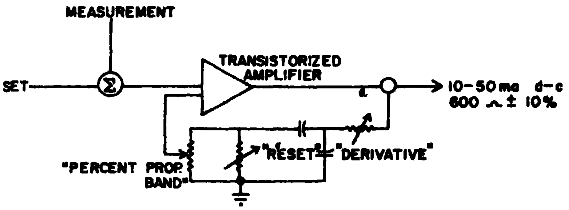

Figure 11-15. Simplified circuit of Foxboro universal controller.

The particular method which Minneapolis-Honeywell Regulator Company uses for obtaining a derivation signal from comparing the controlled variable signal and set point is illustrated in Figure 11-16. Two opposing input forces are applied to the beam of the actuating signal servo circuit. One force is due to the controlled variable signal applied through a magnet unit. The other is the set point force which is applied to the beam by an adjustable spring. Any difference between these two opposing forces deflects the beam. The detector senses this deflection and changes the inductance of the oscillator, unbalancing the bridge circuit of which it is a part. Thus the output of the circuit itself changes between – 10 and + 10 volts in response to plus and minus deviations between the controlled variable signal and the set point. This output is also applied to a second coil in the magnet unit to rebalance the beam.

The magnet unit would normally consist of a coil with two windings attached to the beam and which moves in the field of a permanent magnet. The force exerted by the magnetic field on the coil is proportional to the current flowing through the coil. Whether the force attracts or repulses depends on the direction of the current flowing through the coil. Hence by having the flow through the two windings in opposite directions, a force results which is proportional to the difference between the two currents.

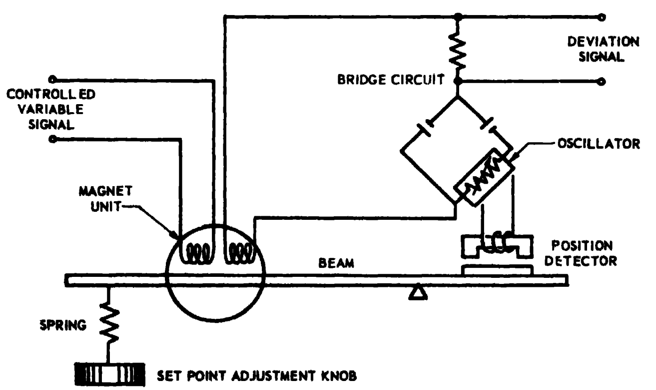

Figure 11-16. Deviation signal computer. (*Courtesy of Minneapolis Honeywell Regulator Co.*)

The position detector consists of two pieces of ferrite, one mounted on the movable beam and the other fixed rigidly on the chassis. A coil is wound around the latter. The coil inductance changes with the spacing between the two pieces of ferrite.

A third method to obtain the set point and deviation signals is used in Crane's Swartwout controller and Taylor Instrument's a.c. electronic control system. A schematic of the latter is shown in Figure 11-17. The transmitter displaces the core of a differential transformer. In doing so, it generates a voltage in the secondary of the transformer. The resulting controlled variable signal from the transmitter of 0 to 200 millivolts is compared with the signal from the feedback differential transformer in the a.c. recorder and the signal difference is amplified to drive a servomotor which repositions the core of the feedback differential transformer. This servomotor also operates the pen drive mechanism.

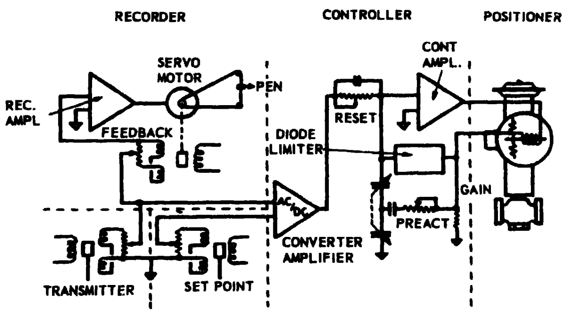

Figure 11-17. Electronic control system. (*Courtesy of Taylor Instrument Cos.*)

The signal from the transmitter is also compared with the output of the set point differential transformer. Manual positioning of the core of the latter transformer adjusts the set point. The resulting deviation signal is converted into a d.c. signal in the converter amplifier and applied to the controller proper. The controller circuit shown has proportional-position, reset and rate actions, the latter being called "preact" by Taylor. The diode limiter circuit prevents amplifier saturation. This overcomes so-called reset wind-up providing good off-band control (*cf.* page 254) even where rate action is not provided, and a proportional plus reset controller is used. Reset and rate action are obtained through resistor-capacitor networks as usual. In this case reset action is provided in the forward path that leads into the control amplifier while the feedback contains the network for rate (preact) action.

The controller output current of 1 to 5 milliamperes d.c. operates an electro-pneumatic valve positioner such as will be described further below.

Transmitters

Electric circuits offer a greater variety of modifications than pneumatic circuits. Consequently, the extent of standardization that exists with pneumatic controls cannot be obtained with electric control systems. Most every controller requires its own transmitters.

The control potentiometer of the Leeds & Northrup Series 60 system is located in the Speedomax recorder or indicator. The servomotor which positions the pen also positions the slider of the control potentiometer. Similarly, a potentiometer is needed in the final control element to feed back its position. In this case, any transmitter can be used provided it has an output which is suitable for the Speedomax instrument.

Foxboro's, as well as GPE's, flow transmitters which were illustrated in Figures 4-34 and 4-35 have built-in electronic amplifiers and outputs suitable for their respective controllers. Some interchangeability does exist here but this is more the exception than the rule.

Another Foxboro method consists in converting the measurement into mechanical motion. Figure 11-18 illustrates how the mechanical motion of the measuring element is converted into an electrical signal by their Dynaformer Transducer, which is a modification of the conventional differential transformer. The input winding is connected to 115 volts a.c. from a voltage stabilizer. Output coils *A* and *B*, each with the same number of turns, are wound and connected so that voltages induced in them will oppose. A copper ring circling the iron core is pivoted through an arc of 40 degrees in the air gap of the core by the measuring element.

At zero measurement, the copper ring is centered in the air gap, as shown in the illustration. In this position, the ring has a small but equal effect on the magnetic flux in each half of the core. This means that the induced voltages in output windings *A* and *B* remain equal, and, being opposed, cancel out. Net output is zero.

As the measuring element moves with increasing measurement, it pivots the copper ring toward output winding *A*. The alternating current induced in the

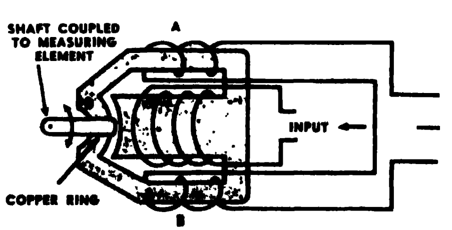

Figure 11-18. Dynaformer transducer. (*Courtesy of Foxboro Co.*)

copper ring produces a countermagnetic force which now tends to oppose, or neutralize some of the flux in the upper half of the core. Flux in the lower half of the core simultaneously increases. As a result, the induced voltage in output winding *A* decreases, while the induced voltage in winding *B* increases. The difference between these voltages, constituting the transducer output, is proportional to the physical position of the copper ring—and thus proportional to measurement.

Where the measurement is an electric quantity, such as in thermocouples and resistance thermometers, the signal is suitably amplified and then applied to the controller. The Taylor potentiometer transmitter as was illustrated in Figure 1-12 is a typical example.

In Minneapolis-Honeywell's control system, the transmitter represents a variable resistance rather than a voltage- or current-generating unit. This eliminates the need for a separate power supply at the transmitter, except with millivolt transmitters. The method of converting process pressure, for example, into an electrical signal is illustrated in Figure 11-19. The measuring element

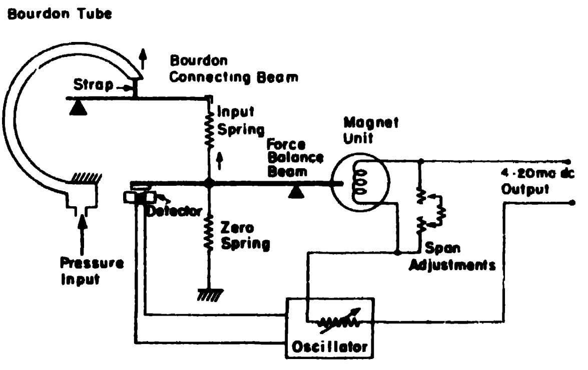

Figure 11-19. Pressure transmitter. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

is either a Bourdon tube or bellows assembly depending on the range of measurement. The response of the measuring element to the process pressure deflects the input spring which exerts a force on the force-balance beam, changing the air gap in the detector assembly. The operation of the detector and the magnet unit were described in connection with Figure 11-16. The inductance in the oscillator circuit changes with the air gap in the detector. When this happens, the oscillator, which acts like a variable resistor, modulates the current in the circuit between 4 and 20 milliamperes d.c. The amount of feedback to the magnet unit is controlled by the span adjustments.

Automatic-to-manual Transfers

Some automatic-to-manual transfer arrangements have been mentioned before. Additional details are discussed in the following. It is generally considered necessary to be able to remove the controller for maintenance work and to continue control by manual adjustments of the final control element. The switching from automatic to manual and back to automatic control should proceed smoothly without any sudden change of the final control element. The ability of smooth transition is commonly called bumpless transfer. The manual control unit of a Taylor Transcope Recorder-Controller is shown in Figure 11-20. This chassis plugs into the recorder housing and is located in a narrow rectangular area directly above the recorder slide. Visible from the front is the selector switch on the left, for choosing the desired mode of operation; the manual adjustment on the right for controlling the amount of current supplied to the transducer or actuator when in manual operation; and a meter in the center that indicates output current when the selector switch is in either the "manual" or "automatic" position.

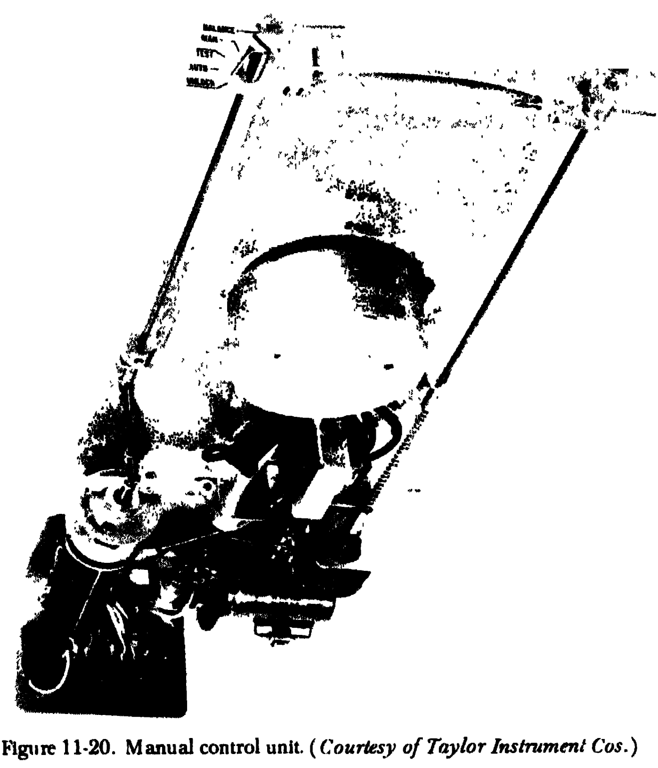

Figure 11-20. Manual control unit. (*Courtesy of Taylor Instrument Cos.*)

The selector switch has five positions: Balance, Manual, Automatic, Test, and Unlock.

The *Automatic* position is the normal operating condition. In this position, the controller output from 1 to 5 milliamperes d.c. is connected directly to the final control element. The meter in the center of the manual control unit shows the output signal from the automatic controller. The output from the manual power supply goes into a dummy load resistor which is adjusted to the same resistance as moving coils and connecting leads, or whatever the output load of the controller is.

In the *Test* position, the automatic controller is still connected with the final control element, but the meter in the manual control unit now shows the output of the manual power supply instead of the automatic controller output. Switching between Automatic and Test positions permits adjusting the manual power supply until the meter readings in either position are equal. It is then possible to switch to the Manual position and have a bumpless transfer. In the *Manual* position, the automatic controller is no longer connected into the circuit and can be removed for maintenance and repair, while the process is on manual operation. The meter reads the output of the manual power supply. As long as the automatic controller is not removed, its output is connected into the dummy load resistor.

In the *Balance* position the process continues to be under manual operation, but the meter now reads the output of the automatic controller. By switching back and forth between the Manual and Balance positions, the outputs of the manual power unit and the automatic controller can be equalized. At this point, bumpless transfer from manual to automatic control can be made.

In the *Unlock* position, the process is on automatic control, the meter shows the controller output, the manual power supply is switched off, and a mechanical lock is released so that the automatic-to-manual unit can be removed from the recorder housing for servicing.

Ratio and Cascade Controllers

In ratio controllers as well as in cascade controllers, described in the next section, the set point is no longer fixed, but becomes a variable magnitude. Ratio control could be defined as multiplication; where one variable—the primary—is measured, its value is multiplied by a constant, and the product becomes the set point for which the control of another variable, the secondary, is automatically adjusted.

Cascade control is similar to ratio control in that it relates the magnitude of two variables to each other. While ratio control adjusts the set point according to the measured value of the primary variable, cascade control adjusts the set point according to the controller output of the primary or master controller.

The two terms, "ratio" and "cascade" control are often used interchangeably. Also, the control instruments are generally the same though the principle of application differs. Hence, ratio controllers may be considered cascade controllers, and vice versa.

In electronic controllers, like the Foxboro controller of Figure 11-13, terminals are usually provided to connect an external set point source to the controller, cutting out the manual set point adjuster of the controller itself. Connecting the output of a primary or master controller into the external set point terminals makes a ratio or cascade controller.

With proportional-speed floating control, GPE Controls uses the arrangement of Figure 11-21 for flow ratio control. The d.c. signal from the secondary flow transmitter feeds directly into the secondary flow indicator and the ratio potentiometer. The d.c. signal from the primary flow transmitter is connected to the primary variable indicator and the voltage divider. The current available for operation of the electrohydraulic valve actuator with proportional-speed floating action depends upon the magnitude of the flow transmitter signals, the

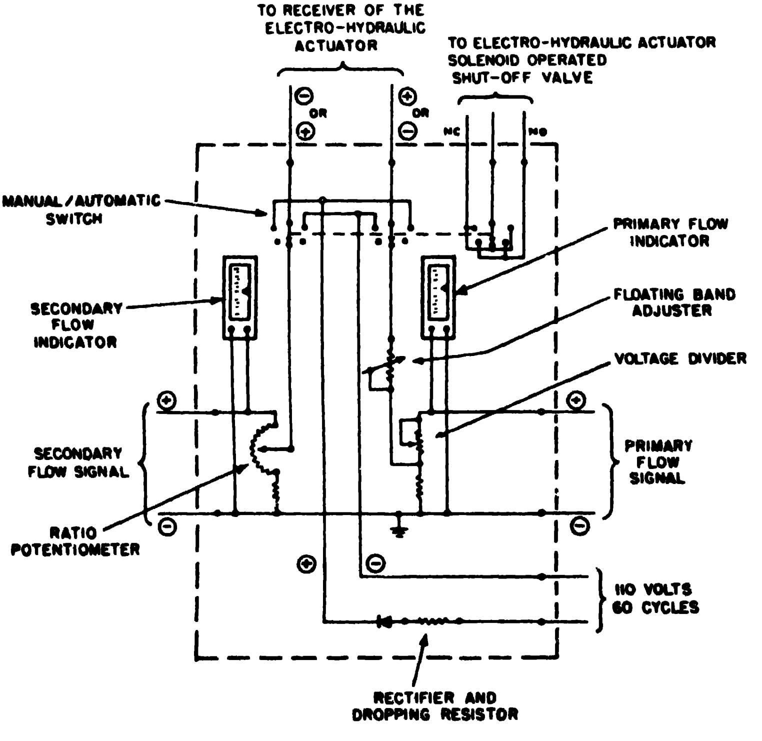

Figure 11-21. Schematic of flow ratio control. (*Courtesy of GPE Controls, Inc.*)

setting of the ratio potentiometer, and the setting of the floating band potentiometer. If both the primary and secondary flow signals are of equal magnitude and the ratio potentiometer is set for a 1 : 1 ratio, no output signal results and the two voltages balance. If, however, the two signals are of unequal magnitude, and the ratio potentiometer is set for a 1 : 1 ratio, the resulting unbalance produces an output signal which is transmitted to the electrohydraulic actuator. The actuator then moves to reestablish the desired ratio. If the ratio potentiometer is set for any ratio other than 1 : 1, a signal is sent to the actuator, whenever one of the flows deviates from the preset ratio. The floating band adjuster changes the speed of the actuator for a given deviation.

Auto-selector Controllers

Foxboro's electronic Consotrol Auto-Selector Control Stations permit the automatic selective control of a number of related process variables. Two or more controllers are so connected that whichever has the highest output will send its signal to an auto-selector unit. The auto-selector unit output signal, 10 to 50 milliamperes d.c., actuates a final control element through an actuator transducer, or positioner.

Sometimes it is desired to have one controller in the auto-selector station take control when its measurement signal reaches a predetermined low limit, and another controller take control when its measurement input reaches a predetermined high limit. These conditions can be satisfied by properly positioning a two-position switch located on the back of each controller. In one position an increasing signal from the measurement transmitter will cause an increasing output from the controller, and in the other, a decreasing signal from the transmitter will cause an increasing output from the controller. A similar two-position switch is located on the back of the auto-selector unit, and by positioning it either high or low selection can be obtained.

Figure 11-22 shows a schematic diagram of a Foxboro auto-selector control station. Assume that auto-selector controller No. 1 is delivering a 40-milliampere d.c. signal to the dummy load R_1. At the same time controller No. 2 is delivering a 10-milliampere d.c. signal to its dummy load R_2. The resistance of R_1 equals that of R_2.

The voltage at A is higher than that at B, since the current in R_1 is larger than in R_2. The polarity of the voltage across each diode is such that diode D_1 will conduct and diode D_2 will not conduct. Hence, the signal to the auto-selector is from controller No. 1.

If the process is now varied so that the measurement signal to controller No. 2 calls for increased output, the voltage across R_2 will rise. As soon as it exceeds the voltage across R_1, the polarity of the voltage across each diode will reverse and the signal to the auto-selector unit will be from controller No. 2.

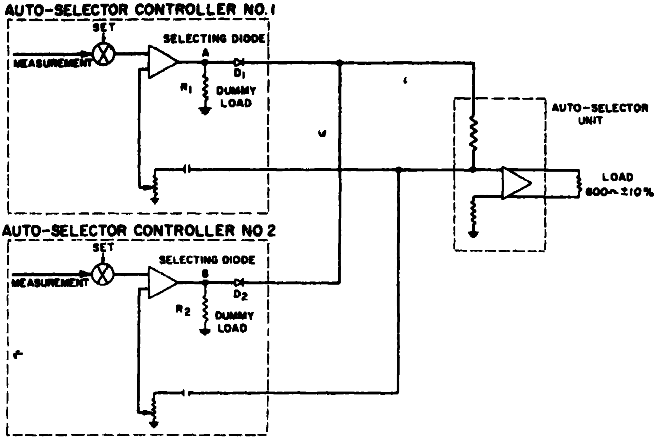

Figure 11-22. Schematic of auto-selector control. (*Courtesy of Foxboro Co.*)

Totalizers

Totalizers combine several measurements to obtain a resultant output which may be applied to measure and control a process. The Hays automatic remote-totalizing controller which operates by means of an electrical arrangement shown in Figures 11-23 and 11-24 is used as an example. The device totalizes simultaneously the flow of several widely different fuels for the furnace of a steam generator, or for an industrial furnace, in order to control the Btu input. The power units are electrically connected to fuel meters Nos. 1 and 2, respectively, and mechanically to their respective receiving potentiometers. The sending potentiometer is added as a means of determining the total Btu input. It can be operated by a steam pressure controller, a temperature controller, or manually. Either fuel, No. 1 or No. 2, may be assumed to be the base fuel and the remaining fuel the make-up fuel. The quantity of both may vary and the quantity of each fuel making up the total may vary; yet the total Btu is maintained correctly. The flow of the make-up fuel is automatically adjusted to control the Btu input to the desired value.

Fuel meters No. 1 and No. 2 measure the flow of the two fuels, and are provided with a pilot device, illustrated in Figure 11-11. When the rate of flow of one of the two changes, the magnetically operated mercury switch of the pilot device in the corresponding fuel meter is actuated, energizing the power unit, until the measuring system is rebalanced. While the power unit is rotating it positions the receiving potentiometer so that its position is proportional to the amount of fuel burned.

The setting of the two receiving potentiometers is averaged by use of a center-tapped auto-transformer, and this average value is applied to the end coils of the relay. The relay controls the movement of a magnet bar, similar to the arrangement shown in Figure 11-11. In actuating the mercury contacts of the control switch it operates the valve-positioning power unit, which adjusts the flow of the make-up fuel.

For manual operation, a fuel selector switch is provided in the circuit between the totalizer and the valve-positioning power units which adjust the fuel flow. By means of this switch it can be determined which fuel is the base fuel and which the make-up fuel.

With the sending potentiometer in a given position representing a definite Btu input demand and the base fuel being burned in a quantity less than sufficient to meet the demand, the make-up fuel is automatically controlled by the totalizer to the required rate of flow to make up the balance. The voltage of the receiving potentiometers at fuel meters Nos. 1 and 2 is averaged in their effect on the relay; and this average is equal to the effect of the sending potentiometer.

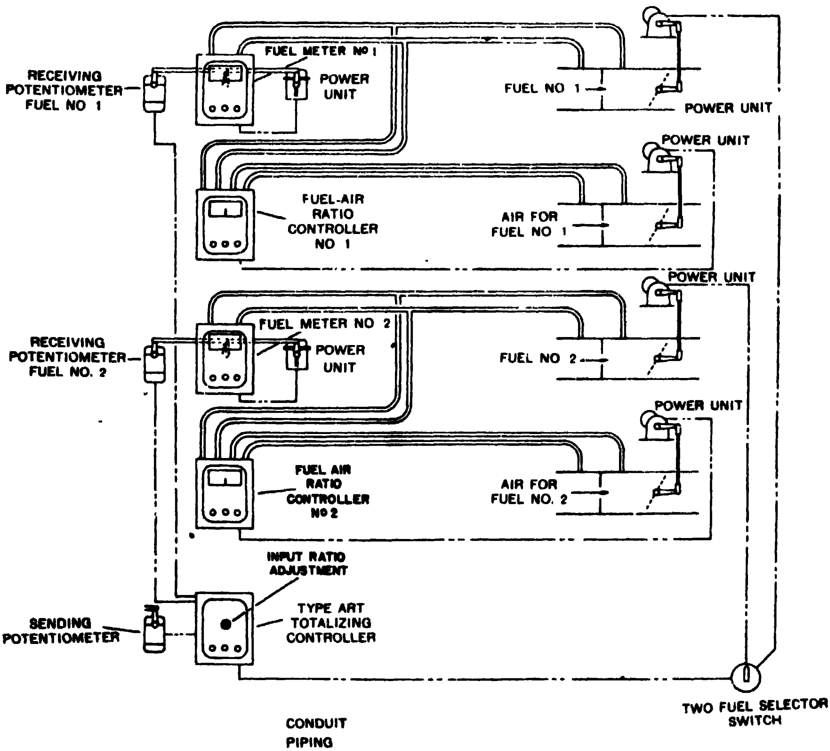

Figure 11-23. Schematic of remote totalizing controller. (*Courtesy of Hays Corp.*)

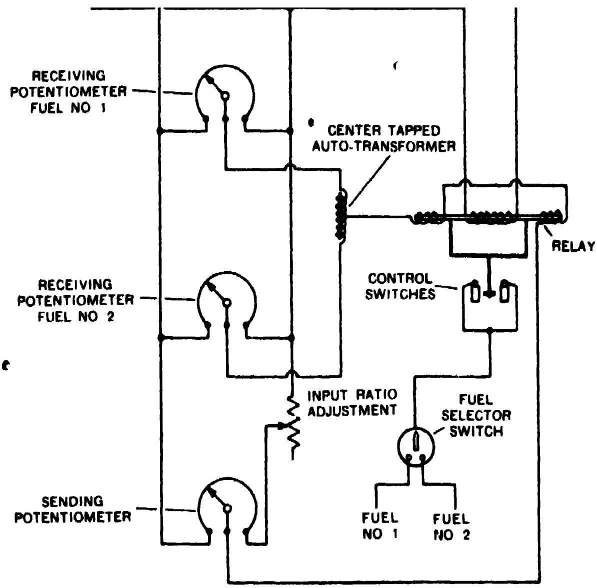

Figure 11-24. Circuit of remote totalizing controller. (*Courtesy of Hays Corp.*)

Whenever the voltage on the coils of the relay is changed either by a change in the flow of one of the fuels or in the setting of the sending potentiometer, contact is made in one of the mercury control switches. This contact operates the valve-positioning power unit controlling the make-up fuel until the required rate of flow is secured. The corresponding fuel meter measures the change in fuel flow and operates the power unit in proportion to the new fuel flow. The power unit moves the receiving potentiometer to balance the totalizing circuit and the relay and breaks the contact in the control switch.

The input ratio adjustment resistance is operated by a knob in front of the case of the totalizer. It can be used to change the ratio of total heat input to one furnace in relation to the heat input to another furnace when the heat input sending potentiometers, corresponding to each furnace, are operated simultaneously, as for example, by a steam pressure controller.

The air required to burn the fuels is individually proportioned to the fuels by fuel-air ratio controllers. These measure the rate of fuel flow and air flow and proportion the air to the fuel by operating the device controlling the flow of air.

12. Self-Operated, Pneumatic, and Hydraulic Controllers

SELF-OPERATED CONTROLLERS

Self-operated controllers actuate the final control element directly by means of the measuring element. Where they can be used, considerable savings are possible. Their use generally excludes the interconnection of indicators or recorders.

Figure 12-1 shows the construction of Taylor's self-operated temperature controller. A Class II vapor pressure system is used and the pressure is directly applied between the bellows and the bellows housing. The valve is direct-acting, and an increase of pressure in the thermal system will close it against the counterforce of the compression spring. An adjusting wheel under the spring allows for change in the spring compression and adjustment thereby of the amount of pressure required in the thermal system to operate the valve. An additional spring—the safety spring—is provided to transmit the movement of the bellows housing to the valve stem. After the bellows has expanded sufficiently to close the valve fully, any further expansion will compress the safety spring. This permits the necessary additional expansion of the bellows in case it is subjected to temperature in excess of its rating, and thus protects it from rupture or distortion.

Suppose this valve is in the steam line to a water heater and the bulb measures the water temperature in the heater. If the temperature increases, so will the pressure in the thermal system, thus moving the valve toward its closed position and diminishing the steam supply. The amount the valve moves is a function of the increase of temperature. If, however, its movement is not enough to throttle the steam supply sufficiently to lower the temperature to its desired level, the adjusting wheel can reduce the spring tension somewhat to obtain the necessary throttling. This means that for conditions of relatively constant load or where limited temperature fluctuations can be accepted, the self-operated controller will operate satisfactorily once the adjusting wheel is set to its correct position. Adjustment of the regulator for different temperatures is possible only within the relatively narrow temperature ranges of such regulators.

In the foregoing example, the valve opening changes in response to tempera-

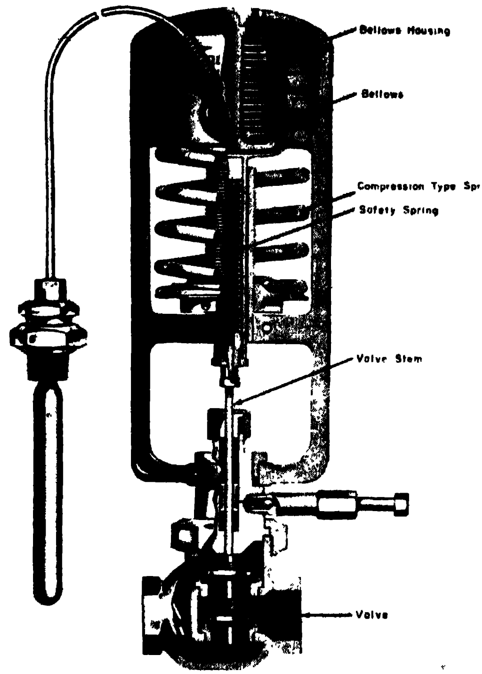

Figure 12-1. Self-operating temperature controller. (*Courtesy of Taylor Instrument Cos.*)

ture variations. Changes in upstream or downstream pressure affect the regulator only after the temperature has been affected by it, and even then a full correction for the condition cannot be obtained. Where load changes are more severe, it is therefore preferable to keep the downstream pressure constant with a pressure regulator, and to change the pressure regulator setting automatically when the temperature changes.

The Duo-Matic Temperature Regulator made by Leslie Company operates on this basis (Figure 12-2). This is essentially a temperature regulator and a piston-operated reducing valve combined in one unit. The action of the temperature regulator is the same as in the previous example; the only difference is that the temperature regulator does not position the valve directly. Instead, it actuates a lever that compresses the pressure limit spring, shown in the illustration, whenever the pressure in the vapor-filled thermal system increases, and *vice versa*.

If the temperature decreases, the pressure in the thermal system also decreases and the compression of the pressure limit spring is somewhat reduced. This deflects the diaphragm downward, which in turn pushes down the stem of

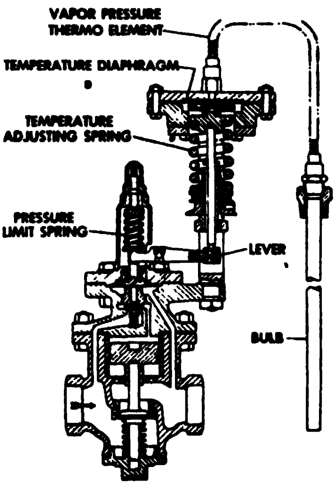

Figure 12-2. Duo-matic temperature regulator. (*Courtesy of Leslie Co.*)

the pilot valve. As the pilot valve opens it admits more steam on top of the piston. This moves the main valve plug downward from its seat, thus admitting more steam to the process in response to the signaled drop in temperature. The downstream pressure is admitted to the bottom side of the diaphragm which balances the pressure limit spring for a given pressure.

Manual adjustment of the compression of the *pressure limit spring* determines the maximum outlet steam pressure. Manual adjustment of the compression of the *temperature-adjusting spring* determines the temperature at which the pressure from the thermal system begins to oppose the pressure limit spring and decrease the outlet steam pressure. By means of the temperature adjusting spring the temperature at which all steam to the heater will be shut off can be accurately set.

The action of the unit keeps the steam pressure to the heater always proportional to the temperature at the measuring bulb, and this pressure is automatically maintained regardless of the volume of steam used by the heater or variations in supply pressure.

Self-operated controllers also find application in maintaining liquids at a predetermined level. Figure 12-3 illustrates such an arrangement (McAlear Manufacturing Company). The float movement is transmitted to the outside through a shaft. A weighted lever is mounted on the shaft. The movement of this lever is transmitted to another weighted lever directly controlling a rotary-stem valve. The power for the operation of the valve is derived from the rising or falling liquid which positions the float. This limits the device to those applications where variations of liquid input and output are not extreme or rapid, and

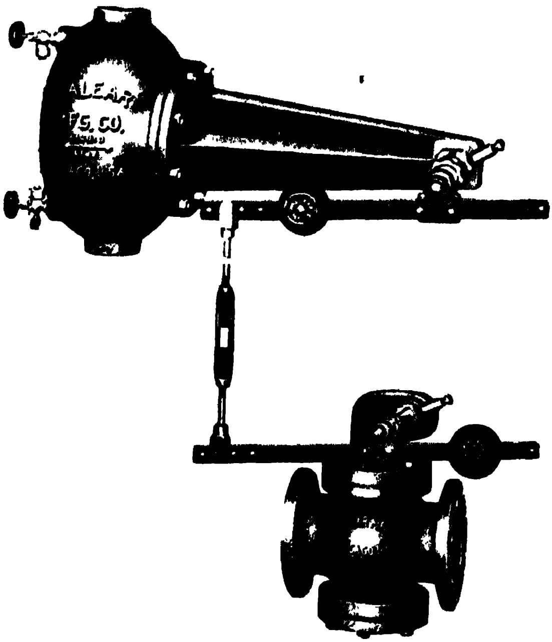

Figure 12-3. Liquid level controller application. (*Courtesy of McAlear Mfg. Co.*)

where the specific gravity of the fluid is sufficient to provide the buoyancy necessary to operate the valve. It is not recommended for use with high-pressure differentials across the valve or for applications requiring valves larger than 4 inches.

PNEUMATIC CONTROLLERS

Basic Mechanism

The basic principle used in almost every pneumatic controller is the nozzle-and-flapper arrangement illustrated in Figure 12-4. While a number of refinements may, and in many cases *must* be added, this principle is workable and is successfully used in simple controllers like the Honeywell Pneumatic Temperature Controller. The thermal system operates the flapper. As the flapper uncovers the nozzle, flow through the nozzle increases. This increase in flow produces a larger pressure drop through the bleed restriction, and consequently a decrease in air pressure applied to the control valve. Inversely, as the flapper approaches the nozzle, the nozzle back pressure increases.

The nozzle back pressure will increase to the magnitude of the supply pressure, usually 15 psi*, when it is completely closed by the flapper, disregarding the leakage which occurs around the flapper. When the nozzle is fully uncovered, the back pressure will drop to a value which is equal to atmospheric pressure plus the pressure drop across the nozzle opening. The resulting minimum back pressure differs with design. In moving the flapper toward the nozzle, it is possible to obtain any intermediate pressure between the minimum pressure and 15 psi. The most common standard pressure range is 3 to 15 psi.

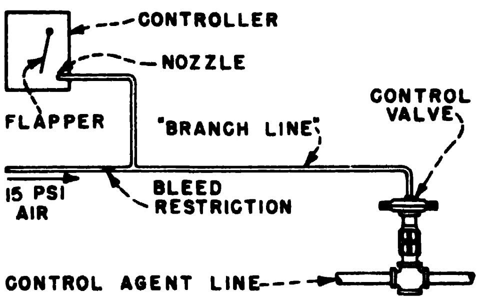

Figure 12-4. Schematic of a pneumatic control system. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

In actual practice the relationship in controllers like the one just described is not linear. This has little effect in this case because this controller is designed for high gains which are equivalent to narrow band widths. Within such narrow bands the nonlinearity is not noticeable. Suppose a temperature controller has a range of 150°F and the nonlinearity in the control air pressure is as indicated by the dashed line in Figure 12-5. The ordinate gives the valve movement in response to temperature deviations from the set point at 75°F. The abscissa refers to two band widths. The upper row of figures corresponds to a proportional band of 3°F. Under this condition the valve passes from fully open to fully closed between 73.5 and 76.5°F. The valve should be 50 per cent open at 75°F. Under the nonlinear condition, however, this position is obtained at 74.1°F,—an error which would be negligible in most applications. However, considering the lower row, which refers to a band of 150°F it can be seen that under the nonlinear condition the valve would be 50 per cent open at 30 instead of 75°F, which would be quite inacceptable. The nonlinearity in the graph has been chosen arbitrarily but illustrates its rapidly increasing influence with decreasing controller gain.

*In this and the following chapters, pressures which are mentioned in the text are always gauge pressures, unless otherwise noted.

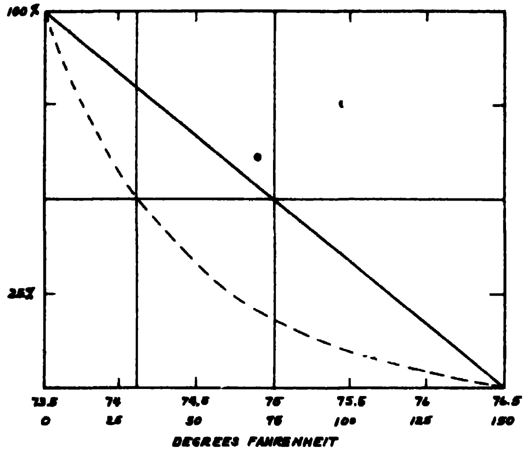

Figure 12-5. Effect of non-linearity at various gains.

To approach more linear response several remedies are used. One is that minimum nozzle back pressures are generally 3 psi, since below this range the nonlinearity increases rapidly. Another is to limit the flapper movement with relation to the nozzle to an extremely small value, generally somewhere between .0001 to .001 inch for full-scale operation. This is made possible by feedback action, as will be described later. A third remedy is to use a pilot valve. This allows changing the nozzle back pressure through a range of, *e.g.*, 2 to 3 psi, to obtain pressure changes in the output of the pilot valve of 3 to 15 psi. The small pressure range through which flapper and nozzle operate under these conditions further increases their linearity.

The addition of the pilot valve also serves the purpose of increasing the response speed of the final control element. In an arrangement as shown in Figure 12-4, all the air that is required to increase the pressure to the valve must flow through the restriction, and all the air that has to be removed to decrease the pressure must leave through the nozzle. The nozzle opening may have a diameter of 1/64 inch and a restriction of about .008 inch in diameter. The resulting time lag in controller operation makes this arrangement impractical for many applications. A pilot valve supplies the controlled valve with air directly from the supply line through a supply port having about ten times the area of the restriction ahead of the nozzle, and exhausts directly to atmosphere through another large port.

The small nozzle opening is required primarily to reduce the force against which the flapper has to act. The area of a 1/64-inch nozzle is about .0002 square inch. When the flapper completely closes the nozzle, the maximum air pressure of 15 psi will push against the nozzle with a force that is about

.0002 × 15 = .003 lb. Actually, the nozzle is never completely closed and in many designs a sucking force (Bernoulli effect) results that further reduces the small force from the direct action of the air pressure or even exceeds it in the opposite direction. In any event, the force that acts on the flapper is thus small enough to become negligible.

Proportional Controllers

Figure 12-6 illustrates the Mason-Neilan pressure controller. Its design allows it to be mounted directly on the control valve. The controlled pressure is admitted to a Bourdon tube. When the pressure increases, the free end of the Bourdon tube rotates the flapper clockwise about the bearing, tending to cover the nozzle. The resulting increase in pressure is transmitted to the control valve and is also applied to the proportional bellows, which tends to raise the flapper to uncover the nozzle. This feedback action stabilizes the flapper position at a definite point for each value of controlled pressure. With a decrease in controlled pressure, the flapper will uncover the nozzle, and output pressure will decrease. The proportional bellows will then tend to lower the flapper bearing and to make the flapper cover the nozzle. The actual output pressure thus becomes exactly proportional to the movement of the free end of the Bourdon tube.

The function of the proportional-band adjusting knob is to vary the gain by changing the effective length of the proportional leaf spring. As this knob is

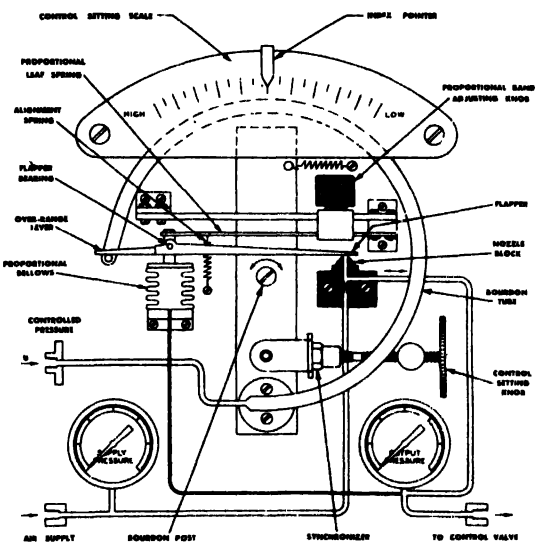

Figure 12-6. Pressure controller for valve mounting. (*Courtesy of Mason-Neilan Regulator Co.*)

moved to the left, the effective length of the proportional leaf spring is decreased, thus stiffening the resistance to the bellows movement. Movement of the knob to the right increases the effective length and decreases the resistance to bellows movement. The position of the adjustment knob determines the amount of movement of the Bourdon tube required to produce a change in the output pressure from 3 to 15 psi, and therefore determines the gain of the controller. A gain of 2 is the smallest for which the controller can be adjusted. The smallest band width that can be attained is 3 psi, which means a change of the output pressure from 3 to 15 psi for a change of 3 psi in the controlled pressure.

An alignment spring is attached to the free end of the proportional leaf spring and adjusted in tension to equal the force exerted by the proportional bellows at 9 psi output pressure, *i.e.,* the pressure which corresponds to the set point, since it is the midpoint between 3 and 15 psi. At this point the net load on the leaf spring is zero.

Adjustment of the set point is accomplished by turning the control setting knob to rotate the Bourdon tube assembly about the plate post as a center, thus changing the Bourdon tube tip position. The direction in which the index pointer moves indicates the effect of the adjustment, *i.e.,* toward "high" to increase and toward "low" to decrease the controlled pressure.

The purpose of the synchronizer is to permit synchronizing the actual controlled pressure with the index setting. This is accomplished by turning the synchronizer, but not the adjustment knob, to rotate the Bourdon plate, thus changing the position of the Bourdon tip without affecting the position of the index.

In Chapter 5, the measuring mechanism of the Level-Trol (Fisher Governor Company) was described. The torque tube unit and float assembly were shown in Figures 5-14 and 5-15. The controlling action of the Level-Trol is illustrated in Figure 12-7. Air is supplied at 40 to 100 psi and used as operating medium for the control arrangement. It is reduced to 20 psi in the combination regulator valve and filter and passes from there through orifice *J* into relay diaphragm chamber *L*, and on through the small tubing *D* inside the Bourdon tube *C* and to nozzle *A*. The flapper is positioned by the displacer float and when the nozzle is restricted by the flapper due to a rise in liquid level, pressure is built up in the system between *A* and *J*. Thus any change in liquid level results in a change in pressure in the chamber *L*.

When there is an increase of pressure in chamber *L* the diaphragm assembly which comprises diaphragms *M* and *P* is pushed downward, and the inlet valve *O* is pushed open. This allows supply pressure to come into chamber *N* until it pushes the relay diaphragm assembly back to its original position and the inlet valve *O* is closed again. A decrease in pressure in chamber *L* will

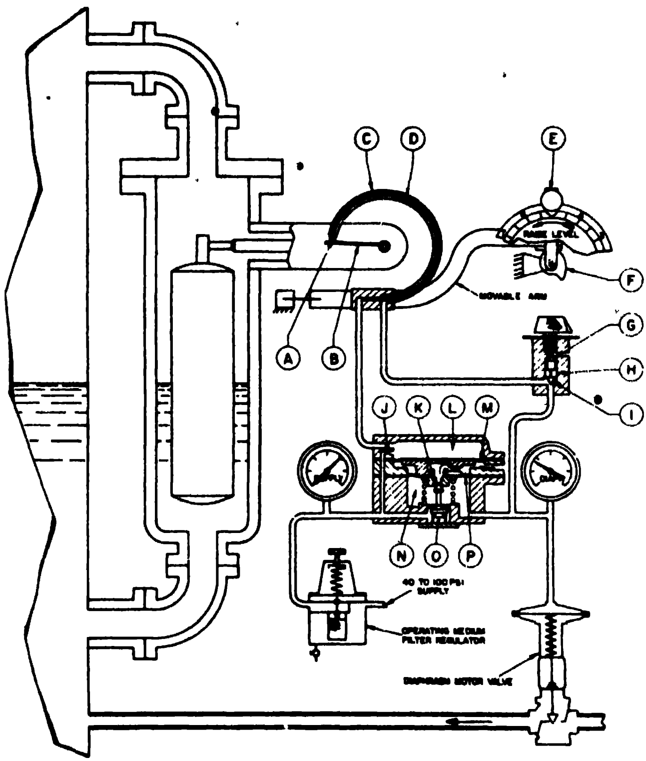

Figure 12-7. Schematic of Level-Trol. (*Courtesy of Fisher Governor Co.*)

cause the diaphragm assembly to move upward and to open exhaust valve *K*, allowing the pressure under the small diaphragm *P* to bleed out until the diaphragm assembly again returns to its original position and exhaust valve *K* is closed. The ratio of the two diaphragm areas, *M* and *P*, is 3 to 1, or such that a change of 4 pounds on the large diaphragm *M* results in a 12-pound change in output pressure to the diaphragm valve.

The three-way valve supply assembly *H* located in a branch from the diaphragm valve supply line to the compensating Bourdon tube *C* is the gain adjustment mechanism. The valve is manually positioned between the inlet port *I* and the exhaust port *G*. When the valve is seated against the exhaust port *G*, all the diaphragm pressure is transmitted to Bourdon tube *C* causing the Bourdon tube to back away from the flapper. On the other hand, if the valve is seated against the inlet port *I*, no pressure is transmitted to the Bourdon tube. Intermediate positions of the valve, of course, result in intermediate pressures to the Bourdon tube.

Consider, for example, the level in the vessel at a point midway on the float. If the outlet flow is smaller than the inlet flow, the level in the vessel and in the float cage will rise. This produces an upward force on the float which will cause flapper *B* to rise toward nozzle *A*. This will build up pressure in the relay chamber *L* with the consequent increase of pressure in chamber *N*, as previously described. The pressure in chamber *N* is transmitted to the diaphragm of the control valve causing it to throttle the flow.

At the same time, the pressure in Bourdon tube *C*, which is always proportional to the pressure transmitted to the valve, is being increased by the feedback action through the three-way valve assembly *H*; this causes the nozzle *A* to move away from the flapper, thus stopping the pressure build-up in chamber *L*. The ratio between the pressures transmitted to the valve and to the Bourdon tube depends on the amount of opening of the three-way valve. Hence, the amount of change in valve pressure, and therefore valve movement, that is necessary to stop the pressure build-up in chamber *L*, *i.e.*, to rebalance the controller, is regulated by the three-way valve. Since the relationship between level change and valve movement is the gain, it is determined by the adjustment of the three-way valve assembly *H*.

The Bourdon tube is mounted on a movable arm; it is actuated at one end by a cam member *F* and pivots at the other end of a flexure spring. Cam member *F* is positioned by pointer arm *E*. With this construction it is possible to change the relative position of the Bourdon tube and nozzle to the flapper, thus causing a change in the controlled level position. By positioning the pointer arm about the rim of the calibrated dial, the controlled liquid level in the vessel may be raised or lowered.

Controllers for Proportional-position, Reset, and Rate Action

The mechanisms applied in pneumatic controllers generally belong to one of two categories: position balance controllers and force balance controllers. In the first case the relative position between flapper and nozzle is determined by mechanical linkages, in the second case by the balance of pneumatic air forces applied across a diaphragm. An example of each of these types will be discussed.

Figure 12-8 is a schematic diagram of one of Foxboro's Proportional-position Controllers, the M40 type. This is a position balance controller. In this arrangement, pressure in a vessel is maintained at a predetermined level by automatically adjusting a control valve as soon as a change in the controlled variable—the pressure—occurs. The pressure is sensed by the measuring element which, through the link-and-lever arrangement, transmits the signal to the pen arm movement. The pen is positioned to record the measured pressure and through a further linkage the proportioning lever is moved which pivots around its lower end.

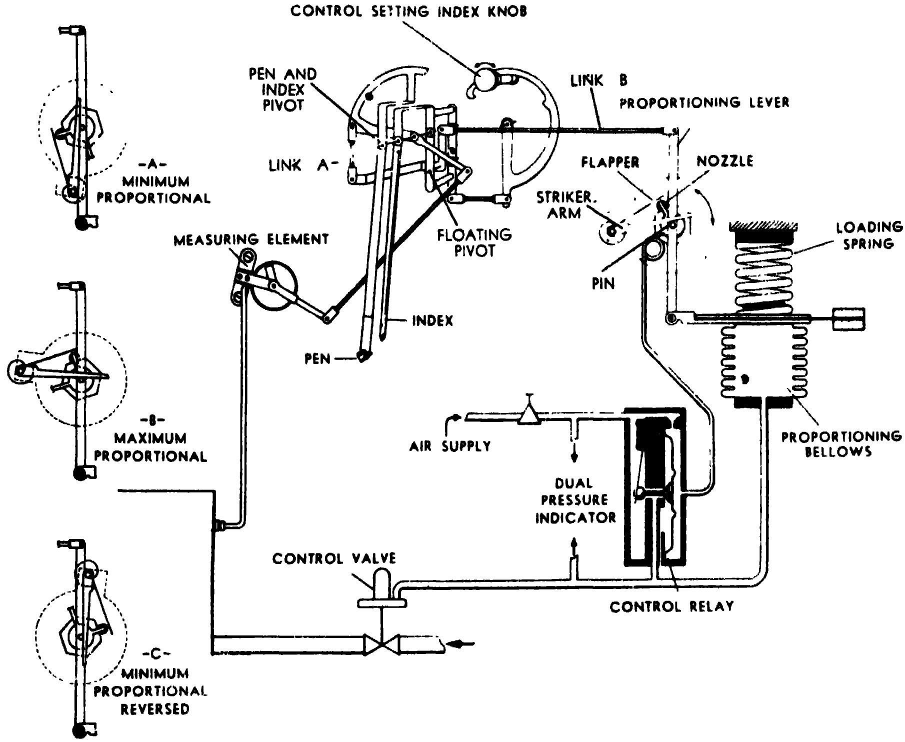

Figure 12-8. Schematic of M-40 proportional-position controller. (*Courtesy of Foxboro Co.*)

The flapper is rigidly connected by a common shaft with the so-called striker arm, which rides with its free end on a little pin in the center of the proportioning lever, as can be seen in the illustration. Since the striker arm is not exactly horizontal, it will rotate through a small angle as the proportioning lever is pushed to the right through the link that connects it with the pen arm movement.

The consequence of the striker arm movement is an identical movement of the flapper which will move toward the nozzle. The increased nozzle back pressure acts upon the diaphragm of the pilot valve or control relay (see also Figure 4-23) and opens the air inlet port to admit air pressure to the control valve. The air supply, kept at constant pressure by the supply regulator, is connected with the control relay, from which it flows through a restriction to the nozzle and through the inlet port to the control valve.

The output air pressure, which was increased by the previously described action, is also applied to the proportioning bellows for feedback action. This bellows expands under the increased air pressure by a certain amount, depending on the bellows structure and the spring rate of the loading spring. This will move the proportioning lever upward by a corresponding amount in a vertical direction; it thus raises the striker arm and with it the flapper, which moves away from the nozzle.

There are thus two opposing actions. One originates from the response to a deviation of the controlled variable, sensed by the pressure element and transmitted through a link to the pen arm movement and from there through another link to the proportioning lever. This results in moving the flapper toward the nozzle. The opposing action is due to the change in control air pressure to the valve, which is also applied to the proportioning bellows. The bellows gives an upward movement to the proportioning lever, which moves the flapper away from the nozzle. The result is the accurate positioning of the flapper with a total movement of .0006 inch, and exact linear relationship between the deviation that pushes the proportioning lever in one direction and the corrective signal to the control valve that causes the opposite movement.

The dotted line in the illustration indicates the gain adjustment. Around this circle, the assembly of flapper, nozzle, and striker arm can be rotated. The amount by which the striker arm moves for a given movement of the proportioning lever is determined by the angle between striker arm and proportioning lever. The proportioning lever moves either up or down because of bellows action, or sideways because of measuring element action. If the striker arm is in a vertical position, as indicated in position *A* of Figure 12-8, the up-and-down movements will have no effect on it. Consequently, it is then under the influence of only the measuring element, and the effect of the proportioning bellows is eliminated. Since the movement of the flapper is determined by the striker arm, and the feedback action is zero, the resulting control corresponds to that of Figure 12-4. It is so adjusted that in this condition it produces practically on-off control. As the striker is moved toward the horizontal, position *B*, the bellows up-and-down movement becomes more and more effective by increasingly reducing the resulting flapper movement for a given deviation of the controlled variable. This corresponds to wider and wider proportional bands, *i.e.*, less and less gain. The maximum proportional band—or minimum gain—of this controller is 200 per cent.

If the striker arm is turned through the horizontal, the controller action is reversed, *i.e.*, it will increase instead of decrease the output air pressure for a given deviation of the controlled variable. Further motion of the striker arm will increase the gain until the striker is again vertical (position *C*) but is now on the other side of the proportioning lever.

Adding reset and rate action to the proportional-position controller requires a modification of the action of the proportioning bellows. In Figure 12-9 the modification is shown as required for proportional plus reset action.

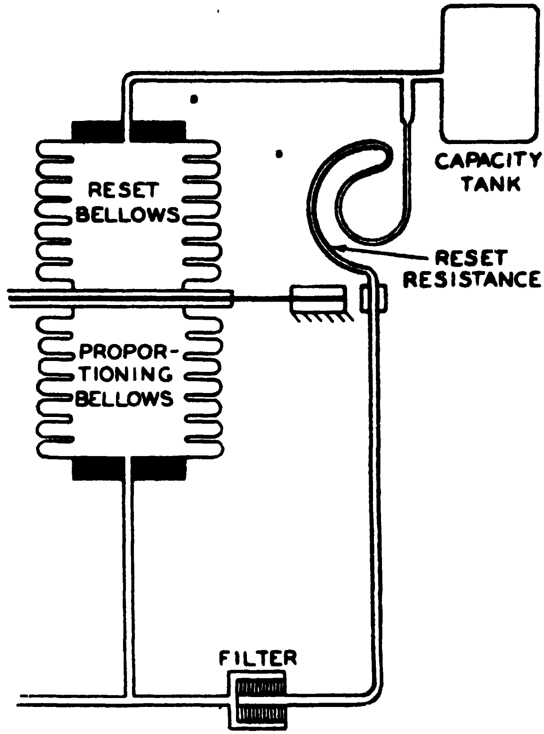

Figure 12-9. Schematic of proportional plus reset circuit. (*Courtesy of Foxboro Co.*)

The controller puts out between 3 and 15 psi to operate the control valve. This means that the output air pressure is 9 psi, as long as the temperature corresponds to the set point. If the measurement of the controlled variable increases by a certain amount, the flapper moves toward the nozzle and the pressure as applied to the control valve increases correspondingly. The proportioning bellows will respond to this change in air pressure immediately, while the response of the reset bellows is retarded because of the reset resistance in the connection between the two bellows. This means that initially the reset action is not effective and proportional action alone takes place.

After a load change, the proportional-position action would not be able to bring the controlled variable back to the set point because of the offset that is unavoidable in proportional-position controllers. However, since reset is added there will be an increasing action caused by the reset bellows which is opposed to the proportioning bellows. This action will produce a movement of the flapper toward the nozzle, causing an additional increase in output air pressure, which of course repositions the proportioning bellows and somewhat more slowly, the reset bellows, which in turn affects the flapper position. These cycles are so fast and of such small amplitude that they result in a smooth gradual movement. The action continues, building up more and more pressure on the control valve; finally, a new balance is obtained between the positioning of the proportioning lever from the measuring element through the pen arm movement and the vertical positioning of the proportioning lever, as the result of the interaction between reset and proportioning bellows.

If the reset bellows acts too fast, there is considerable building up of pressure and consequent overshooting. If it is too slow, it would take too much time to finally return to the set point. Consequently, it is necessary to adjust in the field the reset for the conditions of the particular process. This is done by changing the flow resistance between filter and capacity tank.

Figure 12-10 illustrates the mechanism required for proportional plus rate action. The action of the proportional bellows is no longer opposed by that of another bellows, but a second bellows is added to obtain a combined action in the same direction. Both the inner and outer bellows tend to move the flapper away from the nozzle when expanding. The outer bellows provides the rate action. It is connected with the inner bellows through an adjustable derivative resistance, *i.e.*, a rate adjustment.

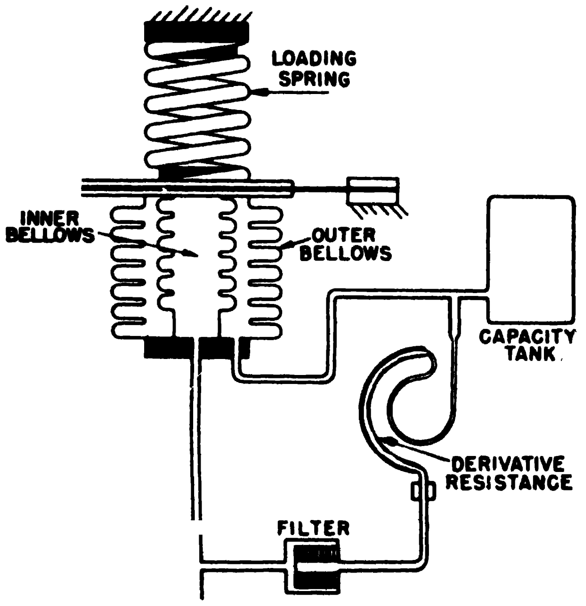

Figure 12-10. Schematic of proportional plus rate circuit. (*Courtesy of Foxboro Co.*)

When the controlled variable deviates from the set point, the flapper is positioned in the usual form. Assume it brings the flapper closer to the nozzle. The increase in air pressure to the control valve produces an immediate response of the inner bellows, tending to move the flapper away from the nozzle toward its original position. The effect is, however, less than with a simple proportional-position controller, since the bellows are smaller. Hence, the initial corrective action is considerably increased. Its effect is, however, gradually lessened because of the outer bellows which also increases its pressure, though retarded by the derivative resistance. Thus the initial oversensitivity is obtained, which is characteristic for rate action and which progressively subsides due to the action of the outer bellows. Once the pressure between inner and outer bellows is again equalized, their combined action corresponds to proportional-position control.

The combination of proportional-position, reset action and rate action consists in replacing the loading spring in Figure 12-10 by the reset bellows of Figure 12-9.

The Minneapolis-Honneywell Tel-O-Set controller is a typical force-balance controller. It is also characterized by its operation in two different stages separated in time: the rate action comes first, followed by the reset action. The advantages of such an arrangement for off-band control were mentioned before.

As shown in Figure 12-11, the principal parts of the Tel-O-Set controller are the base section, the rate section, and the deviation section. The base is a die-cast block containing restrictions *A*, *B*, *C*, and *D*; reset chamber, air filter *F*, external connections, pilot valve, and the band and reset valves.

The rate section like the deviation section is divided into a number of chambers, by flexible diaphragms attached to a movable connecting rod. The measurement signal indicating the magnitude of the process variable enters through port 5 in the base section. It passes into the process variable chamber at the base of the rate section. Because of the arrangement of the diaphragm areas, the upward force exerted by the process variable chamber is equal to the net downward force of the rate action chamber plus the downward force of the rate feedback chamber. Motion of the diaphragm assembly positions the rate flapper. When the process variable changes, the rate flapper is immediately repositioned and the pressure in the rate action chamber changes with the nozzle back pressure. However the rate valve delays the change in the rate feedback chamber.

If the rate valve were completely closed, the process variable pressure would have to be balanced entirely by the rate action chamber. Because part of the rate action chamber pressure acts upward against the small-area diaphragm, it has to increase far more than the process variable before the forces are balanced. The actual difference is 16:1. Therefore, for an instantaneous step

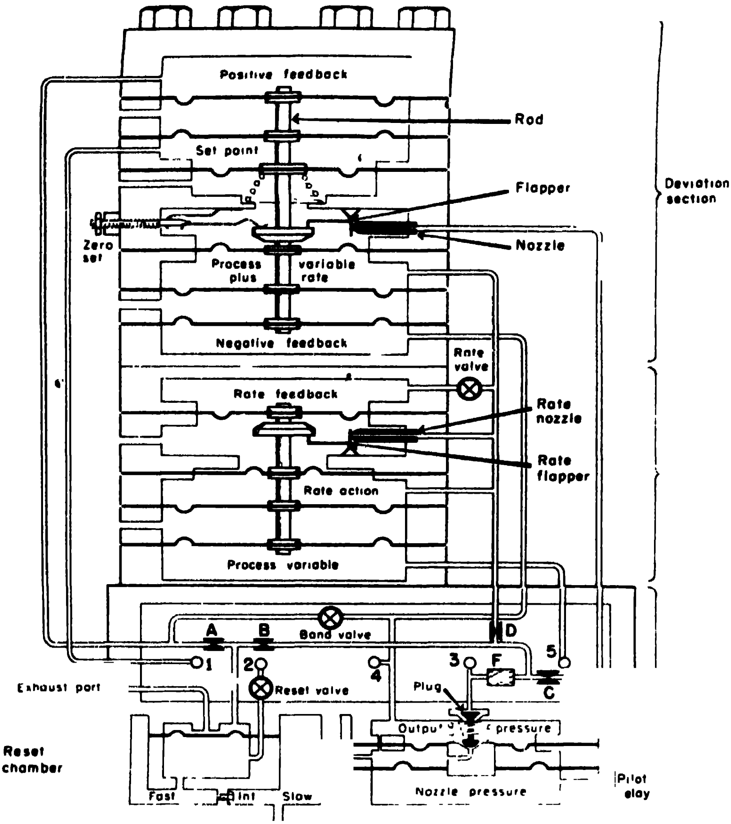

Figure 12-11. Schematic of Tel-O-Set controller. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

change, the change in pressure that is applied to the process variable plus the rate action chamber is 16 times larger than it would be without rate action. And so is the corrective action produced by the rate section. But this correction is only temporary because the rate valve is never entirely closed. Nozzle back pressure immediately begins to bleed into the rate feedback chamber, adjusting the flapper to change the pressure. As the air bleeds into the rate feedback chamber, the nozzle back pressure continues to change until the same pressure exists on both sides of the rate valve. At this point the true process variable pressure is again transmitted to the rate section.

Instantaneous step changes seldom occur. A more gradual change allows air to bleed slowly into the feedback chamber limiting the corrective signal to less than 16:1. The setting of the rate valve determines the magnitude of the corrective action in proportion to the rate of change of the process variable.

The nozzle back pressure signal from the rate section is applied to the process variable plus rate chamber in the deviation section. The diaphragm-connecting rod in the deviation section is supported by a conical spring which is deliberately designed with more force than is necessary to lift the rod. The excess in force is counterbalanced by the adjustable zero-setting leaf spring.

In normal operation, pressure in the positive feedback chamber exerts a downward force on the rod, which is opposed by the upward force of the negative feedback chamber. Set point pressure which is obtained from an external pressure regulator is admitted through port 1 which connects with the set point chamber. Both the set point and process variable plus rate chambers are bounded by two diaphragms of different size so arranged that air pressure will exert a net force in the direction of the larger diaphragm. The net upward force of the set point chamber opposes the net downward force of the process variable plus rate chamber. When the process is at the set point, these forces exactly balance each other and the rod does not move. When the process is not at the set point, forces are unbalanced, and the rod moves either up or down. Consequently, the flapper changes its position relative to the nozzle. This changes the nozzle back pressure by allowing more or less air to bleed from the nozzle. Nozzle back pressure is also delivered to the lower chamber of the pilot relay in the base section. A change in nozzle back pressure moves the diaphragm of the nozzle pressure chamber, thus also moving the block connecting this diaphragm with the one above it. The block operates the upper and lower seats of the pilot valve. (In the diagram, the valve is shown with both ports open, a purely theoretical position that can never occur in normal operation.) The connection to the supply air is made at port 3 and to the control valve at port 4. Thus the plug regulates the air flow between supply and control valve or between control valve and exhaust. A decrease in nozzle back pressure moves the block downward, opening the exhaust port and venting air from the output pressure chamber and hence the control valve until the forces exerted by the two chambers are balanced. An increase in nozzle back pressure lifts the block upward, opening the upper port and admitting supply air to the control valve, at the same time restoring balance between the two chambers.

Proportional-position control is provided by the negative feedback chamber in the deviation section which connects with the output pressure chamber. The force of the negative feedback chamber balances the opposing forces and adjusts the rod to place the flapper in the newly required position. The net result is a change in controller output pressure that is proportional to the deviation. The area of the negative feedback diaphragm is one and one-half times the effective area of the process variable diaphragm. As a result a change of 1.5 psi in process variable is balanced by a 1 psi change in controller output. This is equivalent to a gain of 0.67.

The gain or band width is adjusted by applying a part of the controller output to the positive feedback chamber. This chamber opposes the effect of the negative feedback chamber with the amount of counterforce determined by the setting of the graduated band valve. If the band valve is fully closed, none of the controller output reaches the positive feedback chamber, and only negative feedback has an effect. The gain is then 0.67 as described above. When the valve is fully open, nearly all of the controller output reaches the positive feedback chamber, and the gain is increased to 50. Any gain between these limits of 0.67 and 50 can be attained by intermediate valve settings.

The mechanism that produces reset action operates as follows. Ports 4 and 2 are connected externally. Hence, the output signal is fed back through the reset valve into the lower section of the reset chamber. The diaphragm that separates the upper and lower section of the reset valve, also serves to regulate the opening between the upper section and the exhaust port whenever the pressure in the lower section is larger. Air bleeds from the upper section as long as the pressure in the lower section tends to be smaller. On the other hand, when the pressure in the lower section is greater, the exhaust port is sealed and supply air bleeds in until upper and lower pressures are equal. Consequently, the pressure on both sides of the diaphragm is always the same. If the pressure between restrictions *A* and *B* differs from the pressure in the positive feedback chamber, a flow of air will take place through restriction *A*. This will change the pressure in the positive feedback chamber over and beyond the pressure change due to output pressure feedback which takes place through the band valve. This additional change of the positive feedback pressure is caused by the feedback that flows through the reset valve into the lower section of the reset chamber. Thus, for the duration of any offset, the pressure in the positive feedback chamber is changing constantly and causing corresponding changes in the controller output and hence in the negative feedback chamber. As the signal from the process variable approaches the set point, the difference between positive and negative feedback pressures decreases until finally, when the process variable is restored to the set point, the positive feedback has equalled the negative feedback pressure. In this manner the reset action continues changing the output and eliminates the offset which otherwise would be unavoidable.

The reset has two adjustments: one is a basic adjustment for slow, intermediate, and fast reset, as will be described, the other is the reset valve which gives adjustment within each of the three basic rates. Slow, intermediate, and fast reset, are obtained by changing the capacity of the lower section in the reset chamber. The larger the capacity is, the more air must flow through the reset valve in order to increase the pressure to a given value. There are three slots into which a screw can be inserted. If it was inserted in the "Fast" slot, only the space underneath the diaphragm would be active. Inserting it in the "Int" (intermediate) slot, as shown in the diagram, the additional space to the left of the screw is added. Inserting it in the "Slow" slot would make the total capacity available.

Inverse-derivative Controller

Inverse-derivative action, as previously described, is essentially an initial retardation of the corrective action. The inverse-derivative unit made by Moore Products Company is shown in Figure 12-12. The input pressure applied on top of the unit is either the controlled variable signal or, more frequently, the output signal of a proportional-position or proportional plus reset controller.

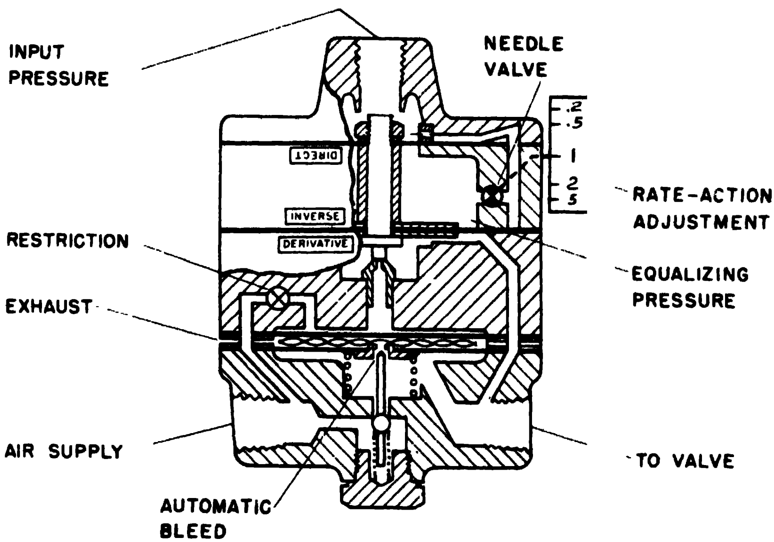

Figure 12-12. Inverse-derivative unit. (*Courtesy of Moore Products Co.*)

In either case, the input pressure changes in response to deviations of the controlled variable. The upper part of the unit contains two diaphragms. They are coupled by a stem so that they always move together. The stem bottom acts as flapper for a nozzle that is part of a pilot valve in the lower portion of the unit. The double diaphragm of the pilot valve with an exhaust in between opens the automatic bleed when it moves upward. When the nozzle back pressure increases, the pilot valve diaphragm moves downward against the pressure and a loading spring underneath the diaphragm. In moving it pushes down on the inner valve, closing the automatic bleed and opening the port from air supply to control valve.

Suppose, the input pressure increases suddenly. This moves the upper diaphragm stack down and with it the flapper end of the stem which increases the nozzle back pressure. Air is now admitted through the inner port to the control valve increasing the transmitted pressure and also the pressure underneath the pilot valve diaphragm. The inner port of the pilot valve closes again when the force of the transmitted pressure plus the force of the loading spring is equal to the force exerted by the nozzle back pressure. Thus, for each magnitude of input pressure there is a corresponding output pressure transmitted to the control valve. However, there is an additional effect. This is due to the needle valve that admits air at a limited rate into the chamber between the two diaphragms in the upper part of the unit. As the equalizing pressure in this chamber increases, a downward force is exerted since, as shown, the lower diaphragm is of larger area than the upper. This lends added impulse to the first effect of the input pressure change. If this input pressure change occurs very slowly, the flow through the needle valve may be just about as fast as the signal change, hence the effect of the inverse derivative is a minimum. The faster, however, this signal change takes place, the greater is the retarding effect of the needle valve. Thus, inverse-derivative action is obtained.

Incidentally, if the upper diaphragm stack is reversed so that the large diaphragm is on top, then the action of equalizing pressure opposes that of the input pressure. The signal effect is then maximum when the change is fastest and, hence the unit provides direct rate action. This diaphragm stack is actually reversible in the unit which thus can be used for either direct rate or inverse-derivative action.

Automatic-to-manual Transfers

The purpose of the automatic-to-manual transfer, as mentioned before under "Electric Controllers," is to allow removal of the automatic controller for servicing and replacement of it by manual control. Several transfer methods are available and some of the most representative are described in the following.

The two-position transfer switch consists of a valve located in the line that connects the nozzle to the pilot valve. If such a valve is installed, for example, in the arrangement of Figure 12-8, and the valve is closed, the effect is the same as if the flapper covers the nozzle fully. The nozzle back pressure would rise and the maximum air pressure would be applied to the valve. Since a pressure regulator is always provided in the supply air line to the instrument, it can be used to throttle the air pressure to the control valve and regulate it. The disadvantage of this system is that the valve will not maintain its position while being transferred from automatic to manual control. It is, of course, possible to slowly throttle the valve in the nozzle line while adjusting the regulator; but the coordination of the two movements requires skill, and on critical processes may still not be smooth enough to avoid upsets, particularly where reset and rate action are involved.

The automatic-to-manual transfer in Foxboro's M 52 Consotrol controller is an interesting example. It is illustrated in Figure 12-13. The controller is divided into an upper and a lower unit, connected by flexible air connections. The upper unit contains the measurement receiver bellows. This bellows is connected with the transmitter, which converts the measurement of the controlled variable into an air-pressure signal. The receiver bellows positions a pointer on the indicating scale. The upper unit also contains the control unit with its setting adjustments. The lower unit contains the relay, nozzle bleeds, manual control parts, and transfer switch.

The receiver line from the transmitter is connected with the upper unit, and the measurement is read on the main scale. The flapper of the "automatic"

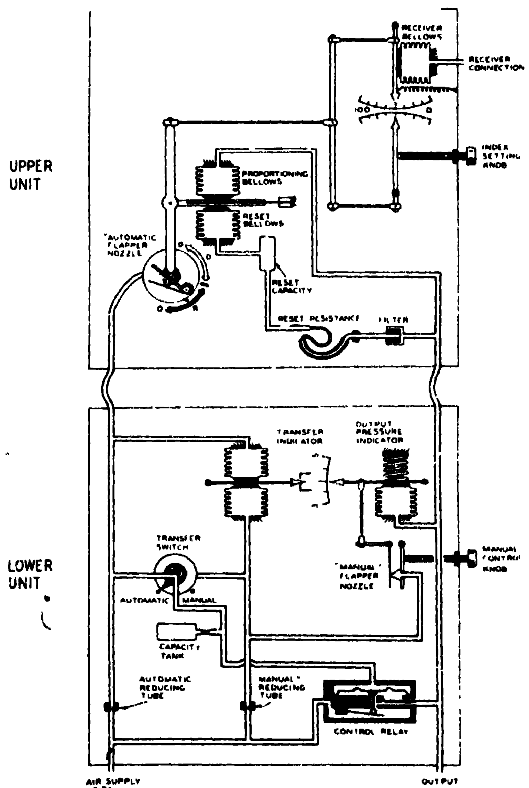

Figure 12-13. Schematic of M-52 controller. (*Courtesy of Foxboro Co.*)

nozzle is automatically positioned by the resultant of the motions of the receiver bellows, index-setting knob, and the proportioning bellows of the control unit. The resulting nozzle pressure is conveyed by flexible tubing to the lower unit.

Air supply enters the controller through the lower unit, and the flow to the "automatic" nozzle is restricted by a reducing tube in this unit.

In automatic operation, the transfer switch is in the position shown in the illustration, thus placing "automatic" nozzle pressure on the diaphragm of the pilot valve, or control relay in Foxboro's terminology. The output of the control relay is connected to the control valve. The output is also indicated on the output pressure indicator, and is conveyed to the proportioning bellows of the control unit by tubing between the lower and upper units.

The "automatic" nozzle is always connected to the upper bellows of the transfer indicator and the "manual" nozzle to the lower bellows. To switch from "automatic" to "manual" the transfer indicator is first brought to its balanced condition by means of the manual control knob. Then, the transfer switch is thrown to the "manual" position. This removes the "automatic" nozzle pressure from the relay diaphragm and substitutes the pressure at the "manual" nozzle. The pressure at this nozzle can be varied by the manual control knob, thus changing the pressure on the relay diaphragm and, in turn, the output pressure.

A ball check automatically closes the output port to prevent the escape of air when the flexible tubing is removed. It will be noted that while it is switched on manual, the entire automatic control system remains connected with the circuit, although it is inactive. Transfer without affecting the position of the valve is thus possible with a two-position transfer switch. However, it should also be noted that the lower unit is relatively complex and only the upper unit can be removed for servicing.

Figure 12-14 shows Fischer & Porter's Pneumatrol controller with a four-position transfer switch which allows changing from automatic to manual control and back again to automatic without affecting the valve position. The four positions in the transfer switch are called automatic (auto), manual (man), service (serv) and test. Under normal operating conditions, the automatic position is used. The flip switch between the two knobs would be in the "relay" position. This makes the gauge, of which only scale and needle are shown in the illustration, read the air pressure transmitted to the control valve.

In switching the manual control, the flip switch is first transferred to the "regulator" position. The gauge scale now indicates the regulator output which can be adjusted by the knob in the lower left-hand corner. This knob controls the setting of a pressure regulator. Once, the pressure from the regulator equals the controller pressure, the transfer switch can be changed to "manual." The process is now controlled manually by manipulating the pressure regulator

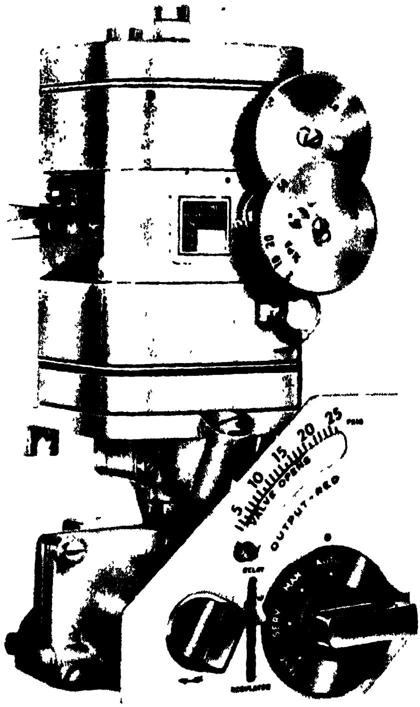

Figure 12-14. Pneumatic controller. (*Courtesy of Fischer & Porter Co.*)

knob. The manually controlled air is applied to the control valve. The controller, though ineffective, continues to operate. The signal to the control valve is fed back as before and reset and rate actions continue to function without affecting the position of the control valve. This permits bumpless transfer back to automatic control at any time without the need to balance. The manual position is useful when it is desirable to cut out automatic control temporarily and to control manually as may be the case in starting up a process.

In the "service" position, air supply and feedback are cut off from the controller which can now be removed.

The "test" position leaves the controller connected to the air supply, but disconnects the control valve line including feedback. This permits conducting tests on the automatic controller without interference from the manual operation. The "test" position is frequently considered unnecessary. For such cases, three-position transfer switches are available.

Minneapolis-Honeywell Regulator Company in their Pneumatik Tel-O-Set instrumentation reduces the transfer from manual to automatic or from automatic to manual to the simple flip of a lever. The operator's matching of the controller output signal and of the manually adjusted signal is no longer required. The manual-automatic lever operates a cut-off relay in the controller. At the moment of switching to manual operation, the relay simultaneously cuts off controlled output pressure and opens a bypass around the reset needle valve. The bypass prevents reset accumulation during manual operation and provides the means for keeping manual loading pressure and pilot relay output in step ready for switching back to automatic operation whenever desired. When on manual control the pressure applied to the control valve is manually adjusted by means of the set point adjustment.

In automatic operation, the feedback mechanism balances the controller output signal and the reset signal. In manual operation—due to the reset bypass—the feedback mechanism balances the manually adjusted loading pressure against the controller output signal. Thus, the controller output signal is continuously balanced against manual loading pressure and permits bumpless transfer at any time.

Ratio and Cascade Controllers

Some general references to ratio and cascade control have been made in the previous chapter and should be referred to.

A Taylor Ratio Controller is illustrated in Figure 12-15. It has two measuring systems: the adjusting system on the left-hand side and the controlling system on the right-hand side. The adjusting system measures the primary variable and resets the set point of the controlling system through a linkage device to a predetermined ratio. The secondary variable is maintained by the controller at whatever value the set point reads. A direct-reading dial (1) governs the ratio of the variables. Inverse and direct ratios from 0:1 to 3:1 may be set. Adjustable stops can be supplied to prevent the controller system from exceeding predetermined limits.

Assume that the controller is set for a 3:1 ratio. Then for every unit change in the primary variable, the ratio controller will make the controlled secondary variable change three units in the same direction; for example a 10-unit change in the primary pen produces a 30-unit change in the controlled secondary variable.

A zero ratio setting means that a change in the primary system has no effect on the secondary system. The primary system then functions as a separate recorder, and the secondary system as a controller recorder without relation to the primary system.

Differentials between primary system and secondary system can be changed by rotation of a knob (2). For example, let a primary temperature be 80°F, a secondary temperature 60°F, and the ratio be set at 3:1 *inverse* ratio. This

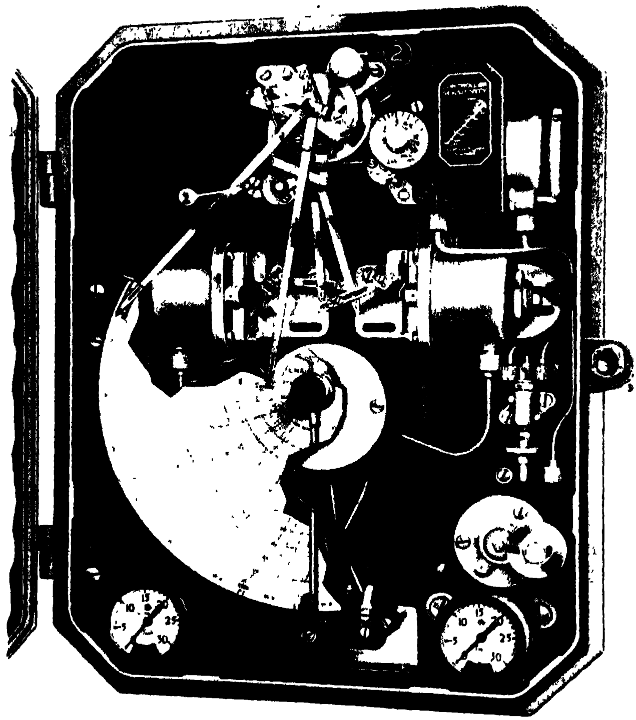

Figure 12-15. Ratio controller. (*Courtesy of Taylor Instrument Cos.*)

means that a 10° *increase* in the primary temperature (to 90°F) will *decrease* the secondary temperature by 30°F (to 30°F). If it is desired to increase the differential, so that when the primary temperature is at 80°F, the secondary temperature is at, *e.g.*, 50°F, it is only necessary to adjust the knob (2).

In using ratio controllers for flow where the flow is recorded on a square-root chart, the ratio does not refer to the rate of flow but rather to the differential pressure of which the rate of flow is a square-root function. In the frequent applications of ratio flow, linear charts are generally preferred.

Figure 12-16 shows the mechanism of the Brown Indexet, used for cascade control in connection with a standard controller. It may be used, for example, with a heat exchanger where the temperature of the product leaving the heat exchanger is controlled by adjusting a control valve in the steam line to the heat exchanger. A temperature controller which positions the valve directly is satisfactory, as long as the upstream steam pressure does not change. A rise in steam pressure would probably result in more heat flow from steam to

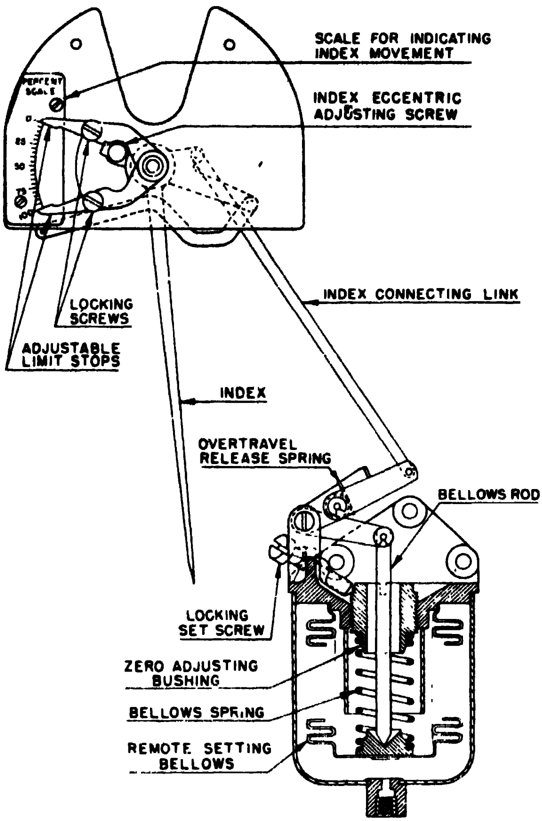

Figure 12-16. Schematic of Indexet. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

product in the heat exchanger and a consequent rise in its temperature. A substantial time lag will delay the response of the controller and its adjustment becomes difficult. Temperature variations due to changes in product characteristics require different settings of proportional band, reset, etc. than those due to changes in the steam properties. To obtain satisfactory control under such conditions, it is necessary (a) to keep the flow of steam constant by means of a flow controller, and (b) to vary the set point of the flow controller by means of a temperature controller whenever the temperature of the product deviates from the desired value. The temperature of the product is the primary controlled variable; the temperature controller is the master controller, and the flow controller could be the Brown Indexet.

The air signal from the master controller is applied to the remote setting bellows shown in the illustration. The bellows rod rests on a conical notch in the bellows and is connected with the index by a link. An overtravel release spring is located on the shaft of the bellows assembly and is actuated by the index connecting link in such a manner as to prevent bending or breaking of the linkage if the index should become fixed at one point or if the index should hit the stop at the maximum index position.

The adjustable limit stops are located above the chart on the index mounting bracket just to the left of center. By using these limit stops, the maximum and minimum travel of the index may be restricted to any one position of the chart. The total index movement may be limited to any percentage of the chart span from 100 per cent to 0. In the latter case the index is locked in place at one point on the chart. This is a similar effect to adjusting a ratio controller for zero ratio. It eliminates the remote setting of the index and operates the Indexet Controller as an independent controller. The master controller will not affect the control system but will only record the variable.

The index which indicates the set point will move over the entire scale for a change between 3 and 15 psi of signal air pressure from the master controller, provided it is not kept from moving across the scale by the limit stops. The relation between the amount of set point change and the amount of deviation in the primary variable is determined by the gain adjustment in the master controller. An adjustable Indexet is available which permits adjusting the amount of set point change in proportion to the amount of signal pressure. It also permits changing the standard condition (*i.e.,* the set point at zero for minimum air pressure and at full scale for maximum pressure) by allowing the "zero" to be shifted to any point on the scale. The effect of both adjustments corresponds to changing the gain and the set point, respectively, at the master controller. The feature is of advantage when the better accessibility of the Indexet makes it desirable.

A combination of ratio and cascade control is used in what is generally called a pneumatic-set ratio controller. In this case, the master controller automatically adjusts the ratio of the ratio controller. For example, it may measure the concentration of a chemical solution and readjust the ratio of flow between solute and solvent for any deviation from the desired concentration. On the other hand, the flow of solute may in itself vary; but since it will readjust the flow of solvent at the controlled ratio, it will be without effect upon the resulting concentration.

Auto-selector Controllers

Auto-selector equipment for electronic control has been described in the previous chapter. Similar methods are available for pneumatic control. The purpose is to override one controller by another under certain conditions. Suppose a heat exchanger cools a process fluid by counterflowing a brine. Neither the outlet temperature of the cooled process fluid nor the inlet pressure of the brine are to drop under a certain minimum. A valve in the brine outlet is to be throttled if one of the two conditions is approached. This is possible through auto-selector control which connects either one of two controllers to a control valve whenever one of the two limiting conditions is reached.

Figure 12-17 illustrates the operation of a Minneapolis-Honeywell auto-selector relay. At the left is a functional sketch of the relay, and the diagram at the right shows the connections between the control valve, the selector relay, and two controllers, such as a brine pressure controller and a temperature controller for a cooled process fluid. The two controller output pressures are applied to opposite diaphragms. The two diaphragms are connected by a

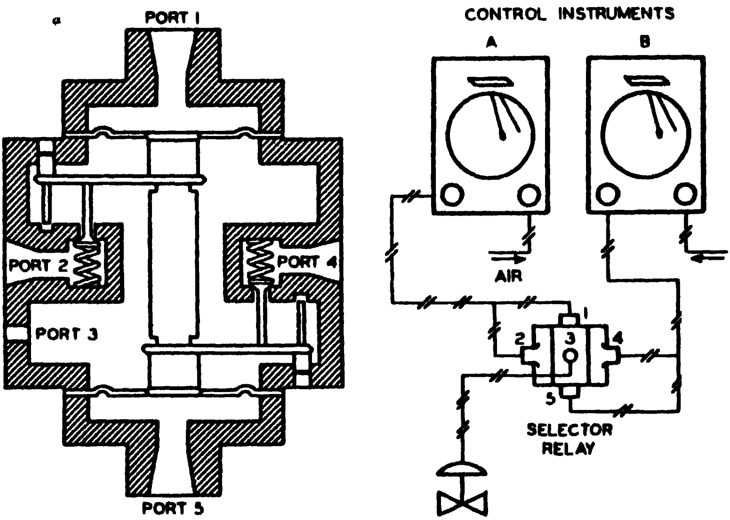

Figure 12-17. Auto-selector relay. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

solid shaft and, hence, always move together. Attached to the shaft by brackets are the stems of two valves, one on the left and one on the right. If the pressure against the upper diaphragm exceeds the pressure against the lower diaphragm, the assembly moves downward, opening the valve on the left. Inversely, the right-hand valve opens when the pressure against the lower diaphragm exceeds the pressure against the upper one. Since the output of controller A is connected to ports 1 and 2, when the output signal of controller A exceeds that of B the valve at port 2 opens, connecting the signal from controller A through ports 2 and 3 to the control valve. On the other hand when the signal from controller B increases and becomes larger than that of A, the diaphragm and valve assembly in the selector relay moves upward, closing the valve at port 2 and opening the one at port 4. Thus, the control valve now responds to the signal from controller *B*.

Totalizers

The Hagan Ratio Totalizer can be used for adding, subtracting, multiplying, averaging, etc. Its basic assembly, as shown in Figure 12-18, consists of four flexible nonmetallic diaphragm pressure elements arranged in opposing pairs. The two elements of each pair are attached to a common post. A beam, rotating about a fulcrum, is connected between the two posts.

Three pressure elements are available for incoming loading pressures or for the application of mechanical forces. These are enclosed within suitable chambers. The fourth element is enclosed in a chamber which contains the pilot valve.

Beam movements are transmitted by direct contact to the end of the pilot valve stem, which operates between the inlet and exhaust ports of the valve assembly. An air pressure supply is connected with the valve inlet. Clockwise movement of the beam causes the valve to open the inlet port, raising the out-

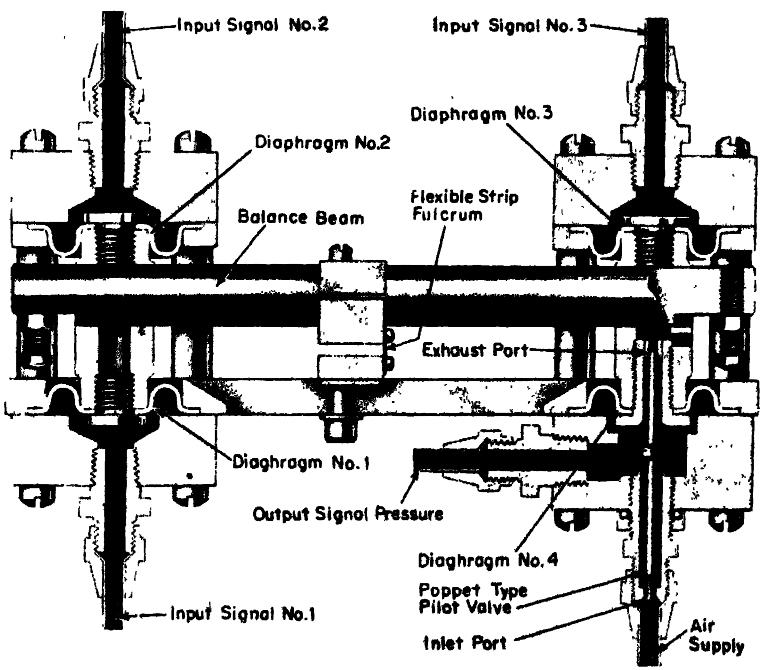

Figure 12-18. Schematic of ratio totalizer. (*Courtesy of Hagan Corp.*)

put signal pressure. Counterclockwise beam movement causes the valve to close the inlet port and open the exhaust port, reducing the output pressure.

When the resisting force due to the output pressure balances the total of forces applied to the three input chambers, the pilot valve closes both inlet and exhaust ports, thus establishing a steady value of output pressure as long as the balance of forces is indisturbed.

The position of the fulcrum is adjustable. Movement of the fulcrum to the left increases the effect on the output pressure of any change in total loading on number 1 and number 2 elements. A fulcrum movement to the right has the opposite effect. Tension springs may be applied to any of the three loading elements. A single spring may be used as a fixed loading for manual set point adjustment or as a bias in connection with signals requiring range suppression. A special attachment is available to control the balance beam movement by mechanical linkages rather than by loading pressures. Mechanical forces are then converted into pneumatic signals.

When applying forces at connections 1 and 3, the output air pressure at 4 is the sum of the two applied forces. By connecting 2 and 3, instead of 1 and 3, subtraction is obtained. Connecting a force only at connection 1 and moving the fulcrum to any desired point gives multiplication or division. A large number of combinations are thus possible, including those of proportional control with remote pneumatic set point adjustment. By adding certain accessories, automatic reset and rate action can be obtained. The output pressure from the ratio totalizer is suitable as a measurement signal for indicating and recording instruments and for controllers.

HYDRAULIC CONTROLLERS

Hydraulic systems operate with a practically incompressible medium such as oil, whereas pneumatic systems operate with compressible media like air. An example is the pressure controller made by Leslie Co. (Figure 12-19). It is used in combination with a diaphragm control or regulating valve. The controlled pressure is applied on top of the diaphragm of the pilot. A slight increase in controlled pressure depresses this diaphragm, stem and nozzle, and opens the pilot valve, admitting additional operating pressure to the diaphragm regulating valve to reposition it. The device can be used as either a hydraulic or pneumatic controller.

The operating medium can be water, oil, or air. The pressure of the operating medium as it passes through the pilot valve acts against the lower nozzle diaphragm, opposing the increase in controlled pressure on the upper diaphragm. The change in operating pressure is thus limited and is a function of the change in controlled pressure. The operating medium is admitted through

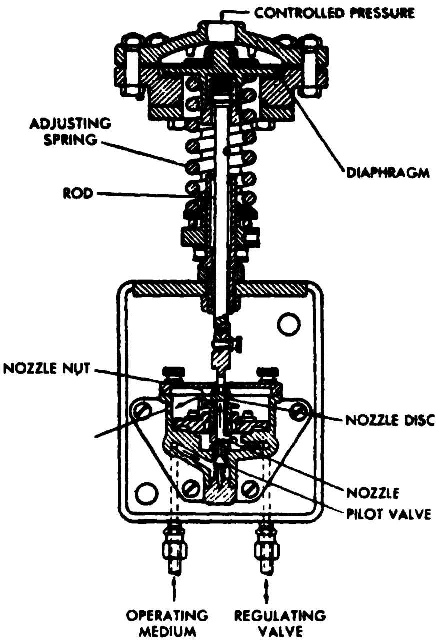

Figure 12-19. Pressure control pilot. (*Courtesy of Leslie Co.*)

the pilot until the pressure under the lower nozzle diaphragm has increased sufficiently to close the pilot valve, thus maintaining the pressure to the regulating valve at a new level.

With a slight decrease in the controlled pressure, the adjusting spring raises the upper diaphragm. The nozzle disc is also moved from its seat on the nozzle and operating pressure escapes from the diaphragm of the regulating valve. When the control arrangement is in balance, the pilot valve and nozzle disc are both seated, thus sealing the operating pressure to the diaphragm regulating valve. A modification of the control pilot also allows control of differential pressures by applying the two pressures to top and bottom of the upper diaphragm, respectively.

Hydraulic controls using jet nozzles give powerful action and fast response. The hydraulic relay made by the North American Manufacturing Company utilizes such a jet nozzle. It is illustrated in Figure 12-20. Hydraulic fluid is pumped through a pivoted hydraulic nozzle at pressures ranging from 100 to 1000 psi. The jet stream from the nozzle is directed at two closely adjacent receiver ports of appropriate size. These ports are directly connected to the ends of a hydraulic cylinder. With the jet pipe in its midposition, equal pressures exist in each receiver port. Consequently, the pressures on each side of the pis-

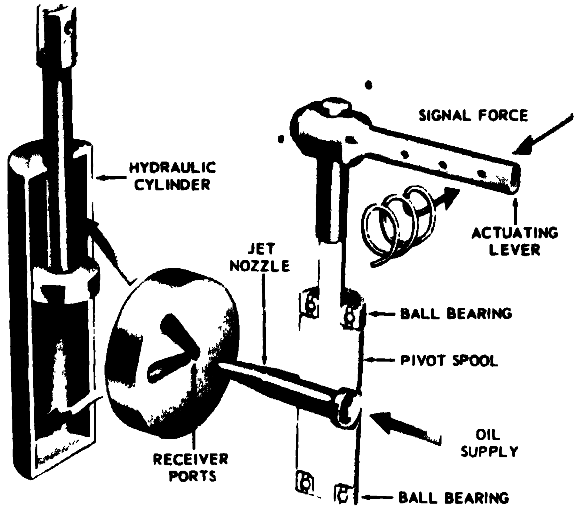

Figure 12-20. Principle of jet nozzle action. (*Courtesy of North American Mfg. Co.*)

ton of the hydraulic cylinder are equal. As soon as the slightest movement of the jet nozzle occurs, one receiver port receives more oil than the other, thus creating a pressure difference across the piston. Force is equal to pressure times the area. The illustration shows a single-ended piston which has a shaft at one end only. Hence, the area against which the hydraulic force acts is smaller on the shaft side of the piston than on the opposite side. For equal pressures, the force would thus be larger in one direction than in the other. For complete balance of forces without any external load acting against the shaft, the jet nozzle would have to be slightly offset from its center position. The product of pressure and piston area can then be made equal on both sides of the piston. A small additional motion of the jet nozzle makes the piston move.

In the jet nozzle midposition, the recovery pressure, which both receiver ports show equally, generally amounts to about 45 per cent. The pressure attained in the hydraulic cylinder with the jet impinging directly on one receiver port may be as high as 90 per cent of the supply pressure or even more. In this position the pressure transmitted to the other receiver port is at a minimum—generally about 5 per cent. In other words, depending on the jet nozzle position, the pressure recovery varies between approximately 5 and 90 per cent of the supply pressure. The pressure differential which is developed across the piston is thus proportional to the jet nozzle movement. The total amount of jet pipe movement is about 2.5 degrees in either direction from the mid-position.

For measuring process pressure or differential pressure across an orifice in the process fluid line, a diaphragm is generally used. A signal force is developed which depends on the pressure (or differential pressure)and the area of the diaphragm. Connecting the center of the diaphragm to the actuating lever in Figure 12-20, and opposing this force by a helical spring, results in a motion of the jet nozzle which is proportional to the measurement signal. Consequently, the speed with which the piston moves is also proportional to the measurement signal. This corresponds with the definition of proportional-speed floating action.

To operate this arrangement as a proportional-plus-reset controller, a so-called hydraulic stabilizer is added. The result of this modification is illustrated in Figure 12-21. In addition to the cylinder *D*, a secondary cylinder, *C*, which is the hydraulic stabilizer is provided. The piston of *C* is connected through a lever to spring *E*. This spring is the same one which produces the counteracting force in Figure 12-20. As the piston in *C* moves from its mid-position to the left, it compresses spring *F*. The process requires a constant pressure *P*, which is regulated by the butterfly valve shown in Figure 12-21. If pressure *P* increases, this deflects the diaphragm and moves the jet nozzle *G* to the left, and the piston in *C* starts moving. The resulting displacement of oil moves the piston in *D* upward, thus throttling the butterfly valve and lowering pressure *P* toward its desired value.

The movement of the piston in *C* produces feedback action. As it moves to the left, it compresses spring *E*, increasing the counteracting force on the jet

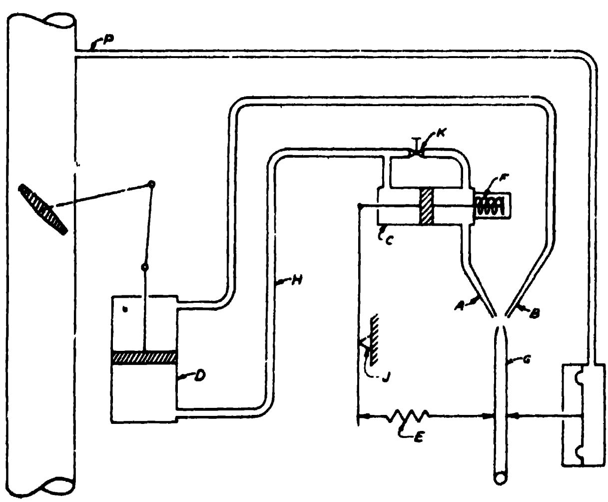

Figure 12-21. Controller with hydraulic stabilizer.

nozzle *G*. This will tend to bring the jet nozzle back to its mid-position, but it will not bring it back all the way. A balance will be obtained somewhere between the pressure in *A*, produced by the deflected jet nozzle, the consequent displacement of the piston in *C* and its feedback action through *E*. The point of balance depends on the magnitude of *P*. A definite position of the jet nozzle thus corresponds to each such magnitude. This is proportional-position action. The fixed relation between position of the butterfly valve and pressure *P* would produce offset in case of load changes, which require a change of this relation.

Therefore, reset action, compensating for offset, is provided by needle valve *K*. As long as offset persists, *i.e.*, the jet nozzle does not return to its mid-position, the pressure *A* communicates through the small opening of the needle valve with the left of the piston in *C*. This makes oil flow into *D* and provides further correction of the butterfly valve. It simultaneously pushes the piston in *C* to the right, which results in pulling the jet nozzle to the left by an additional amount because of spring *E* which is actuated by the lever. This further increases the pressure *A*.

The flow through restriction *K* ceases when the pressure on both sides of the piston is equal. Under these conditions, and because of the action of spring *F*, the piston in *C* assumes mid-position. While this occurs, the action of the butterfly valve returns pressure *P* to its desired value. The jet nozzle *G* moves toward its mid-position because *P* decreases, and consequently pressure *A* drops. The piston in *C* moves to the right, producing an additional pull on the jet nozzle to the left away from the mid-position. The result of these two tendencies is a continued slight deflection of the jet to the left with an increased pressure *H*, and therefore a valve position that gives the pressure *P* its desired value without offset. The reset rate can be adjusted by needle valve *K*, giving it a larger or smaller opening.

The gain is changed by shifting fulcrum *J*. This fulcrum is movable up and down the lever that pivots around it. By changing its position, the magnitude of the feedback action from the piston in *C* through spring *E* to the jet pipe *G* is adjusted. This determines the amount of deflection of *G* in response to a given deviation of pressure *P*, which is equivalent to the gain of the proportional-position action.

13. Time Function Controllers

Time schedule and time cycle controllers are both methods in which control becomes a function of time. In a time schedule controller the set point of the controller is automatically shifted in relation to a predetermined time pattern. A time cycle controller is needed where process operations must be carried out according to definitely timed sequences.

TIME SCHEDULE CONTROLLERS

Foxboro's Model 40 Operation-Schedule Controllers are available in a variety of models to fit a number of process requirements as exemplified by the graphs in Figure 13-1. These graphs illustrate some of the time sequences in which different models can change the set point. As shown in Figure 13-1 *A*, setting the time index opens the control valve and starts counting time. The controlled variable is brought up to the set point, and the control valve is automatically closed at the end of the time period. An adjustable stop on the time setting index permits repeated setting without further reference to the time scale. Figure 13-1 *B*, shows similar action but this model includes deferred action. The timer in this case starts counting time only when the controlled variable has reached the set point. Figure 13-1 *C* illustrates the same action—bringing the controlled variable to a set point and holding it there for a time period—but an additional mechanism is included which shifts the set point of the controller at a predetermined rate of rise. The holding time at the set point may be extended on this model by turning the time index on front of the instrument case to the desired overtime period. The action of Figure 13-1 *D* prevents a process from being "shocked" or damaged by a sudden drop after the timed period, or where it is desired to gradually lower the controlled variable. To obtain such action, this model incorporates a controlled rate-of-fall mechanism to operate before a final shutdown. This mechanism is actuated by a push button. Figure 13-1 *E* shows the action of a model that is capable of switching from one set point to another. The controlled variable is brought to a base set point and held there to allow for the addition of chemicals or to insure uniform starting conditions throughout the process. At the end of the initial timed period, the controlled variable is brought through a controlled rate of rise to the top set point and held there for a timed period. The top period may be

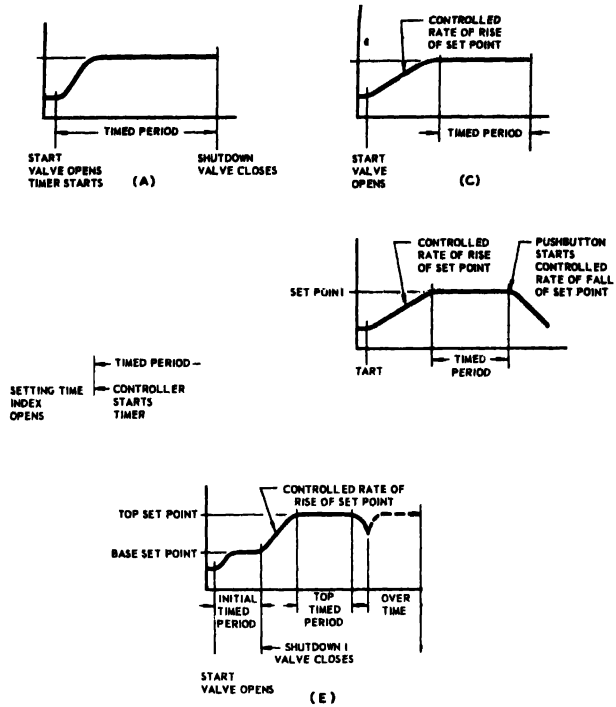

Figure 13-1. Different time schedules.

extended for a preset time by pressing an overtime push button. The process automatically shuts down at the end of the holding period. The base set point and overtime timers are individually adjustable. This model resets all its timers and indexes and starts operation when a push button is depressed.

For process schedules that are repeated frequently without variation, but do not fit into any of the above patterns, a cam-set controller can be used. In this case a lever rides on the periphery of a metal cam. The lever is connected to the set point mechanism. The cam rotates at a constant speed. As the lever follows the contour of the cam, it changes the set point with the shape of the contour. Figure 13-2 illustrates the action of a Taylor Time Schedule mechanism and its interconnection with the recorder controller instrument.

The electric time schedule motor (1) drives the metal cam (7). The cam follower (3) is connected through link (4) to the pen arm mechanism (2) of the controller mechanism, changing the set point automatically in accordance with the program determined by the contour of the cam (7) and speed of rotation of the cam clock (1). The set point of the controller is thus changed in accord-

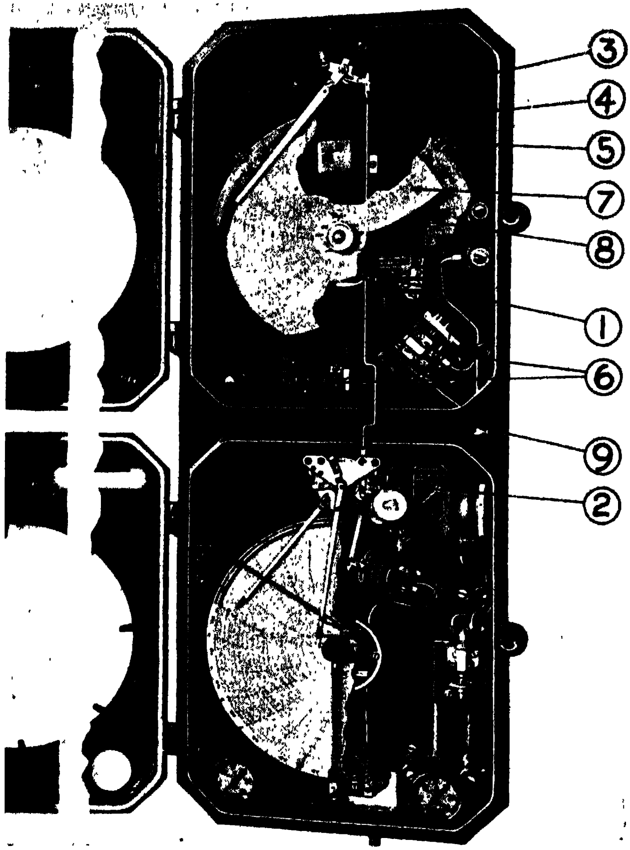

Figure 13-2. Cam-actuated time schedule controller. (*Courtesy of Taylor Instrument Cos.*)

ance with the contour of the metal cam. This cam can be cut in the field to any arbitrary shape, but the cam follower, which rides on the cam, can be lifted only within a limited rate of rise. Where the rate of rise of the controlled variable, as required in the process, exceeds the limits of the cam follower mechanism, the condition can be remedied by an interrupter timer, as described below.

As added features from one to four trip units (6) may be provided, each including either an air valve, or a Microswitch, or both. To operate the trip units a metal disc (8), carrying trip clamps (5) is mounted on the motor shaft with the cam (7). The time disc (8) is imprinted with four time scales, each applying to one of four possible trip units. The trip clamps (5) for each individual trip unit are fastened on their corresponding scale and in the proper position to operate each trip unit at the desired time without interfering with one another.

The time schedule motor may be stopped automatically by a trip unit at the end of the cycle. The cam may then be advanced manually through the friction drive to the starting position at the beginning of the next cycle. This action resets the trip unit for the cycle. A sustained contact push-pull switch (9) keeps the current on unless shut off by hand. If automatic stopping is not desired, the push-pull switch may be used to stop and start the time schedule motor manually.

In cases where the length of the cycle under control, plus the time required for unloading and reloading the apparatus, is greater than the period of rotation of an available time schedule motor, the motor may rotate the cam to the starting position after the cycle is completed and there be automatically stopped by a trip unit. The next cycle may then be started by pressing the button of a momentary contact switch and continued by a hold-in relay. This feature also permits remote operation of the instrument and locking of the case to prevent unauthorized access to the mechanism.

Another added feature that may be supplied when required is the interrupter timer, illustrated in Figure 13-3. This cuts off the power to the time schedule motor either for a certain total duration or at periodically repeated intervals, thereby temporarily interrupting the time schedule and consequently prolonging it. It consists of a synchronous speed motor which operates a Microswitch by means of an adjustable cam. The cam is adjustable from 1 to 100 per cent of timer rotational period. Depending on the position of the toggle switch the cam covers either the range from 0 to 50 or from 50 to 100 per cent. The figures engraved on the face of the cam are in per cent of interruption, which represents that portion of each cycle when there is no electric current flowing to the time schedule motor. The timer is started and stopped by an electric trip unit operated from the time disc.

The advantage of the interrupter timer is that it permits the selection of standard time schedule motors with faster revolutions than would otherwise be permissible, and makes it possible to take advantage of the maximum rate of rise of the cam follower without sacrificing the length of process cycle.

Some applications require two control functions, that are governed by one measured temperature during the same process time. An example of an instrument to accomplish this is the Brown duplex-cam duplex controller. It combines in one housing the measuring and recording mechanism, two time-schedule controllers with their respective cams and two control units. The two cams can have the same or different contours, but in either case they are synchronously driven by a single motor. Although the instrument is a single-record type, its two cams operate two final control elements that maintain the single measured variable at the required value.

A typical application is the control of size cooking in the textile industry. The size is prepared in a single kettle, which has two separately controlled steam coils as heaters. A high-capacity open coil supplies the larger heat requirements for rapid temperature rise, and a low-capacity closed coil maintains equilibrium. The control valve which regulates the steam to the high-capacity

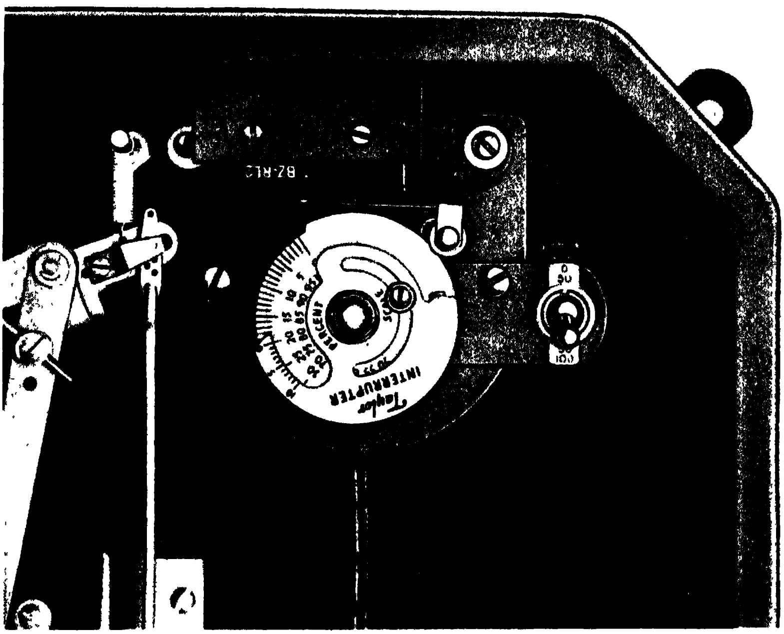

Figure 13-3. Interrupter time for Taylor time schedule controller. (*Courtesy of Taylor Instrument Cos.*)

coil is slowly throttled when the cooking period is reached by the action of cam No. 1. The cooking cycle itself will be carried out in accordance with a pattern determined by cam No. 2.

Other combinations are the duplex-cam dual controller and the dual-cam dual controller. In these instruments, two variables are measured, recorded, and controlled independently. The controller has two separate measuring elements, two records, two cams, and two separate control units. Dual control differs from duplex control in that the two control units are operated by separate measuring elements. In the duplex-cam dual controller both cams are on one shaft, while in the dual-cam dual controller they are driven by separate motors and may be operated at the same or at different speeds, as elected. The latter arrangement thus corresponds to two independent time schedule controllers combined in a single housing.

TIME CYCLE CONTROLLERS

The time cycle controller made by the Fisher Governor Company was specifically developed for time cycle control in oil production, where it is used in flowing wells and gas lift installations. Its operation is illustrated in Figure 13-4. The operating medium can be taken from the upstream gas line or from the well casing and filtered through the high-pressure filter (1). The pressure is then reduced by the high-pressure regulator (2) to about 75 psi and further reduced to 20 psi by the reducing valve (3).

The timing wheel (10) is rotated by means of a spring-wound clock mechanism which needs rewinding every 7 days and rotates the timing wheel at one revolution per day. The timing wheel has a graduated rim which carries 720 closely placed time clips (9). Any number of these clips can be removed from the graduated face of the wheel to form a notch in the operating surface. A spring-loaded trigger (6) rides the periphery of the wheel formed by the out-

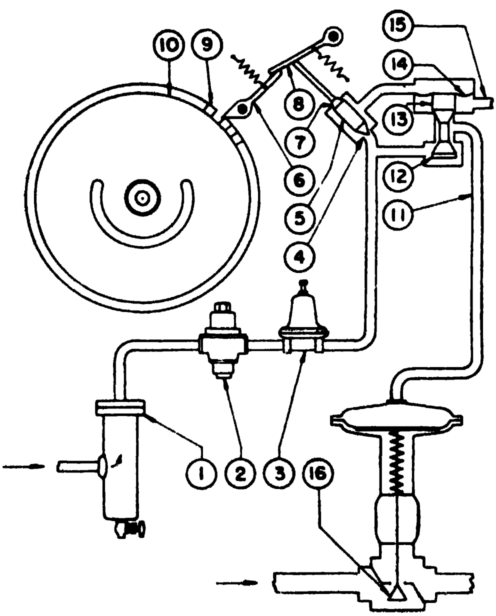

Figure 13-4. Schematic of time-cycle controller. (*Courtesy of Fisher Governor Co.*)

side edges of the timing clips. The wheel turns counterclockwise and as the trigger (6) drops into a notch formed by a removed timing clip, spring tension will rotate the trigger around its hub until it hits the edge of the next clip and assumes the position shown in the illustration. This motion actuates lever (8) against its spring force, and the primary three-way valve follows this movement under the pressure exerted on it by the operating medium in the valve body, closing exhaust port (7) and opening inlet port (4). The supply gas then flows through the primary three-way valve, loading the diaphragm (14) of the secondary three-way valve. The force exerted on this diaphragm closes the exhaust valve (13) and opens the supply valve (12) to load the diaphragm of the motor valve (16).

As the timing wheel continues rotating, trigger (6) is pushed through a clockwise movement. This actuates the primary three-way valve (5), closing supply port (4) and opening exhaust port (7), bleeding the pressure off the chamber above diaphragm (14). The pressure of the operating medium then forces supply valve (12) to close, opening exhaust valve (13). The pressure on the main diaphragm will bleed out through exhaust port (15) and valve (16) will close. Thus each time the trigger drops into a notch, the valve opens, the length of time it stays open being determined by the width of the notch.

Where the cycle involves a number of coordinated actions that are to occur at different times, another type of time cycle controller is used, of which the Bristol Impulse-Sequence Cycle Controller is a good example. The instrument is illustrated in Figure 13-5. It consists of two separate systems. One is the time measurement system comprising the timing disc (15), driven by the timing disc motor (12), and a cam follower (16) which rides on the periphery of the timing disc and actuates switch (17) through a mechanical linkage. The other system operates the pilot valves and is made up of a set of cams (8) on shaft (3) rotated in steps by the cam shaft motor (7). These two systems are connected electrically through the circuit between switches (2) and (17). The time of operation of the pilot valves (1) is governed by the location of notches cut on the time scale around the periphery of the timing disc.

Impulses from the timing mechanism cause the cams (8) on shaft (3) to move forward, each impulse causing the cams to rotate a part of one revolution and to operate one or more pilot valves. The controller shown in the illustration is in the starting position with the cam follower in the notch cut at zero on the timing disc, and the index cam (4) is also at zero. With the cam follower in the notch at zero on the timing disc, time switch (17) is closed on contact (*c*).

A circuit diagram of the arrangement is shown in Figure 13-6. The numbers and letters used therein correspond to those in Figure 13-5, except the designations of R and R_1 which correspond to relay (19). When relay (19) closes, it

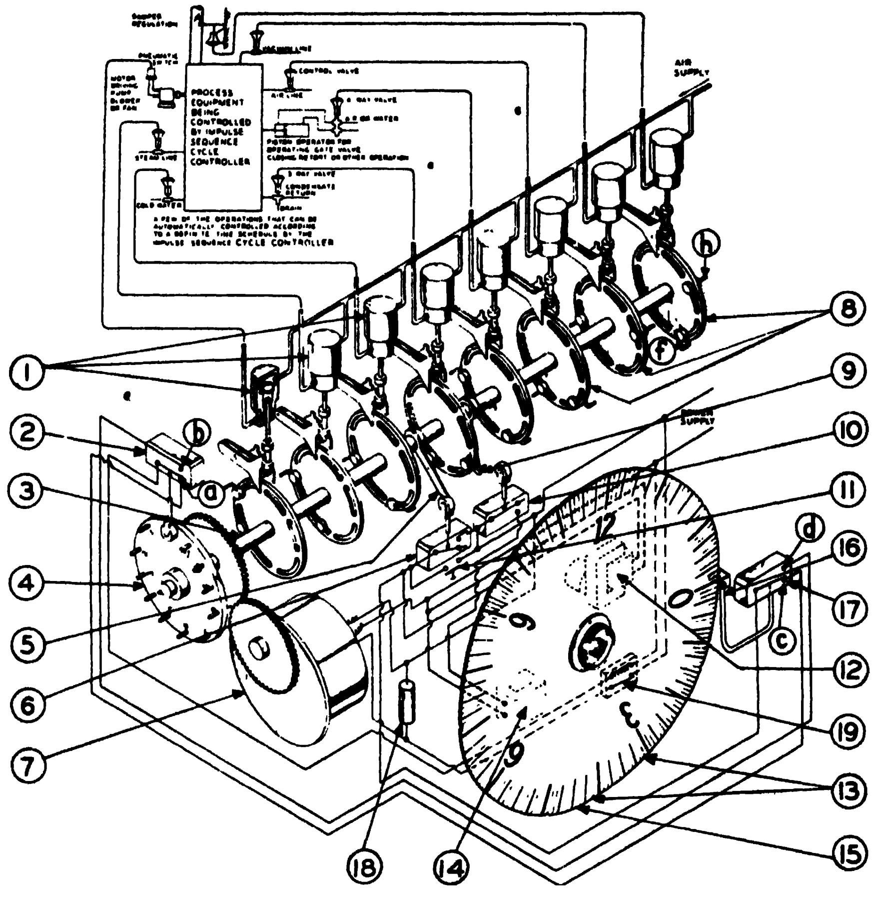

Figure 13-5. Impulse-sequence cycle controller. (*Courtesy of Bristol Co.*)

means that relay coil R becomes energized and pulls in its contact R_1, *i.e.*, closes the circuit.

The cycle of operation is started by manually closing a push-button switch (11). Since time switch (17) is closed on contact (c) and index switch (2) is closed at (a), relay (19) closes, energizing cam shaft motor (7) which starts to run, turning the cam until the follower on index cam (4) is raised by the peg at station No. 1 at which time switch (2) opens contact (a) and closes (b). This action opens the circuit through the coil of relay (19) which will open its contact and stop the cam shaft motor (7).

During the time that motor (7) was running, all the pilot valve cams (8) on the shaft turned 1/12 of a complete revolution and operated one or more

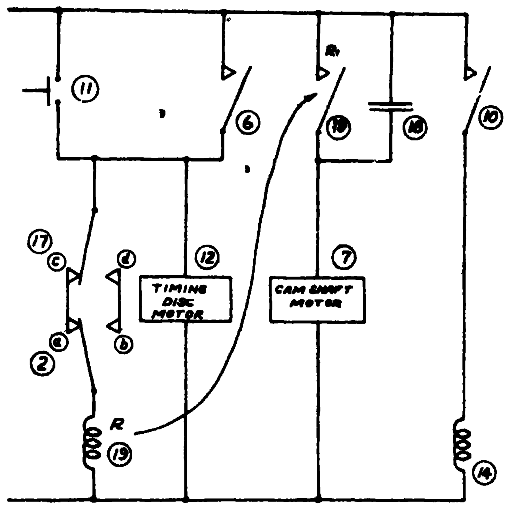

Figure 13-6. Schematic of impulse-sequence cycle controller.

of the pilot valves, depending on the setting of the adjustable dogs on the cams. Cam segment (5) also turned a like amount. Its purpose is to close start switch (6) as soon as the cam shaft motor (7) starts, in order to maintain power on the timing disc motor (12) and keep the circuit including switches (2) and (17) closed during the complete cycle of operation after the push button is released. Switch (6) can be a part of the cycle controller, as shown in the illustration, or it can be incorporated into the process equipment where it is closed at the start of the cycle and opened at the end by the first and last operation to take place in the process. As shown in Figure 13-5 at (*f*) and (*h*), there is a set of adjustable dogs on each cam. Dog (*f*) opens the pilot valve and dog (*h*) closes it.

After the cam shaft motor has moved to the peg at station No. 1, it stops, because of the action above described. The cam shaft motor moves relatively rapidly from one station to the next. It completes this movement before the timing disc motor moves the disc sufficiently to lift the cam follower out of the notch. However, the timing disc motor continues to move, though the cam shaft motor stands still; and as the follower moves to the raised portion of the time disc, the time switch (17) is thrown to contact (*d*). This again closes the relay circuit, and starts the cam shaft motor (7) turning the index cam, but only until the follower leaves the peg at station No. 1. This throws switch (2) back to contact (*a*) and, consequently, stops cam shaft motor (7).

The cams now remain at rest until the next operation is required, at which time another electrical impulse is received from the timing mechanism. The length of this period is determined by the timing disc, since the cam shaft motor does not start again until the next notch in the disc passes over the follower. This closes time switch (17) on contact (*c*).

With the circuit to cam shaft motor (7) thus closed, the cams are turned forward to the next point at station No. 2 on the index cam. As the cams turn to their new position, another set of operations is carried out as one or more of the pilot valves are operated, depending on the location of the dogs on the cams. In this manner, the timing of the operations continues until the cycle is completed, each new step taking place as the disc turns and the next notch on the time scale passes over the follower.

If for a particular process all eleven stations on the index cam (4) are not needed, those not required can be eliminated by merely removing the corresponding threaded pegs. Any number of functions up to eight can be performed, depending upon the number of cams in the cycle controller. Electric switches can be substituted for the pneumatic pilot valves. When the cycle has ended, cam segment (9) closes switch (10), energizing reset coil (14) and automatically moving the timing disc and index cam back to zero.

It is necessary to actuate push-button switch (11) to start the cycle. However, where the cycle is to be repeated, *e.g.*, every two hours, a timer will find application like the Series 306 dial timer made by Automatic Timing & Controls, Inc. This timer has a reversible motor drive. By setting the time cycle, it will rotate in one direction during half the time, and then actuate a switch that takes the place of push button switch (11); it also actuates a second switch which reverses the motor field and the motor then returns to its initial position. After arriving there the switch reverses the motor field again and the motor again rotates in the forward direction. It thus runs continuously back and forth, starting the time cycle controller each time it reaches the end of the forward run.

14. Final Control Elements*

The automatic controller converts the measuring signal into a form that determines the control action, such as proportional plus reset action. This corrective signal is then applied to a final control element which—in the case of an air-operated valve—may comprise the diaphragm actuator and the valve body. It may also include a valve positioner. Electropneumatic and electrohydraulic transducers will also be considered here as parts of the final control element, as will piston actuators, adjustable-speed drives and metering pumps.

AIR-OPERATED VALVES

Diaphragm Actuators

Figure 14-1 is a sectional view of a pneumatic control valve made by the Mason-Neilan Regulator Company. The air transmitted from a pneumatic controller (or a valve positioner) enters the upper diaphragm case, while the lower diaphragm case is vented to the atmosphere. When the top pressure increases the force acting downward also increases. This starts the valve closing. As it does so, the valve spring is compressed and the spring force increases. The valve movement will continue until the spring force is equal to the force due to the increased air pressure. Similarly, when the air pressure decreases, the valve moves upward and the spring expands until a new force balance is attained. Thus the valve stem moves through a definite distance for each change in air pressure applied to the diaphragm.

The assumption is usually made that the travel of the valve stem is linear with changes in air pressure over the customary range from 3 to 15 psi. This is not necessarily true. A linear valve stem travel requires, among other conditions, that the spring response be linear and that the effective diaphragm area be constant. However, the spring accuracy is hardly better than ± 5 per cent and the effective area of the diaphragm changes as it deflects. The deviation from linear response is likely to amount to as much as 10 per cent at the midway of the travel. Another nonlinearity may be produced by the changing thrust forces that act on the movement of the plug in the controlled fluid.

*Some of the material in this chapter appeared in a series of articles which the author wrote for "Chemical Engineering."

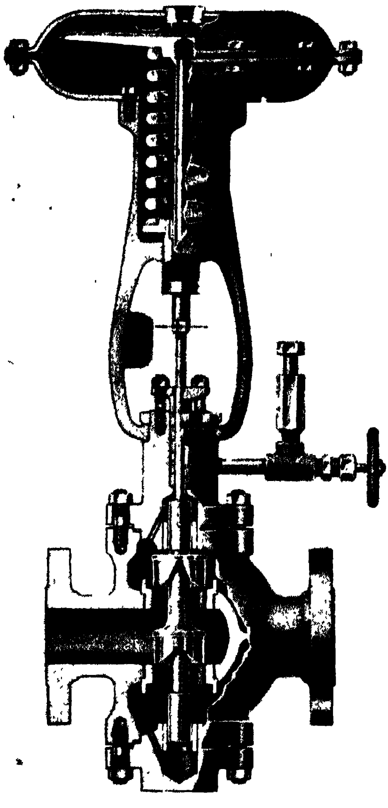

Figure 14-1. Diaphragm control valve. (*Courtesy of Mason-Neilan Regulator Co.*)

One of the difficulties in the use of diaphragm actuators is the spring force that changes with the compression. Assume that a diaphragm has an effective area of 100 square inches. This means that with an air signal change from 3 to 15 psi, it is capable to exert a force of 300 to 1500 pounds. For a valve stroke of, say, 1.5 inches, this requires a spring with a rate of 800 pounds per inch. The spring must have a precompression of 0.375 inch in order to produce a force that will balance the initial signal force of 300 pounds. Compressing it by an additional 1.5 inches—the desired valve stroke—its force increases to 1500 pounds, thus balancing the maximum signal force. No reserve is left for friction forces or for thrust forces which the process fluid will exert on the stem. For example, friction forces must be overcome particularly when starting the stem to move. The signal has to change 1 psi for each 100 pounds of friction forces before motion can start. Furthermore, for each 80 pounds of thrust forces on the valve stem, the valve position must change by 0.1 inch to change the spring force accordingly. The purpose of valve positioners and piston actuators is largely to overcome this limitation.

Valve Positioners

Valve positioners are used wherever the positioning of the valve is opposed by nonlinear forces which are of more than negligible magnitude. They assure that for a definite corrective signal from the controller the valve responds with a definite amount of travel.

The conditions under which valve positioners are advisable can be listed as follows:

(a) Service which causes coking of valve trim, although in such cases even positioners may not be able to give satisfactory operation.
(b) More than normal tightening of packing glands required by the character of the fluid passing through the valve; this can frequently be remedied by "Teflon" packing or where this is not applicable it may be better to consider application of a special valve.
(c) Single-seated valves, including Saunders Patent and diaphragm valves, at high fluid velocities.
(d) Split-range valves—where one valve moves from open to close with a control air pressure change between, *e.g.*, 3 and 9 psi, and another between 9 and 15 psi, both valves being connected with the same control air pressure.
(e) Valves which are expected to respond to 0.20 psi or less of control air-pressure change.
(f) Adjustment of ratio between air signal from controller to movement of stem. Generally, this is determined by the proportional band of the controller action. Where the band is not adjustable, the valve positioner is frequently suitable. An example is given under the heading "Pumps," where the amount of piston movement in an air cylinder is adjustable by a positioner.

The conditions listed for (a), (b), and (c) should require a valve positioner only when the gain is less than 5. Higher gain in the controller would generally result in sufficient increase of corrective action even with small changes of the measurement signal so that a positioner would not be required.

Figure 14-2 shows a Bristol valve positioner connected to a diaphragm control valve. Air or inert gas at a pressure which is kept constant by a regulator and does not exceed 25 psi pressure is led through line *O* to pilot valve *B* which controls the flow through line *G* to the diaphragm of the control valve. The pilot valve is normally kept open by spring *E* and is closed by the movement of floating lever *K* acting on stem *A*. By means of this floating lever, the

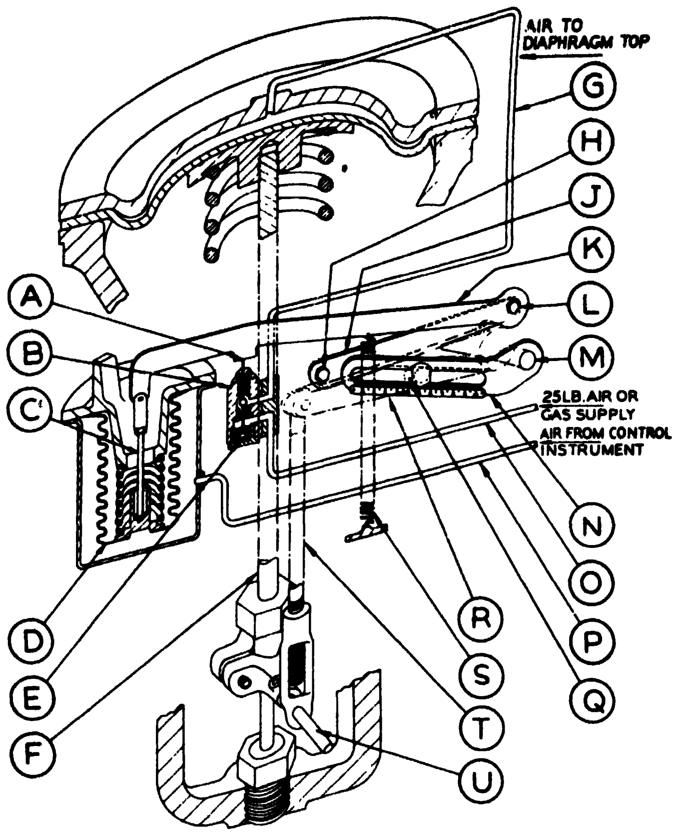

Figure 14-2. Valve positioner. (*Courtesy of Bristol Co.*)

pilot valve is operated jointly by the pressure of the air from the control instrument and the movement of the stem of the control valve to which a connection is provided at *U*. Air from the control instrument coming to the spring-loaded bellows *D* through line *P* gives a movement to the bellows which is in proportion to the pressure from the control instrument. This movement is transmitted through rod *C* to the left-hand end of floating lever *K*.

The other end of lever *K* is pivoted at *L* to lever *J*, which rotates about stud *H* as an axis. Lever *J* in turn is rotated by a bell crank with axis at *M*, in which arm *R* is rotated by the movement of the control valve stem acting through pin *U* and connecting rod *T*, and arm *N* transmits the movement to lever *J* through pin *Q*. Arm *N* has a slotted adjustment for changing the position of pin *Q* thereby adjusting the movement of lever *K* relative to the travel of the valve stem *F*. This adjustment allows covering valve stem travels between 1/4 and 3 inches. Spring *S* holds lever *J* against pin *Q* and also takes up the backlash in the system of levers.

In the illustration, pilot valve *B* is shown in a throttling position, and the corresponding control valve is somewhere midway proportional to the air pressure on bellows *D*. The system is in a state of equilibrium with the air escaping through the exhaust port and around stem *A* as fast as it enters through the inlet port of the pilot valve. Assume now that the pressure of the air from the control instrument increases. This increase in pressure compresses bellows *D* and moves the left-hand end of lever *K* upward. This opens the pilot valve wider and increases the pressure on the diaphragm, which causes the valve stem to move downward, carrying the right-hand end of lever *K* downward in a movement tending to close the pilot valve. This movement continues until equilibrium is again established with the pilot valve still in a throttling position, but with the valve stem of the control valve in a position in direct correspondence to the air pressure from the control instrument acting on bellows *D*. Thus for each value of controller output air pressure there is a corresponding position of the control valve stem.

With a valve positioner, the available force is larger than without. Thus, where a signal of 3 psi on the diaphragm is not able to break the stem loose and move it, the positioner will apply supply pressure and thus multiply the force. However, there are some limitations. Using the previous example of a spring of 800 pounds per inch with a pre-compression of 0.375 inch, let the corrective signal be 3.3 psi. The corresponding spring compression is 0.4125 inch, and the corresponding spring force is 330 pounds. If the corrective signal is now reduced, the maximum signal which the spring can exert toward moving the valve is 330 pounds. It is similar in the upper signal range. Suppose the supply pressure for the positioner is 18 psi which if admitted to the diaphragm is 1800 pounds. Let the controller signal be 14.7 psi. The corresponding spring force is 1470 pounds. The maximum net positioning force for the air is again 330 pounds. At mid-signal, the spring exerts 900 pounds, and the maximum air signal is 1800 pounds. Thus 900 pounds are available. In other words, the available force is always diminished by the counter-acting spring force. Because of this limitation, control valves are usually double-seated valves which balance most of the thrust forces caused by the process fluid.

Piston Actuators

Double-seated valves, as generally used with diaphragm actuators have the disadvantage of unavoidable cavities which can produce excessive erosion and may also lower the so-called C_v values, as will be described further below.

Single-seated valves are to be preferred in this respect. However, to operate a single-seated valve against the same pressure differential as a double-seated valve would require more power.

The piston-operated valve provides this additional power. It is a valve of great compactness, versatility and ease of assembly; it allows accurate positioning for conditions which require a valve positioner on diaphragm-actuated valves. Furthermore, as it usually works with larger air pressures than the conventional valve, greater speed of response is obtained.

Figures 14-3 and 14-4 illustrate the Domotor Control Valve made by the Annin Company and its operation. The particular model of Figure 14-4 is installed with the flow directed over the valve plug (not shown). This makes, in case of air failure, the thrust forces of the process fluid close the valve. Another model is available in which the flow is directed in under the plug and the valve would open in case of air failure. The upper section is a pressure regulator which balances the force which the loading pressure exerts on a dia-

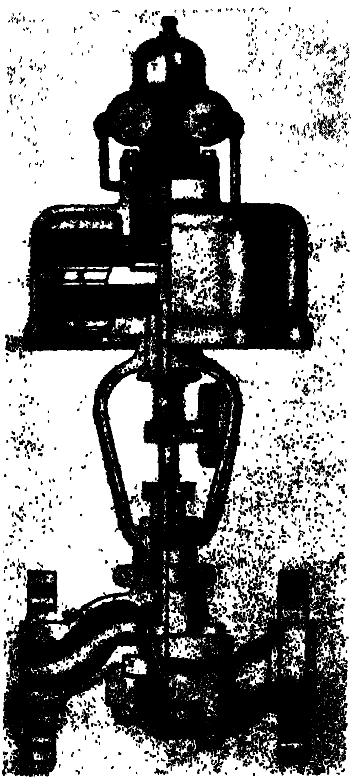

Figure 14-3. Domotor valve. (*Courtesy of Annin Co.*)

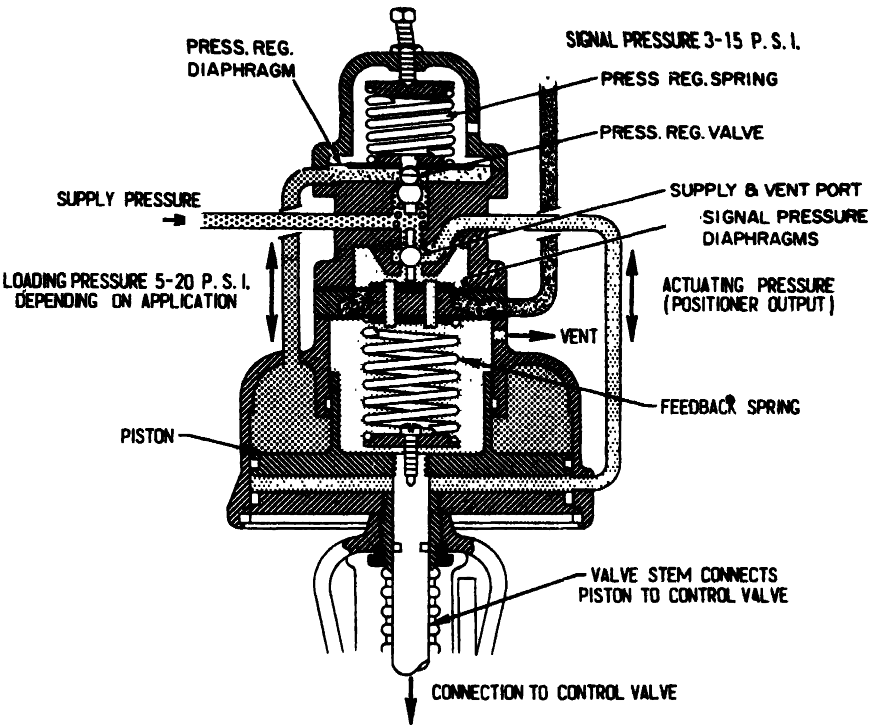

Figure 14-4. Operating principle of Domotor valve. (*Courtesy of Annin Co.*)

phragm against the force of the spring on it. Deflection of the diaphragm controls a small valve which either admits supply pressure to the loading pressure or releases loading pressure to atmosphere. Supply pressures are normally either 25 or 50 psi. The pressure regulator holds a constant pressure on top of the piston, adding air as the piston moves downward and relieving air as the piston rises. The signal pressure is admitted between two diaphragms. The upper one is of smaller effective area than the lower one. Thus an increase of signal pressure moves the diaphragm assembly down together with the small valve plug connected to it. This opens the supply and vent port from supply pressure to actuating pressure and closes the exhaust port. Air is now admitted under the piston. The resulting upward motion of the piston compresses the feedback spring which thus increases the force it exerts on the diaphragm assembly. The repositioning of the diaphragm assembly throttles the supply port and stops piston motion when the forces caused by the signal pressure and the spring balance each other. This results in a piston position which is proportional to the signal pressure. The valve stem is directly connected to the piston.

Because single-seated valves are used and because of the design of this actuator, *the piston* forces alone oppose the thrust forces while the loading pressure works with them. A small loading pressure, such as 5 psi, is generally all that is needed in such cases. With an effective area of 100 square inches, and an air supply of 50 psi, a force of about 4000 pounds can be obtained.

Similar in principle, although differing in detail is the Conomotor Actuator made by the Conoflow Corporation. The Conomotor illustrated in Figure 14-5

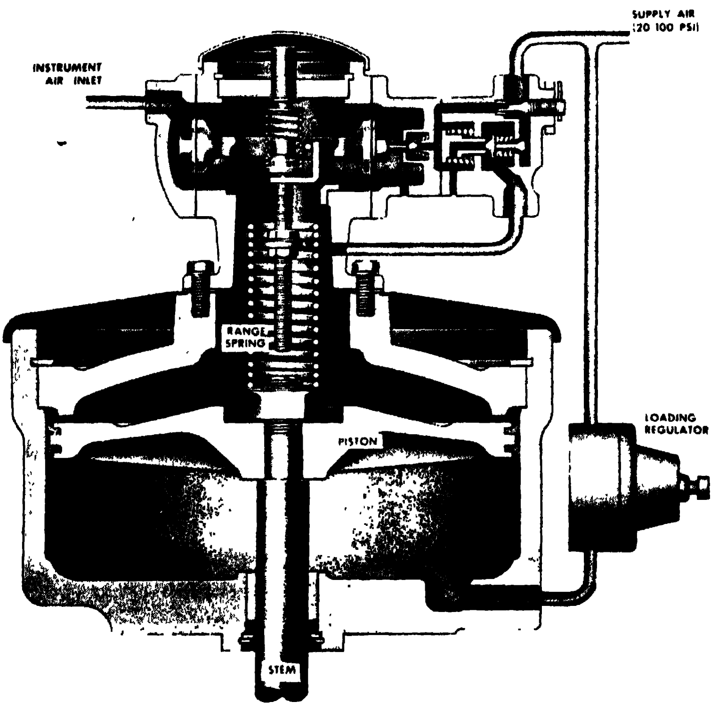

Figure 14-5. Operating principle of Conomotor. (*Courtesy of Conoflow Corp.*)

operates—like the preceding example—with an air cushion of constant pressure. In this case, however, the air cushion is underneath the piston not above. The pressure regulator—or loading regulator—is mounted from the outside. The pressure to the chamber above the piston is regulated through the top-mounted positioner. The instrument air inlet, *i.e.,* the correcting signal from the controller, is applied against a diaphragm, which is connected to a second diaphragm through a rod. The diaphragm assembly positions a pilot valve which admits air pressure to the top of the piston or bleeds it off there. As the piston moves downward, the range spring is stretched. This is converted into a force applied to the rod between the two diaphragms. Balance between the forces due to the air signal and due to the feedback spring determine the piston position.

Such actuators are available in bore diameters ranging from 3 to 12.5 inches, with travels up to 24 inches. They can develop thrusts in excess of 12,000 pounds in either direction with 100 psi differential, and are capable of holding these loads to within 0.002 inch per inch of stem travel when positioned from automatic control instruments or remote manual stations.

Figure 14-6 is a diagrammatic cross section through a piston actuator made by the Republic Flow Meters Company. It comprises: (1) a loading diaphragm and pilot valve assembly deflecting in accordance with air loading pressure received from the control instrument on the diaphragm; (2) a power piston, actuated by the pilot valve; and (3) a return motion linkage and compensating cam assembly, feeding back the movement of the power piston stem to the pilot valve.

A deviation of the controlled variable from the set point causes a change in the air output from the control instrument which is applied to the top of the

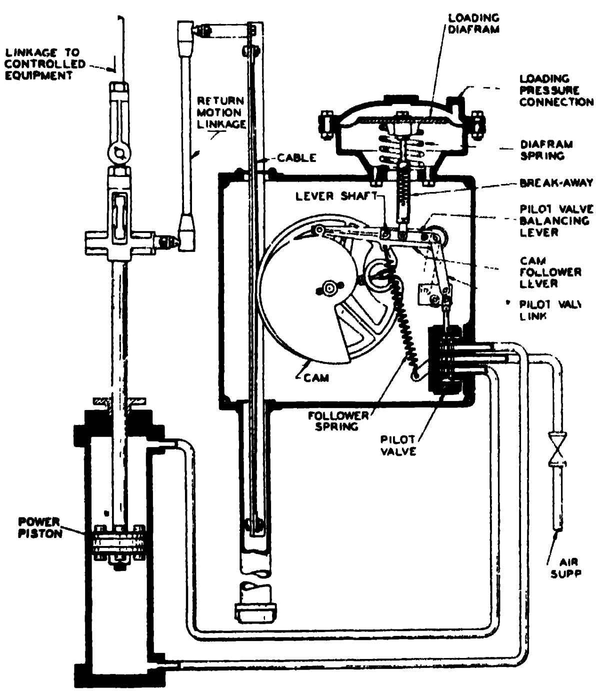

Figure 14-6. Pneumatic operator. (*Courtesy of Republic Flow Meters Co.*)

loading diaphragm of the unit in Figure 14-6. The diaphragm movement is transmitted to the pilot-valve balancing lever and from there through the pilot-valve link to the pilot valve. Operation of the pilot valve is such that it allows air to flow to either the top or the bottom of the power piston. While one side receives air, the other is vented. The resulting motion of the power piston positions the valve, damper, or any other suitable element. While the power piston moves to a new position, it feeds its motion back to the pilot valve through a return motion linkage and a cable that rotates the cam. Thus it positions the cam follower lever, which acts upon the piston valve in a direction opposite to the initial displacement caused by the corrective signal from the control instrument. This results in resetting the pilot valve to its initial neutral position, after it has moved the power piston to a position determined by the control air pressure and the amount of feedback of the power piston movement. Since the cam can be cut to any shape, changing the amount of feedback at will, it is possible to obtain any desired relation between control air pressure and amount of power piston movement.

Electropneumatic Transducers

In order to operate diaphragm-actuated and piston-actuated air-operated valves from electronic controllers, the electric signal must be converted into a pneumatic pressure. Electropneumatic transducers and positioners serve this purpose.

Typical for the electropneumatic transducer is the device made by Fisher Governor Company. Its operation is illustrated by Figure 14-7. The main components are the moving coil assembly, consisting of the coil and the magnet, and the relay. The latter regulates the air pressure output. The output line is connected to the diaphragm of a control valve, so that air flows only when the signal pressure increases or decreases. The relay contains two diaphragms rigidly connected with each other; hence they move always together. The space between the diaphragms is vented to atmosphere through the exhaust. The free

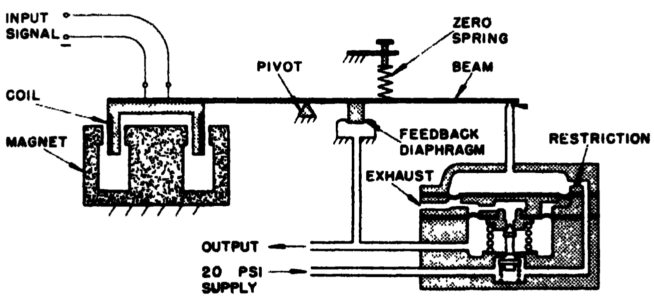

Figure 14-7. Electropneumatic transducer. (*Courtesy of Fisher Governor Co.*)

area of the top diaphragm is larger than that of the bottom diaphragm so that a smaller air pressure on top can balance a larger air pressure against the bottom diaphragm. When the diaphragm assembly moves downward it positions an inner valve, admitting air pressure from supply to output. Inversely, when they move upward they close the port between supply and output but open the one between output and atmosphere through the exhaust. An increase in input signal to the moving coil raises it and causes the beam to move closer to the nozzle. The resulting restriction at the nozzle produces an increase in nozzle pressure and in the upper chamber of the relay. The relay diaphragm assembly will move down, opening the inner valve to the supply pressure. Air flows into the central chamber of the relay, increasing the output pressure until the relay diaphragm assembly is pushed back to its original position and the inner valve is closed again. The increased output from the relay goes to the control valve and also to the feedback diaphragm. The force of the pressure on the feedback diaphragm acts on the beam. When the feedback force balances that of the coil, the system is in balance and the relay output pressure is exactly proportional to the input current.

A decrease in the input signal to the coil moves it down and uncovers the nozzle, decreasing the nozzle pressure. The unbalanced pressures acting on the relay diaphragms force the assembly up, opening the exhaust port. Air pressure from the control valve and the feedback diaphragm bleeds through the exhaust port until the diaphragm assembly is back in its original position and the exhaust port is closed again.

An electropneumatic positioner differs from the electropneumatic transducer in not having a feedback diaphragm. Instead, it generally connects a feedback spring through linkages to the stem of the valve which is being positioned. The force exerted by the spring being proportional to the valve stem position is then connected to the beam in a way similar to the feedback diaphragm described above.

ELECTROHYDRAULIC CONTROL ELEMENTS

The use of hydraulic fluids in the final control elements has several advantages: (1) high pressures can be used, up to 3000 psi and occasionally higher, (2) the fluid, as compared with air, is practically incompressible and therefore is faster and more powerful in action, and (3) the fluid has self-lubricating qualities. Hydraulic pressures position a piston, a rotary actuator or a fluid motor and thus impart the desired motion to the final control element.

Electrohydraulic Actuators

Figure 14-8 illustrates an electrohydraulic two-position actuator. A piston is positioned by the action of a four-way solenoid valve such as made by the

Automatic Switch Company. The inlet pressure is connected to *Q*, the bottom of the cylinder to *T* and the top to *S*. When the solenoid is de-energized, as shown, flow will be from *Q* to *T*, thus driving the piston up, and the exhaust from the piston top will flow through *S* and out at *R*. When the solenoid is energized, flow will be from *Q* to *S*, and the cylinder bottom will exhaust through *T*, *U*, and *R*. The piston will then move down. Practically, the full hydraulic pressure is available to position the piston. If, for example, 1000 psi are applied across a piston of 10 square inches, the positioning force is 10,000 pounds.

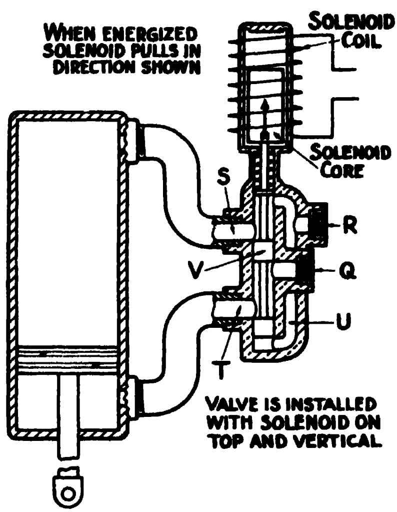

Figure 14-8. Electrohydraulic two-position actuator. (*Courtesy of Automatic Switch Co.*)

General Controls' Hydramotor valve, the operational principle of which is illustrated in Figure 14-9, is a powerful, motor-operated on-off valve. The electric motor drives an oil pump which applies hydraulic pressure to a piston. The valve itself (not shown) is connected with the piston by the piston stem. After a predetermined amount of piston stem travel, a switch, actuated by the stem as shown, breaks and stops the electric motor. The valve is now in the "on" position. The solenoid, shown in the upper left, keeps the relief valve closed, and the hydraulic pressure remains on top of the piston. When the outside controller cuts off the power to the Hydramotor, the relief valve opens, relieving the oil pressure on the piston, and the piston driven by the spring underneath returns to its upper position.

The specific need of previously described electronic controllers calls for final control elements that are capable of responding to the comparatively weak sig-

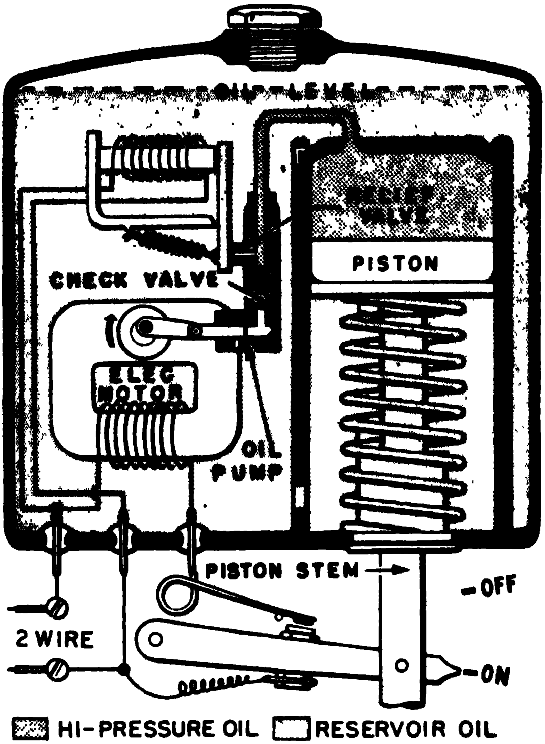

Figure 14-9. Schematic of Hydramotor valve. (*Courtesy of General Controls Co.*)

nals of such controllers. Suitable electropneumatic transducers were already mentioned. They depend however on external pneumatic power. Electrohydraulic valve actuators do not have this limitation. An example is the Vickers electrohydraulic valve actuator, an operational diagram of which is shown in Figure 14-10. The main components are the electric motor coupled to a hydraulic pump (not shown), the moving coil signal system, the servo valve, the cylinder, and the mechanical feedback system.

The pump provides a continuous flow of 1 gpm which is maintained at 600 psi by means of a built-in pressure regulator. A small portion of this flow is directed through the jet pipe which squirts the oil through a receiving port into the end chamber of a spool valve. The pressure in this chamber depends on whether the jet pipe is positioned directly over the receiving port or whether it is slightly deflected. With a very small motion of the jet pipe, the pressure in the chamber changes from maximum to minimum. The relation between this pressure and jet pipe position is nearly linear.

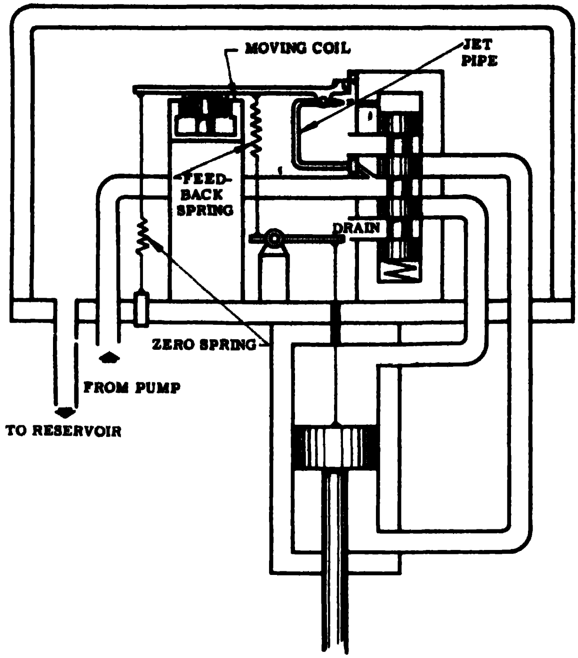

Figure 14-10. Schematic of electrohydraulic valve actuator. (*Courtesy of Vickers, Inc.*)

The spool is positioned between the pressure in the chamber and a helical spring. Hence, for a given supply pressure, the spool position is strictly controlled by the jet pipe position. The spool is designed as a four way valve, and can perform three different actions: (1) it can direct hydraulic flow into the cylinder space above the piston, and drain the space below the piston into the reservoir, (2) it can block the oil on both sides of the piston, and thus essentially lock the piston in position even against high thrust forces on the piston stem, and (3) it can direct hydraulic flow into the cylinder space below the piston and drain the space above the piston into the reservoir. The rate of flow thus admitted to the cylinder is regulated by the jet pipe which positions the spool accordingly. The jet pipe itself is a steel tube of small diameter. In bending it, the tube acts like a spring. The motion is virtually frictionless and is produced by the force of the moving coil to which the signal of an electronic controller is connected.

Thus, the small electric power is converted into a comparatively large force to position the piston rod of the electrohydraulic valve actuator. As the servo valve action moves the piston, the latter rotates a lever by means of a cable. The lever in turn controls the tension of the feedback spring. The system is so adjusted that when the force produced by the moving coil equals the force by the feedback spring, the jet pipe is in such a position that the spool valve blocks its own ports and locks the piston in its position. A change in signal and hence moving coil force produces a flow through the servo valve, a motion of the piston, feedback through the spring, and finally rebalancing of forces with a new piston position. Thus, a position is obtained which is proportional to the electrical signal.

The Vickers electrohydraulic valve actuator is available with strokes of practically any length. The no-load speed is about 50 inches per minute and the stalling thrust of the standard unit is 2400 pounds, although stalling thrusts up to 25,000 pounds can be accommodated.

The Vickers actuator which was described above can be used for proportional-speed floating action control by removing the mechanical feedback linkage. In this case, the piston continues to move as long as it receives a corrective signal. The direction of motion would depend on whether the corrective signal is an increase or decrease from the base signal. The stem speed would be proportional to the signal only for small signal changes. For larger changes the actuator would move at its maximum speed independent of the size of the signal change. For fast corrective action, this is usually desirable.

Electrohydraulic Transducers

The electrohydraulic valve actuator described in the preceding paragraph contains an electrohydraulic transducer or servo valve Its two-stage construction, consisting of a jet pipe in the first stage and a four-way valve for the second stage, has several advantages as compared with single-stage designs. The most important is the extremely high pressure gain, which permits full pressure across the actuating piston even with extremely small input signals. This results in small dead bands even where considerable friction is present and maintains the piston position under load fluctuations. Where such high pressure gain is not needed, single-stage valves—as described in the following—are frequently used.

Figure 14-11 is a schematic of the Rotojet transducer made by GPE Controls, Inc. Hydraulic fluid at pressures up to 1000 psi enters the center shaft and is conducted through the rotor disk to two directly opposed jet nozzles on the circumference of the disk. The jet streams emerging from these nozzles impinge upon their respective receiver ports. The dual jet arrangement balances the reaction forces that act on the rotor disk and its shaft. They also double the flow capacity.

When the input signal to the moving coil changes, shaft and disk rotate through a very small angle. This causes the jet stream to impinge unequally on the receiver ports. The pressures recovered at the manifolded receivers thus

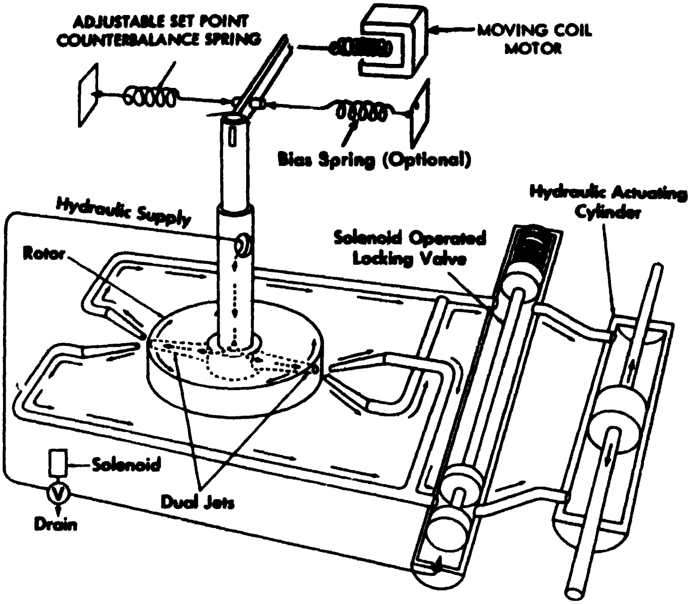

Figure 14-11. Schematic of Rotojet transducer. (*Courtesy of GPE Controls, Inc.*)

become unequal, and the piston starts to move. The direction of the piston movement depends whether the input signal increased or decreased and hence whether the resulting motion of the disk was clockwise or counterclockwise. The speed of the piston movement is proportional to the magnitude of the input signal. This means that this electrohydraulic transducer may be used as a proportional-speed floating controller. It can also be used as a proportional-position controller. For this purpose, a device is needed that feeds back the position of the actuating piston, such as a potentiometer which converts the position into an electric signal. This feedback signal may be applied to a second winding on the moving coil and produce a force that opposes the input signal. This gives proportional-position action. For a given input signal to the moving coil any desired position of the actuating piston can be obtained by changing the spring tension.

Figure 14-11 also illustrates the solenoid operated locking valve. Absence of hydraulic pressure against one end of the valve spool permits the spring on the other end to expand. This locks the hydraulic fluid in the actuating cylinder which can no longer be moved. The hydraulic pressure is removed either when the hydraulic supply fails or when the remotely controlled solenoid valve is de-energized connecting the valve spool pressure to drain. In either case, the actuating piston locks in its last position.

THERMO-DRIVE

The Swartwout Division of Crane Company uses a rather novel principle in its Thermo-Drive Actuator. It is, however, limited to maximum thrust loads of 300 pounds and to speeds of 6 inches per minute. Strokes from 0.5 to 1.5 inches are available. The operation, which is similar to that of an electrical refrigerator, is illustrated in Figure 14-12. The unit is filled with a volatile liquid. All internal parts of the actuator are submerged in the liquid which, within the insulated vapor chamber, is subject to a constant heat input from the floating heater. The heat causes constant vaporization of the liquid, thus tending to increase pressure within the system.

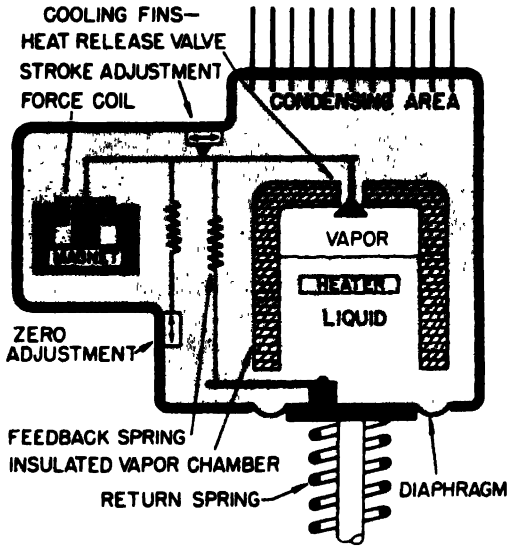

Figure 14-12. Schematic of Thermo-Drive actuator. (*Courtesy of Swartwout Division of Crane Co.*)

The force coil (moving coil), coupled with the feedback mechanism, controls the heat-release valve which regulates the release of vapor to the condensing area. While rate of heat input is more or less constant, rate of heat release is controlled. When the rate of heat release is reduced, pressure builds up within the actuator, extending the diaphragm and moving the valve stem downward. When the rate of heat release is increased, the diaphragm retracts, causing upstroke.

The feedback spring moves with the diaphragm and balances the force exerted by the force coil; thus it produces a valve stem position which is proportional to the input signal applied to the moving coil.

ELECTRIC ACTUATORS

The simplest control valve is probably the solenoid valve, though they are available only for two-position controls. Packless type solenoid valves are particularly advantageous because of their compact, leak-proof structure which does not require a stuffing box. They are limited as to pressure and temperature, and packed types must be used in cases beyond these limitations.

Two-position service should not be viewed as referring only to fully open and fully closed conditions. Whenever changing between two finite valve positions is applicable, two-position action should be considered. High-low or by-pass adjustments are usually available with solenoid valves which allow the setting of any limits between which the valve will operate.

Figure 14-13 shows a cross-sectional view through a solenoid valve made by the Atkomatic Valve Company. It is a self-contained pilot-actuated valve. The seat is closed with a disc of composition material. Above the seat is the high-pressure side, *i.e.*, the fluid inlet, and below it is the low-pressure side, *i.e.*, the fluid outlet. The valve stem is a relatively heavy cylindrical piece, which is widened in its lower part to house the composition disc and also to provide guides for the up-and-down motion. These guides do not prevent the high

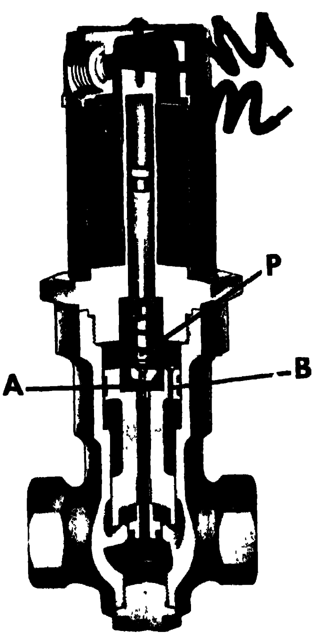

Figure 14-13. Cutaway view of solenoid valve. (*Courtesy of Atkomatic Valve Co.*)

pressure from the valve body from freely communicating with the chamber formed by the center part of the stem, which is smaller in diameter than both ends. The upper end of the stem is a piston which, by means of piston rings, seals against the walls within which it moves. The stem is bored along its vertical axis and closed at its upper end by the pilot valve *P.* There is thus a direct connection to the low-pressure side of the valve.

When current is applied, the plunger lifts pilot valve *P*, relieving pressure on top of the piston through the pilot seat orifice *A* to the low-pressure side of the valve. Since this orifice is larger than the orifice *B*, pressure on the lower side of the piston will exceed that on top and move the piston upward, opening the valve. When the current is cut off, pilot valve *P* closes the pilot seat orifice *A*. This will equalize the pressure above and below the piston through the orifice *B*. The spring will then return the piston to close the valve and the line pressure itself will keep the valve closed.

The advantage of this arrangement is not only that it allows operation against high pressure with relatively small electric power, but also that the effects of water hammer are greatly diminished, because the closing movement can be properly slowed down by means of the diameter relation between orifices *A* and *B*.

One application of interest is the elevator field where a controlled rate of speed is required to eliminate shock in the stopping of the elevator. In this application, orifice *B* is closed off and the upper skirt of the piston is bypassed through a needle valve on the outside of the solenoid valve body. This needle valve controls the rate of flow across the piston and therefore adjusts the speed of closing of the valve.

Conoflow's motor actuator is illustrated in Figure 14-14. In using it with an electronic controller, an additional amplifier is generally required to power the reversible a.c. motor. The actuator consists of a gear box, motor, slide-wire potentiometer for feedback, and limit switches. The purpose of the limit switches is to prevent stalling of the motor when the final control element reaches the end of its stroke. The limit switches permit adjusting the stroke length from 1/4 to 4 inches. The stem can move at 4 inch per minute against a 500 pound maximum thrust.

For considerably larger thrust forces and strokes other motor actuators are available, such as the Futronic Valve Control made by the E-I-M Company. They are made for thrusts from 18,000 to 150,000 pounds, and with a wide range of speeds and stroke lengths. Though they are more elaborate than the Conoflow actuator, the principle of using an additional amplifier, a reversible motor and a gear train is the same. For lighter loads, servomotors are used, while a.c. polyphase motors cover the intermediate and heavy load requirements.

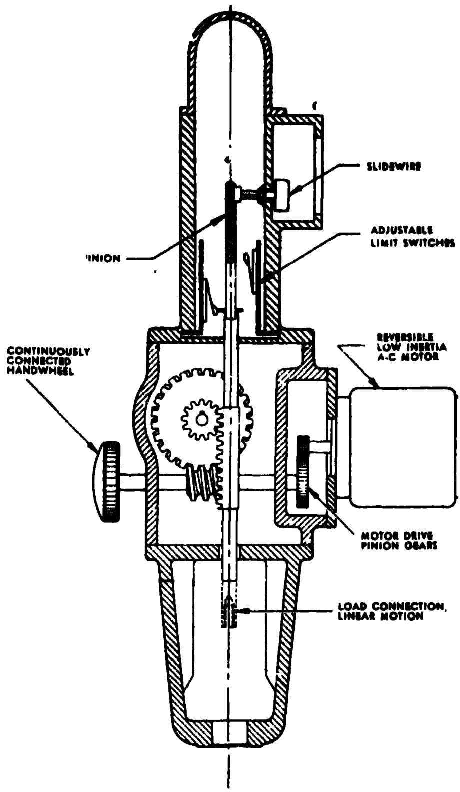

Figure 14-14. Motor actuator. (*Courtesy of Conoflow Corp.*)

VALVE BODIES

The term "equal percentage" is often used when speaking of control valve flow characteristics. It refers to a valve that produces a change in flow rate for a unit change in stem position which is proportional to the rate flowing just before the change is made. In other words, when the flow rate is small, the change in flow rate is small, when the flow rate is large, the change in flow rate is large; and the change is always proportional to the rate at which the fluid flows.

In a valve having linear characteristics, the flow is proportional to the stem motion. For example, 50 per cent of stem motion changes the flow rate through 50 per cent of maximum flow rate. There are many other possible characteristics, although linear, equal-percentage, and quick-opening characteristics are the most common.

The relation between valve stem travel and flow rate, *i.e.*, the flow characteristic depends on the contour of the valve plug since it determines the free flow area between valve plug and circular valve seat for any given plug position.

Plug Shapes

Figure 14-15 shows the three most common valve plug shapes: disc plug, contoured plug, and V-port plug.

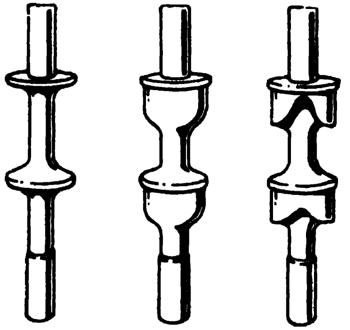

Figure 14-15. Basic valve-plug shapes.

The beveled surface of the metal disc and seat are ground to fit each other, insuring tight closing. These valves are often referred to as quick-opening valves, since the fastest change in rate of flow occurs in the first portion of the travel. Contoured and V-port plugs can not operate near closure, as do disc plugs. A sharp break occurs in their valve characteristic at a certain percentage of flow. This break is due to design characteristics and prevents use of the valve at or below this value since otherwise the resulting control would be erratic. This is not the case with the disc plug.

A variation of the beveled disc valve is the Taylor Hi-Flow valve. The shape of the disc is such that it approaches a linear flow characteristic more than a standard beveled disc would do. This linear flow characteristic is most pronounced between approximately 25 and 65 per cent of the stem travel. It is similar in this respect to many contoured and V-port plugs. However, it differs because it has the unlimited rangeability of beveled-disc valves.

It is generally difficult to choose between a contoured and V-port plug when their characteristics are not the decisive factor. V-port plugs are better guided since the plug walls slide inside the port walls. The ports serve as a guide for the plug. Contoured plugs lack this extra support. However, where corrosion particles, solids in suspension, or high-viscosity fluids are involved, a contoured plug is better suited than the V-port plug which clogs more readily. V-plug ports also have a tendency to spin and to be noisy, however they show better stability at high loads, while contoured plugs may become unstable because of unbalanced thrust forces that act on the plug.

Valve Characteristics

Figure 14-16 gives flow curves for Mason-Neilan's percentage ported, percentage contoured, and linear plugs. The two equal-percentage curves do not coincide. This is typical since the equal-percentage and all other characteristics are only approximations and do not necessarily follow an exact mathematical

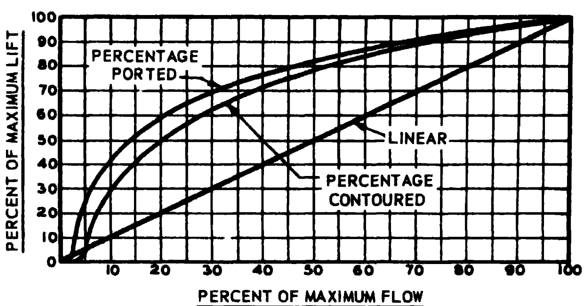

Figure 14-16 Typical flow characteristics.

Table 14-1 shows comparative figures that refer to a number of valve types supplied by some valve manufacturers. The figures indicate the increase of flow in per cent of the maximum flow, which means that for a maximum capacity of 100 gpm they would indicate the increase in flow in gpm as the valve is opened by equal increments—first from 0 to 20 per cent of its travel, then from 20 to 40, then from 40 to 60, then from 60 to 80, and finally from 80 to all the way open. This shows approximately in what part of the valve movement, the maximum, minimum, or any intermediate increase of flow rate through the valve occurs. The figures are largely taken from the valve characteristic curves published by the manufacturers. Minor errors will have been caused by this transferring of readings; but it is not the purpose of this table to give exact information, which the valve characteristic is not supposed to give, but rather to show the difference in valve responses in their general aspect.

Table 14-1 Increase of Flow in Percent of Maximum Flow.

% Travel	Ideal	Cono-Flow	Fisher				Foxboro				Hammel-Dahl			Honeywell			Kieley & Mueller				Leslie		Masoneilan		Taylor			
	Equal Percentage	Equal Percent V-Port	V-Pup	Charact V-Port	Throttle Plug	Quick Opening	Stabiflo	Butterfly	Needle Type	Balanced Poppet	Equal Percent	Linear	Quick Opening	Equal Percent V Port & Contoured	Linear V-Port	Linear Contoured	Equal Percent	True Linear Contoured	Modified Linear V Port	Quick Opening	Equal Percent V-Port & Contoured	Quick Opening	V-Port	Equal Percent Parabolic	V-Port	Hi-Flow	Throttle Plug	Beveled Disc
0 to 20	2.5	4	4	7	12	29	4	7	8	40	4.5	12	100[1]	4	7	8	3	18	7	32	4	95	4.2	7.6	4	10	12	32
20 to 40	3.8	12	5	13	17	30	5	8	7	27	5.5	20	–	6	17	20	4.5	20	13	31	5	5[2]	5.3	6.9	16	22	28	29
40 to 60	9.7	20	11	23	22	22	11	12	13	19	11	24	–	13	26	34	10.5	20	22	18	12	–	12.5	13.5	29	31	30	21
60 to 80	24	27	25	28	24	15	24	30	25	9	25	20	–	31	25	30	24	22	31	9	24	–	24	25	29	23	18	11
80 to 100	60	37	55	29	25	4	56	43	47	5	54	18	–	46	25	8	58	20	27	10	55	–	54	47	22	14	12	7

[1] at 25% travel

[2] at 30% travel

Which valve characteristic is chosen depends on the nature of the process, the load change, and the response required in the flow. Frequently an investigation of the process and the piping is required before the right valve can be chosen. However, it must be kept in mind that in all such considerations and calculations certain idealized conditions are assumed which rarely if ever exist. Amongst these conditions are: (a) the air output from the controller must be linear to changes in the controlled variable; (b) the effective area of the control valve diaphragm must be constant; (c) the valve spring rate must be linear; (d) the influence of changing thrust forces on the valve plug in the controlled fluid must be negligible; (e) the valve characteristic must correspond to the characteristics of the process; and (f) the nonlinear relationship between area of valve opening and flow passing through the valve must also be negligible.

All these considerations are actually irrevelant when a high gain is used. As long as load changes take place within small limits and conditions of the process are not too exacting, results will be satisfactory. This is even more true when reset action is used since this will always drive the controlled variable back to the set point. When less gain is used, the lack of fulfillment of the above assumptions may become a disturbing factor, especially when frequent and large load changes occur. However, the result of offset under such condition may be much more pronounced than the consequences of valve characteristics, linearities, etc.

Valve Action on Failure

A valve may open, close or remain in its last position when the actuating power fails. The diaphragm-actuated valve either opens or closes when the air-pressure signal from the controller fails. This generally depends on the position of the valve plug as shown in Figure 14-17.

As a safety measure, many processes require that the valve either opens or

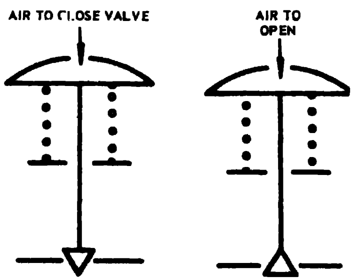

Figure 14-17. Air-to-close and air-to-open control valves.

closes on air failure. For example: on a steam line it can be very dangerous if the valve opens on air failure because the valve then supplies a maximum of steam to a process which is no longer under control. Therefore, before installing a valve, it is very important to determine whether the valve opens or closes on failure and if the particular action is suitable for the process.

A valve which opens on air failure is called an air-to-close or direct-acting valve. Closing on air failures means an air-to-open or reverse-acting valve. In general, an air-to-close valve can be converted into an air-to-open valve by inverting the plug and seat-rings.

Some valves are so designed that air can be connected above as well as below the diaphragm. In this case, to reverse the action of the valve requires only changing the air connections and readjusting the tension of the valve spring.

Diaphragm-actuated valves are inherently suited to either open or close on air failure. Once the air pressure is removed, the spring pushes the valve stem through its travel. To lock such a valve, in case of air failure, in its last position is rather cumbersome and requires expensive locking mechanisms.

For springless valves, the reverse is true. For example, if a hydraulic piston is the actuator, then failure of hydraulic power removes all positioning forces from the piston and thrust on the valve plug determines valve position. However, it is easy to provide an automatic hydraulic lock which will maintain the valve in its last position independent of thrusts. It is also possible to provide such a springless valve with a mechanism to assure opening or closing of the valve in case of failure.

Rangeability

The limitation of the usable range of the valve is expressed by the so-called rangeability factor. If the valve can be used between 2 and 100 per cent of its stem travel, the rangeability is $100/2 = 50$. If it is limited to a range between 10 and 100, it is $100/10 = 10$. These rangeability factors as provided by manufacturers should again be taken only as an indication and *not* as accurate data for actual operation. A good practical figure in all but beveled disc valves is an average rangeability of 8, approaching 15 on larger valves but decreasing to as much as 5 on small valves.

In determining the rangeability required for an actual case, it is necessary to take into account pressure drop as well as flow. Calling the maximum flow Q_1, and the corresponding pressure drop p_1, and calling the minimum flow Q_2 and its corresponding pressure drop p_2, then the rangeability is $(Q_1/Q_2)\sqrt{p_2/p_1}$. For example, if the maximum flow be 360 gpm at 12 psi and the minimum flow 60 gpm at 27 psi, the required rangeability would be $(360/60)\sqrt{27/12} = 9$.

Single- and Double-seated Valves

The control valve in Figure 14-1 and the plugs of Figure 14-15 belong to the double-seated category. They have two plugs and two seats. Single-seated valves with only one plug and one seat are also available. The double-seated valve is so designed that one plug moves with the stream, the other against it. This balances most of the thrust forces that act against the valve stem. On the other hand, the single-seated valve has considerably larger thrust forces that either limit the pressure against which the valve can be positioned or require a more powerful valve actuator. These thrust forces increase as the plug moves toward the seat. This makes them act like a spring that is being compressed although generally in a rather nonlinear fashion. This characteristic results in an increased stability of single-seated valves as compared with double-seated valves. It also leads to the piston actuators with air cushions which apply the actuating air pressure against the thrust forces of single-seated valves and utilize the thrust to combine with the loading pressure in moving the valve stem against a decreasing actuating signal.

The single-seated valve allows tight closing, especially when used with composition disc inserts like Teflon, Neoprene or Buna-N. Double-seated valves should not be expected to close tightly, no matter how perfectly they may be machined and ground, as the dimensional changes produced by process temperatures usually suffice to make them leak.

Sizing Valves

Pressure drop, flow and specific gravity are determining factors in selecting a suitable size for control valves. Other factors such as type of fluid, gas or liquid, critical flow conditions for gases and vapors and viscosity of liquids, influence valve size. Before selecting final valve size, valve and process characteristics must match to compensate for nonlinearities in the control valve and process.

One of the most useful factors to determine the size of a valve is the flow coefficient or C_v factor. Practically all manufacturers supply C_v factors for their valves. These factors form the basis for all calculations. The C_v factor is the number of U. S. gallons of water per minute at 60°F that flow through a valve at maximum opening and a pressure drop of 1 psi. measured in the inlet and outlet pipes directly adjacent to the valve body.

Basic flow formula for liquids is

$$Q = kA\sqrt{\frac{P_1 - P_2}{G}} \qquad (1)$$

where Q is flow rate, gpm.; P_1 and P_2 are pressures measured across the valve, psi.; G is specific gravity referred to water; k is a constant and A is port area of valve, sq. in.

Since $G = 1$ for water, Equation (1) becomes

$$Q = kA\sqrt{P_1 - P_2} \qquad (2)$$

Furthermore, by assuming that pressure drop $(P_1 - P_2)$ equals 1 psi., Equation (2) simplifies to

$$Q = kA \qquad (3)$$

Equation (3) expresses the flow of water through a valve of port area A with a pressure drop of 1 psi. However, this is the definition of C_v which can be substituted for kA. Hence inserting C_v for kA in Equation (1) gives

$$Q = C_v\sqrt{\frac{P_1 - P_2}{G}} \qquad (4)$$

For example: a standard 1-in. double-seated valve may have a C_v factor equal to nine. Suppose the pressure drop across the valve is 64 psi. and the liquid has a specific gravity of 1.44. In this case, $Q = 9\sqrt{64/1.44} = 60$ gpm.

Valves are rated by the pipe sizes of their end connections. The maximum flow area which they provide must be in the same order of magnitude as the pipe size. Since, area is proportional to the square of the diameter, a 2-inch valve passes about four times the flow of a 1-inch valve. Again, a 4-inch valve passes about four times the flow of a 2-inch valve or 16 times the flow of a 1-inch valve.

The C_v factor which is a flow coefficient changes in the same manner. Hence, remembering that a 1-inch valve has a C_v of about 10, it follows for a 2-inch valve that C_v equals 40. For a 4-inch valve, C_v equals 160. Although these figures are only approximate and vary from manufacturer to manufacturer, they usually suffice for rough calculations. For more precise calculations, the valve manufacturer's data, should be consulted.

Fluids that pass through a valve may be either liquids, steam, or gases (including vapors). The same basic flow equation holds for all three fluids. Practical equations are in common use for each fluid. The equations include conversion factors which allow for direct insertion of the flow rates when expressed in the usual units. These equations are:

$$Q_L = C_v\sqrt{\frac{P_1 - P_2}{G}} \qquad (5)$$

$$Q_S = 63.5\, C_v\sqrt{\frac{P_1 - P_2}{G}} \qquad (6)$$

$$Q_G = 1360\ C_v \sqrt{\frac{(P_1 - P_2)\,P_1}{GT}} \tag{7}$$

When Q_L = flow of liquid, gpm
Q_S = flow of steam, lb/hr
Q_G = flow of vapor or gas, cfm.
V = specific volume of steam, cu ft/lb at existing upstream conditions
G = specific gravity—which for liquids is related to water, but for vapors or gases to the density of air.
T = absolute temperature of gas (°F + 460)

It is not essential to express the pressures as absolute or gauge pressures for the pressure drop since the difference is the same. However, in Equation (7), it is important that the additional factor P_1 be expressed in absolute pressure units.

In steam, vapor and gas flow, a critical flow condition will be reached when the absolute upstream pressure is twice the downstream pressure. Any further increase of the pressure drop will not change the maximum flow because turbulent conditions, set up in the valve by the high pressure drop, oppose any increase of flow. Hence, where this condition is reached, a practical assumption is made. Pressure drop becomes simply 50 per cent of the upstream pressure in psia.

When liquids go through a valve, they pass from a higher to a lower pressure. At the lower pressure, the liquid may vaporize. If such conditions exist, it generally suffices—for practical purposes—to choose a valve one size larger than calculated for the liquid. It is important to expand the piping rapidly on the downstream side to take care of the expansion of the fluid.

All fluids possess a quality known as viscosity, but this property only becomes important in control valve sizing when handling highly viscous liquids. For such cases, the Foxboro Company uses the following method.

First, the valve size is calculated under the assumption of nonviscous flow. Then a viscosity correction factor is established for the viscous conditions. Calculated valve size is multiplied by the viscosity correction factor to get the corrected valve size. It is necessary for this calculation to know the viscosity in stokes or saybolt seconds universal at the flowing temperature.

The following equations are then used to correct for viscosity.

$$K = \frac{31.6\ Q_L}{d \times V_s} \tag{8}$$

$$K = \frac{14{,}700\ Q_L}{d \times V_{ssu}} \tag{9}$$

where K is viscosity index; Q_L is flow, gpm.; d is valve size assuming non-viscous conditions, in.; V_S is viscosity, stokes and V_{ssu} is viscosity, saybolt seconds universal. Once the viscosity index is established, the viscosity correction factor is found from Figure 14-18.

For example: a valve is calculated for 60 gpm. of liquid, 25 psi. pressure drop and a specific gravity of 1.25. These values are substituted in Equation 5 to find the C_v factor. The resulting C_v factor is 13.4 which corresponds to a valve size of 1.25 inch. Suppose the liquid has a viscosity of 55 stokes. From Equation (8), the viscosity index K is calculated to be 27.6. The corresponding correction factor read from Figure 14-18 is 1.65. Hence, corrected valve size is 1.65 × 1.25 or 2.06 inches. A 2-inch valve is probably the best choice for these conditions.

It is not infrequent that a valve has to be sized for a certain flow with provision for a planned increase of two or three times in the original flow capacity of the line at some later date. While the valve operates satisfactorily under initial conditions, it may not satisfy future needs for increased flow capacity. In these cases, valves with reduced trim are used.

Reduced trim simply means the substitution of the standard plug and seat-rings by a smaller set. This substitution gives the necessary reduction in capacity while retaining the full, nominal body size.

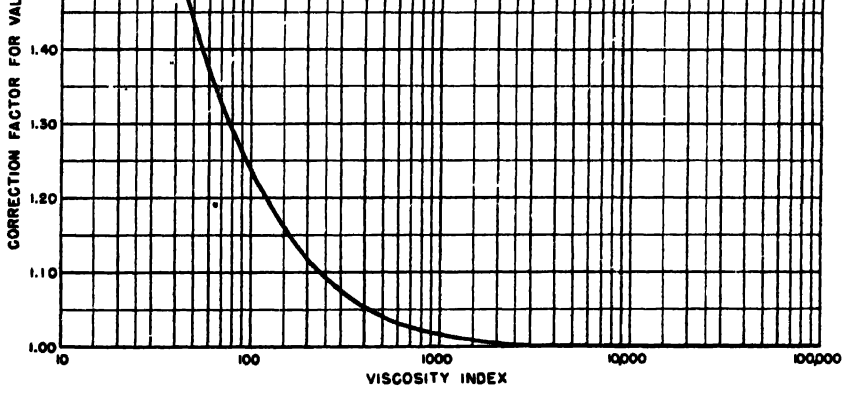

Figure 14-18. Viscosity correction curve for control valves. (*Courtesy of Foxboro Co.*)

After installation, a control valve is sometimes found to be oversized. Frequently, it is easier and more economical to exchange the plug and seats than to replace the entire valve. Reduced trim also finds application where high pressure drops or other conditions require great mechanical strength. It is customary to use 1-inch valve bodies for valves smaller than 1-inch and simply provide plug and seats for the smaller pipe size.

Reduced-trim valves may also facilitate installation. Usually, control valve sizes are smaller than pipe sizes and hence, require reducing connections. By using reduced trim, it is frequently possible to use a valve body equal to pipe size and thus eliminate reducing connections.

Pipelines, hand valves and other elements absorb energy from the fluid which passes through the control valve. The magnitude of the resulting pressure loss or pressure drop is a function of the flow rate. Hence, as the control valve increases or decreases the flow, pressure drop across the valve changes. This change affects Equations (1) through (7) because the pressure drop is no longer constant.

Since the pressure drop through the line increases with flow, pressure drop available across the valve must decrease. This effect reduces flow through the valve at higher flow rates. Figure 14-19 illustrates this condition. The valve characteristic, without consideration of line losses, is also shown. As the line drop increases, maximum flow passing through the valve gradually diminishes, and the flow characteristic is correspondingly modified.

Where only a small percentage of the total pressure drop occurs in the control valve, the valve cannot adequately regulate the flow. To utilize a valve for control purposes, it is necessary to have a considerable drop through the control valve. A minimum pressure drop of 20 per cent of total pressure drop through the valve is generally acceptable. However, a valve drop of 30 per cent or more is definitely preferred.

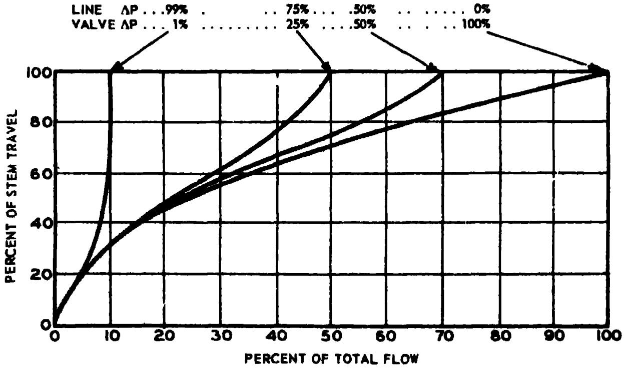

Figure 14-19. Pressure drop in lines and across control valves.

One method which improves the pressure drop proportion is to connect a pressure regulator in series with the control valve. In this case, pressure drops occurring beyond the regulator need not be considered.

Control Valve Construction

Figure 14-20 shows the principal parts of a typical control valve.

The bonnet assembly is attached to the valve body. The body stem moves through the bonnet which contains a means for sealing against leakage such as a stuffing box assembly with suitable packing or a sealing bellows. The blind head may be with or without guide bushings.

Typical guide bushings are shown in Figure 14-20. The valve plug, in this case, has extensions on top and bottom which are the valve-plug guides. These

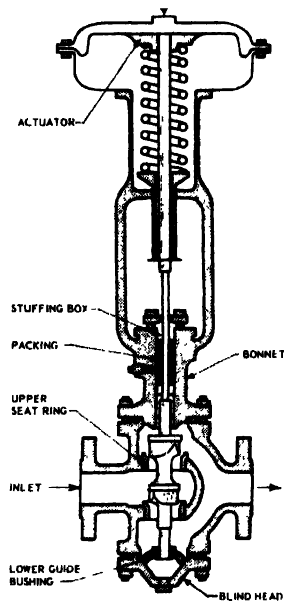

Figure 14-20. Pneumatic control valve.

guides keep the valve-plug motion in alignment. Drain holes connect the space behind the guide bushing with the process fluid. Otherwise fluid could collect in these pockets and prevent the valve plug from moving. Valve guide bushings are particularly needed in the contoured plug. In the V-port plug of Figure 14-20, the cylinder from which the V's are cut out may serve as the guide, as was pointed out before.

The yoke is the structure which is supported rigidly on the bonnet assembly and carries the diaphragm actuator.

Valve trim consists of those internal components within the valve body which come in contact with the process fluid passing through the valve. Valve trim includes components such as seat rings, valve stems and valve plugs.

Valve bodies are generally cast. The most frequently used materials are cast iron, cast steel and bronze. The kind of process fluid determines what material to use. If corrosion resistance is an important factor, valves can be supplied in almost any metal which can be cast. For corrosion service, typical alloys are stainless steel, nickel, "Monel" and "Hastelloy."

Cast iron is commonly used for noncorrosive fluids and in some cases for slightly corrosive fluids. For example, cast iron is generally used for water service, although water is corrosive on cast iron.

Cast carbon steel is used more extensively than either iron or bronze. It is suitable for use on air, saturated or superheated steam and noncorrosive oils and gases up to 850°F. Where welding-ends are specified, cast carbon steel is preferred because of its good welding properties.

For high-pressure and high-temperature—up to 1000°F—service, carbon-molybdenum steel is frequently used instead of carbon steel.

Chrome-molybdenum steel is a good choice for high-pressure steam as well as for oils and gases which become more corrosive at increased temperatures. Also this steel offers good resistance to erosion.

Stainless steels, generally Types 304 and 316, are used for a number of corrosive fluids. Type 316 is a favorite in highly corrosive applications. Annealing should be specified for Types 304 and 316 to take full advantage of their corrosion-resistant properties. Type 304 is also suitable to −300°F.

Cast bronze is used for steam, air, water and noncorrosive gases. Certain dilute acids and oils at limited temperatures can also be handled.

Other valve materials are:

(1) Nickel for reducing solutions and strong concentrations of hot caustic soda and other alkaline or neutral salts. Not desirable where strong oxidizing agents are present.

(2) "Durimet 20" for any concentration of sulfuric acid at room temperature, or similar highly oxidizing conditions.

(3) "Monel" for alkalis, salt solutions, food products, organic substances and many of the air-free acids. Preferred for reducing rather than oxidizing conditions.

(4) "Hastelloy B" for mineral acids of extremely corrosive nature. Used successfully with hydrochloric, phosphoric and sulfuric acids and wet hydrogen chloride gas. Not recommended for oxidizing agents.

(5) "Hastelloy C" for free chlorine or acid solutions of ferric and cupric salts. Withstands strong oxidizing agents.

An important point to determine is the pressure and temperature at which the valve is to be used. For standard body ratings of various alloys, see Table 14-2.

Smaller valves, 2-inches or less, are usually of the screw-end type. On larger valves, flanged ends are most common. With flanged ends better connections can be made and the valve can be readily removed when necessary.

TABLE 14-2. STANDARD VALVE BODY RATINGS

	Pressure (psi)	Maximum Temperature (°F)
Cast iron, flange-end	125	366
Bronze or cast iron, screw-end	150	366
Cast carbon steel or cast stainless steel, flange-end	150	500
Cast iron, screw- or flange-end	250	410
Bronze	300	466
Cast carbon steel or cast stainless steel, flange-end	300, 400 or 600	800

Dimensions of flange-end valves have been standardized by the Instrument Society of America as shown in Table 14-3. Hence, a valve can be removed and replaced by another valve of the same size from almost any manufacturer without any change in piping.

With cast iron and steel valves the bonnet and blind heads are fabricated from carbon steel bars or steel forgings.

For valve seats and plugs, stainless steel is generally used. However, in specifying this material, it is not sufficient to consider only corrosive conditions or pressure-temperature limitations; also pressure drops, erosive conditions and

TABLE 14-3. VALVE FLANGE FACE-TO-FACE DIMENSIONS.

Pipe Size (in.)	Face to Face Dimension,* in 125-psi Iron 150-psi Steel	250-psi Iron 300-psi Steel	600-psi Steel
1	7¼	7¾	8¼
1½	8¾	9¼	9⅞
2	10	10½	11¼
2½	10⅞	11½	12¼
3	11¾	12½	13¼
4	13⅞	14½	15½
6	17¾	18⅝	20
8	21⅜	22⅜	24

* ISA, "Recommended Practice RP-4.1."

wire-drawing must be considered. Wire-drawing refers to the scratching of the metallic surface of the valve by the fluid passing through at high velocity. Steam is a particularly serious offender in this respect.

Clean fluids with pressure drops of 200 psi or less can be successfully handled with Types 304 or 316 stainless. However, where serious abrasion is present such as in slurries or dust-bearing gases, pressure drops of 50 psi or less can wear an untreated stainless steel surface surprisingly fast. Furthermore, the maximum temperature at which stainless steel should be used is about 750°F because its hardness becomes seriously affected.

For example: Type 440-C stainless steel can be surface hardened to give a hardness of approximately Rockwell C-55. The surface then has excellent erosion resistant properties and is suitable for high pressure drops.

About the hardest surface available is "Stellite." This finish is a special nonferrous alloy of cobalt, chromium and tungsten. Hardness of this alloy is not materially affected by heat up to 1500°F. "Stellite" parts may be solid. Frequently, "Stellite" is welded onto the wearing parts of seats, plugs, guide-bushings and valve-plug guides. "Stellite" is unaffected by most common chemicals.

Other materials that resist abrasive conditions are chromium carbide and tungsten carbide.

Bronze is used in low-pressure service where stainless steel may corrode. In cases where the valve body consists of special materials such as "Durimet 20," "Monel," nickel or "Hastelloy," trim parts are usually made of the same material.

Practically all packings, except those of pure "Teflon," require lubrication to reduce friction between packing and valve stem. The greasy texture of "Teflon" provides a practically frictionless surface and requires no additional lubrication.

However, "Teflon" has very poor resiliency. When used as a solid ring, this characteristic prevents it from providing a seal unless compressed to a point where friction becomes excessive. V-rings provide satisfactory service and are extensively used.

"Teflon" may also be used in combination with asbestos. This "Teflon"-asbestos combination consists of pure long fibers of woven asbestos impregnated with "Teflon" and woven into rings. Teflon is useful at temperatures up to 500°F. When higher temperatures occur, cooling fins are generally necessary.

For a comparison of the performance of valves with and without cooling fins, see Figure 14-21. Fins built into the bonnet offer as much air-cooled surface as possible between the valve body and the packing. Temperature readings shown in Figure 14-21 were obtained from laboratory tests of the Fisher Governor Company.

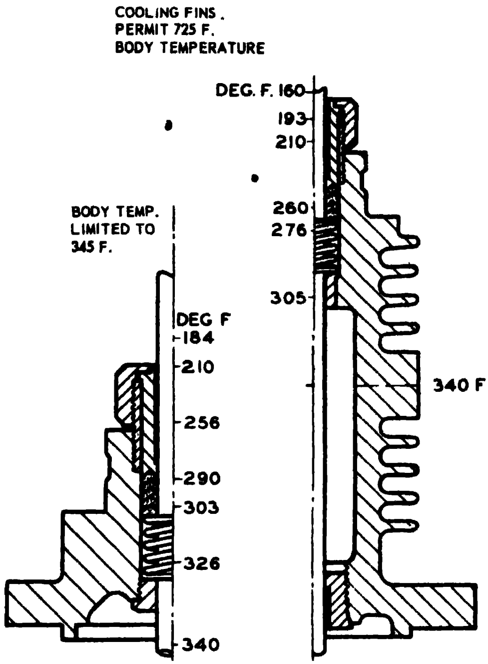

Figure 14-21. Temperature distribution without and with cooling fins.

Valve-body temperature of the valve without fins was about 345°F. For this case a packing temperature of 303°F was measured. Hence, a cooling effect of 42°F occurs between body and packing. However, for the valve with cooling fins, valve-body temperature was 725°F. Temperature at the packing did not rise above 260°F. Therefore, cooling effect is 465°F or more than ten times that of the conventional valve.

Special Control Valves

Special valves may control flow of fluids having unusual properties. In this category are valves for controlling small flows; toxic, corrosive and valuable fluids; liquids containing abrasive materials; and slurries.

Other valve designs provide control for low pressure drop through valve at high fluid velocities; for mixing or diverting flow; and for large flows at low liquid pressures. Also, certain valve operators can provide additional power at valve stem to overcome unbalanced thrust forces on the valve plug.

Valve specification and maintenance of special and standard valves are further requirements to assure correct valve action and adequate flow control.

Small Flow Valves

A flow coefficient or C_v factor less than one is rarely available in conventional plug valves. Flow control at C_v factors less than one generally requires spline plug valves, needle valves or their equivalents. Figure 14-22 illustrates the spline plug, retainer and seat of the Microflo control valve made by the Hammel-Dahl Co. This valve is available in sizes corresponding to C_v factors ranging from 0.001 to 0.63. The valve has equal percentage characteristics for C_v factors between 0.1 and 0.63 and linear characteristics at smaller flows.

Figure 14-22. Trim of Microflo valve. (*Courtesy of Hammel-Dahl Co.*)

The section of the spline plug which moves inside the seat ring has slots or grooves milled and ground into the plug surface. Outside diameter of this section is one-quarter inch. Total stem travel is one inch. Even at maximum lift, the spline plug is guided through the full depth of the seat.

For maximum hardness, the spline plug and seat ring are made of "Stellite" alloy. For the extremely small openings in these valves, the effects of wire drawing and erosion increase. To minimize these effects, a material of suitable hardness is necessary. A stainless steel retainer holds the valve seat in the valve body.

Bellows-Seal Valves

Control valves are sometimes installed in pipelines handling toxic or valuable fluids. Here even minute leakage as may occur with ordinary packings cannot be tolerated. Hence a bellows-seal is used to isolate valve stem action from the atmosphere. Bellows-seals are also helpful where the process fluid would solidify upon contact with air, or in vacuum service where air infiltration from the outside is not desirable.

Bonnet, stem, bellows and packing of a typical bellows-seal valve is shown in Figure 14-23. This one is made by the Hammel-Dahl Company. The lower stem, to which the valve plug is connected, slides at its upper end in a hexagonal guide. Slots are provided in this guide to permit venting between valve body and the space between bellows and the outside sealing tube. In addition to guiding the valve stem, the hexagonal guide prevents the stem from rotating, and thereby protects the bellows from damage.

For greater safety, a three-ply bellows consisting of three bellows closely fitting one into the other seals the valve stem. Inside the bellows, and concentric with the stem, is the bellows tube. This tube carries at its upper end the combination bellows tube collar and safety travel stop. Their purpose is to provide a rigid guide for the bellows and at the same time to limit the amount of contraction and expansion of the bellows to protect it from damage. In case of bellows rupture, the "Teflon" packing at the top provides an additional safety measure.

A pressure gauge (telltale gauge) may also be inserted between bellows and packing. A certain pressure variation will be indicated when the stem moves

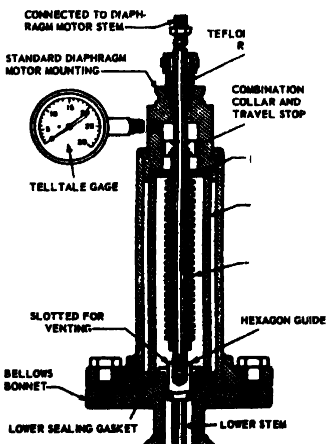

Figure 14-23. Bellows seal.

and changes the compression of air in this confined space. A similar variation will be indicated when the temperature changes and expands or contracts the air in the same space.

If the bellows rupture, the pressure increase is more pronounced, providing the fluid pressure is high enough to indicate the change. The telltale gauge can also be replaced by a pressure switch which closes an electrical alarm when the pressure exceeds a preset value.

Three-Way Valves

Figure 14-24 depicts a Minneapolis-Honeywell three-way valve body. Such a valve is used either for diverting a stream into two separate streams or for mixing two fluids in controlled proportions. If the flow enters on the right, it can leave through the bottom and left connections. With the stem all the way up, all flow leaves through the left. As it moves down more and more flow leaves through the bottom and increasingly less through the left connection. This would be flow diversion. On the other hand, in mixing two fluids, one would enter on the left and one from the bottom, and the mixture would leave

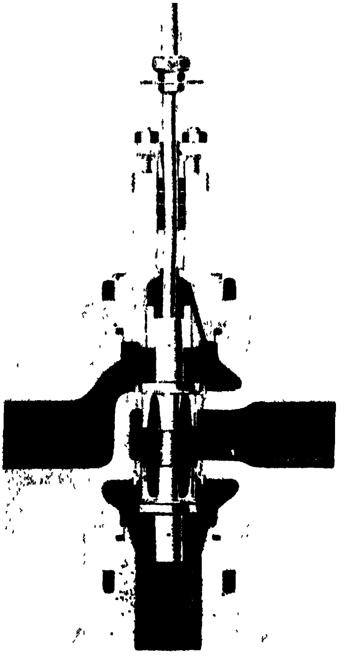

Figure 14-24. Three-way valve body. (*Courtesy of Minneapolis-Honeywell Regulator Co.*)

through the right. The ratio of the two ingredients can be changed by moving the stem up and down. In using three-way valves for mixing, the pressure drop across each port should have essentially the same magnitude to obtain satisfactory control. Also, the flow rate of either fluid should not change through more than a 5:1 ratio between maximum and minimum values.

Butterfly Valves

This type of valve is particularly suited for controlling large flows, especially at low pressures. It is also used to advantage in lines carrying considerable amounts of suspended matter, which would cause excessive fouling of plug-and-seat types of valves. Figure 14-25 is a Foxboro butterfly valve of

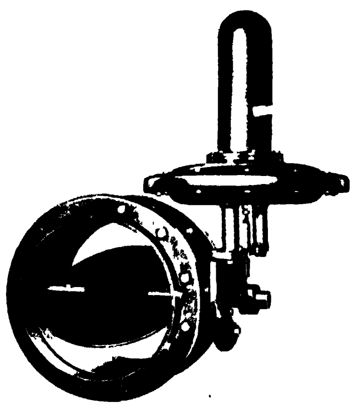

Figure 14-25. Butterfly valve. (*Courtesy of Foxboro Co.*)

light-duty construction without a stuffing box, which is relatively inexpensive and suitable for applications where some leakage at the shaft is not objectionable. There are of course other models of heavier and pressure-tight construction, including those that are appropriate for high pressures and velocities.

The valve characteristics of butterfly valves, as can be seen from Table 14-1 on page 353 approach equal-percentage characteristics. Butterfly valves usually operate through about 70, frequently 60, degrees of their total rotary movement; 100 per cent travel means the travel limited to 70 degrees, of whatever the angle is through which the valve will operate. Butterfly valves produce practically no pressure drop when they are fully open. As pointed out before, the lack of pressure drop in a valve makes control difficult (*cf.* Figure 14-19).

The unbalanced forces across the disc of butterfly valves change considerably during the rotation of the disc. This creates a condition, particularly, at higher flow velocities, where different amounts of air pressure are required to rotate the disc through a given angle at different positions. When the valve is used on high-velocity flow this must be considered. Valve positioners may be required under such conditions.

The major advantages of the butterfly valve are its negligible pressure loss, its applicability to materials with large amounts of suspended solids, and frequently (at least in larger sizes) its lower first cost as compared with standard valves.

Saunders Patent Valves

Figure 14-26 shows a Kieley & Mueller Saunders Patent diaphragm control valve. Valves of this type combine three characteristics. (1) They are packless and can therefore be used with highly toxic, flammable, explosive, and valuable fluids, as well as with materials that solidify in contact with air, and on vacuum service. The possibility of rupturing the seat diaphragm should not be overlooked, however. An emergency packing gland, as described for

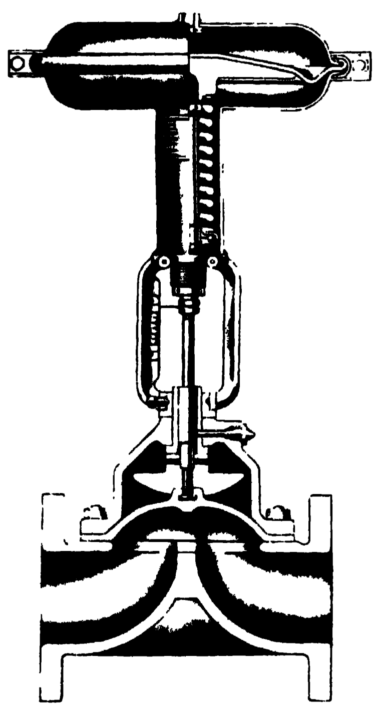

Figure 14-26. Saunders patent valve. (*Courtesy of Kieley & Mueller.*)

bellows-sealed valves, may be considered. (2) There is no valve trim involved except the seat diaphragm which consists of reenforced rubber, synthetic rubber, or plasticized material. This allows handling of highly corrosive fluids. (3) They resemble the butterfly valve in the lack of body pockets, recesses, corners, grooves, and sharp changes in the direction of flow which makes these valves self-cleaning and allows their application to slurries and semisolids. The latter characteristic also produces a valve coefficient about 60 to 70 per cent higher than that of a double-seated valve. While primarily designed for on-off services, these valves provide proportional-position action when equipped with a valve positioner.

The most important limitations of these valves are pressure and temperature. They generally cannot be used for pressures above 150 psi, since the resulting force against the diaphragm becomes too excessive, and early rupture may be the result. The thrust forces on the valve stem also are much larger than in the case of conventional plug valves and limit the pressure rating. Most synthetics are not good for temperatures above 180°F. However, some are available for special applications with temperatures up to 400°F.

ADJUSTABLE-SPEED DRIVES

Control valves are not the only final control element. In fact, they are frequently used only because not enough consideration is given to other final control elements, which possibly are better suited for a particular control problem.

In many process lines, the control valve is preceded by a centrifugal pump. The fact that the pump speed can be controlled and the control valve can be eliminated is frequently overlooked. There is more to this; the control valve demands a centrifugal pump—it could not be used with a positive-displacement pump, though the latter is more efficient and often better suited for the particular job. Using an adjustable-speed drive leaves the freedom of choosing the most desirable pump for each job. Pneumatic and electric actuators are available for most adjustable-speed drives, and thus they can readily be made part of the control loop.

Speed control of process pumps in lieu of flow control by control valves is only one of many applications of adjustable-speed drives. Other applications include speed control of agitators, centrifuges, screw conveyors, feeders, filters, and fans.

Where direct current is available, speed control of a d.c. motor by adjusting its field excitation is a simple matter. In general, however, only alternating current is available. In other instances it may be desirable to connect to some non-electric source of rotary power and thus become independent of electric power. In such cases, one of the following methods* can be used:

1. *d.c. Motors driven from a.c. converted into d.c. by motor generator sets.* An a.c. motor drives a d.c. generator. The d.c. generator provides the power for the d.c. motor. The driven equipment is connected to the shaft of the d.c. motor. The speed is adjusted by rheostats in the field excitations of the d.c. generator and motor.

2. *d.c. Motors driven from a.c. converted into d.c. by rectifiers.* This means that the motor-generator is replaced by rectifiers. The most common systems use either gas-filled tubes (thyratrons) or silicon rectifiers. These elements conduct in one direction only. Thus with a 60-cycle supply, there are 60 pulses per second passing through the element. By smoothing out the pulses, d.c. power is obtained. The effective voltage that results is a function of the duration of each pulse. This pulse duration can be controlled by suitable circuitry in the thyratrons as well as in the silicon rectifiers. The output of the rectifier is applied to a d.c. motor. While the field excitation of the motor is generally kept at a constant voltage by additional small diode rectifiers, the armature current and hence the motor speed is changed through control of thyratrons or silicon rectifiers.

3. *a.c. Motors.* A wound-rotor a.c. motor acts somewhat like a transformer, the wound rotor being the secondary. By connecting an external load to the secondary and changing the load resistance, the speed can be controlled. Efficiency and performance are improved by combining a wound-rotor a.c. motor and a d.c. motor on a common shaft. In this case, the output of the secondary is rectified and used to power the d.c. motor. Speed of the drive is controlled by changing the field excitation of the d.c. motor. This changes the load on the secondary of the a.c. motor and hence changes its speed.

4. *Magnetic drive.* Of the magnetic drives, the eddy-clutch is probably best suited for process control. The essential parts of a typical eddy-current clutch are (1) the drum which is mounted to the shaft of an a.c. motor, (2) the clutch spider mounted on a second shaft—the output shaft, and (3) the stationary field clutch coil. The motor shaft and output shaft are mounted along the same axis but are mechanically separated. Drum and clutch spider mounted on these shafts are also separated by an air gap. Direct-current flowing in the stationary field generates a magnetic flux which produces eddy currents in the rotating drum. These eddy currents create an electromagnetic force which is the means of transmitting torque from the drum to the spider. The amount of torque transmitted is proportional to the d.c. excitation applied to the stationary coil. The two shafts cannot rotate at the same speed, since torque can be

*There are many other methods available, and only some of the more prominent ones are described in the following.

produced only when there is relative motion or "slip" between drum and clutch spider. This means that for a given torque, the slip increases with a decrease of excitation current. Since the slip increases, the speed of the output shaft decreases.

The d.c. excitation calls for a rectifier. However, the required d.c. power is very small. Control of this d.c. gives thus control of the speed.

5. *Mechanical drives.* The a.c. motor is connected to the driven equipment through a mechanical transmission, *e.g.*, V-belts, chain drives and friction drives. By changing the pitch of the belt or chain sheaves or by changing the point of contact between metal balls and discs in an all-metal traction system, the transmission ratio is adjustable and the output speed can be changed.

6. *Hydraulic drives.* These are probably the most versatile of the adjustable-speed drives. Their wide speed range, small size, fast dynamic response, low cost and inherent explosion-proof characteristics makes them particularly suitable for process control. There are hydrostatic and hydrodynamic drives. The latter use the kinetic energy of a liquid whirled around and driving an impeller on the output shaft. For driving process equipment, however, the hydrostatic drive is better suited than the hydrodynamic drive. With the hydrostatic method, a hydraulic pump and a fluid motor are used. The hydraulic pump is driven from the shaft of any process equipment or from an electric motor. The pump action produces oil circulation through a fluid motor which is coupled to the shaft of the driven equipment. As a result of the oil circulated under pressure through the fluid motor, rotary motion is obtained. Several methods for speed adjustment are available. Amongst them are:

(A) Adjustment of delivery rate of hydraulic pump. The speed of the fluid motor is proportional to rate of flow of fluid pumped through it.

(B) Adjustment of fluid motor displacement. As the displacement of the motor is reduced, its speed increases, and its torque decreases. The method is preferred where the required torque decreases with speed, as it happens often with agitators. A considerable smaller unit can then be used with this method than it would with method (A).

(C) Methods (A) and (B) are combined. In this case, the hydraulic pump is first adjusted until maximum speed by this method is reached. From there on, the fluid motor displacement is reduced, and the speed can be increased considerably further. Extremely wide speed ranges can thus be obtained.

(D) A bypass valve can be used. This changes the rate of flow through the fluid motor and hence changes its speed. The performance is not as good as with the other methods and there are certain limitations. However, where applicable, this is the method which is lowest in cost.

(E) A servo valve. This regulates the rate of flow admitted through the fluid motor and thus changes its speed. The principal advantage of this method is that a single hydraulic pump can supply any number of control loops.

METERING PUMPS

The term "metering pumps" has come into use for pumps in the process industries that add chemicals to the process at a controlled rate. With the above described adjustable-speed drives, any pump can be made into a metering pump.

Thus, Figure 14-27, illustrates a metering Eco gear pump with a Vickers adjustable-speed hydrostatic drive and an a.c. motor as prime mover. This Vickers drive combines in a single unit both hydraulic pump, fluid motor, and pneumatic actuator for the speed control. However, hydraulic pump and fluid motor may also be split in two and connected by tubing for the hydraulic fluid. This permits locating metering pump and fluid motor in an explosive atmosphere, while electric motor and hydraulic pump can be located remotely in a safe atmosphere. The Eco gear pump delivers the process fluid at a rate which is exactly proportional to the speed at which it is driven and which is controlled by the pneumatic actuator. There are a number of materials avail-

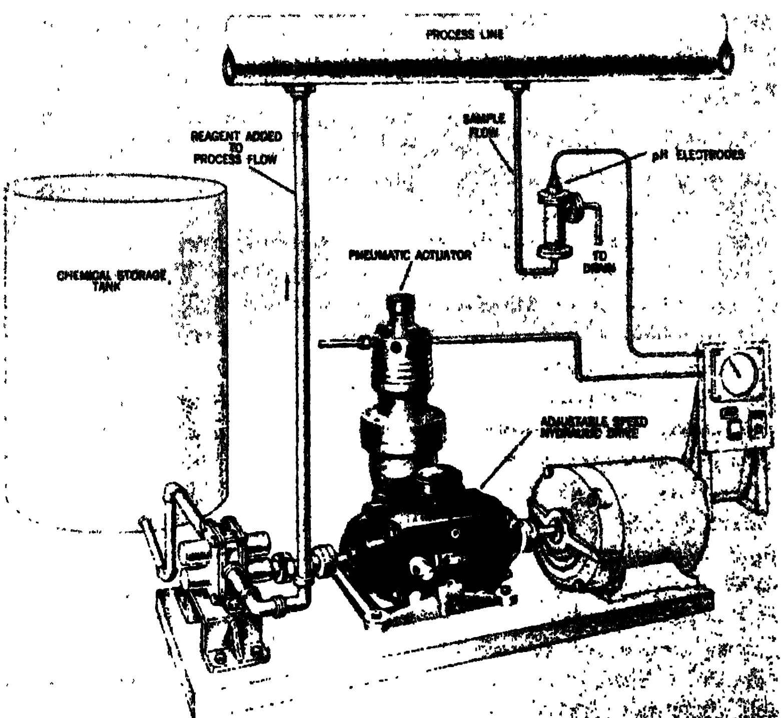

Figure 14-27. Chemical pump with adjustable-speed hydraulic drive. (*Courtesy of Vickers, Inc.*)

able for the Eco gear pump, such as "Teflon," "Hastelloy C," and "Monel," to suit the requirements for most any chemical.

The Pulsafeeder made by the Lapp Insulator Company is shown in Figure 14-28. This is a positive-displacement metering pump where the pumping mechanism is separated from the pumped liquid by a pulsating diaphragm. The piston pumps a hydraulic liquid back and forth. With each forward stroke the increased oil pressure bulges the diaphragm out, which then exerts a pressure on the pumped fluid on its outside surface. This pressure opens the discharge valve and the fluid passes through it. As the piston moves back the diaphragm recedes and the consequent suction opens the suction valves. Since some particle may temporarily lodge in the suction valve and affect the accuracy of the pump, two suction valves instead of one are provided. The diaphragm is available in various types of rubber and plastics, stainless steels and other metal alloys.

Any leakage of the hydraulic liquid between cylinder wall and piston is replaced on every suction stroke by the automatic functioning of a vacuum compensator valve which draws in replacement oil from the oil reservoir. Con-

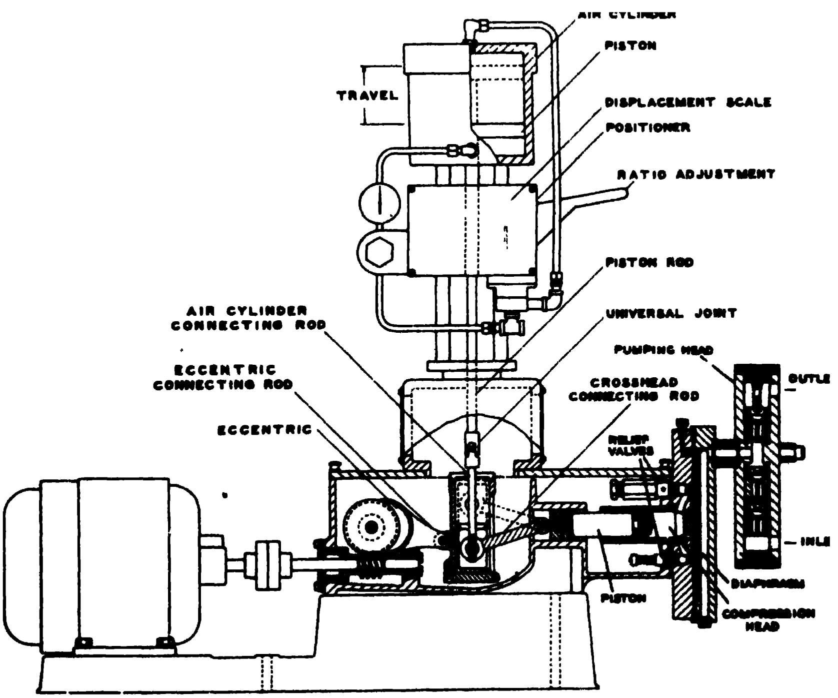

Figure 14-28. Schematic of Pulsafeeder. (*Courtesy of Lapp Insulator Co.*)

versely, any excess pressure built up during the forward stroke of the piston is relieved by the automatic functioning of a pressure compensator valve, which blows off oil under excess pressure ahead of the piston back into the oil reservoir.

The pumping rate of the Pulsafeeder is established by the length of the pumping stroke. Increasing the stroke length will displace more liquid and increase the pumping rate. The length of the pumping stroke is determined by the relative positions of the crosshead connecting rod and the eccentric connecting rod. As shown in the illustration, the rotary motion of an electric motor is converted into the pulsating motion of an eccentric connecting rod. The eccentric connecting rod, the piston rod, and the crosshead connecting rod are joined in the rocker arm assembly. This consists of a small cylinder which is moved back and forth through a fixed angle about a pivot by the pulsating motion of the eccentric connecting rod. The crosshead connecting rod can be moved up and down in this small cylinder by raising or lowering the piston rod. If the crosshead connecting rod was moved upward as shown in the dashed line (Figure 14-28), its motion and hence the piston stroke would be zero since this point coincides with the pivot about which the rocker arm assembly moves. Pushing the crosshead connecting rod downward toward the position shown increases the stroke gradually and therefore increases the volume displaced by the pump. A universal joint between piston rod and rocker arm assembly permits the oscillations of the rocker arm while the piston rod remains rigid.

The controller output pressure is applied to a positioner which regulates the secondary air supply to an air cylinder. The positioner is required mainly because of the unequal loading of the piston rod due to the oscillations of the rocker arm assembly.

A positive-displacement pump of the plunger type made by the Milton Roy Company allows a number of interesting control applications. One arrangement is mentioned here because it combines adjustment of both length of stroke and speed of the pump. The system is shown in Figure 14-29. The pH in the main line is the controlled variable, and the pump adds a chemical solution to the flow, the quantity of which must be that required to maintain the pH in the main flow. The amount of chemical solution to be added depends on two factors: (1) the pH of the main line liquid before adding the chemical solution, and (2) the rate of flow in the main line. These are two variables that require different settings of proportional band, reset, etc. in a controller. Using the same setting for both would result in unsatisfactory control in at least one of the two. Good control, however, is obtained by having the flowmeter control the speed of the pump motor by means of a Thy-mo-trol,* and by controlling

*The Thy-mo-trol is an adjustable-sp d drive with motor generator made by General Electric Company.

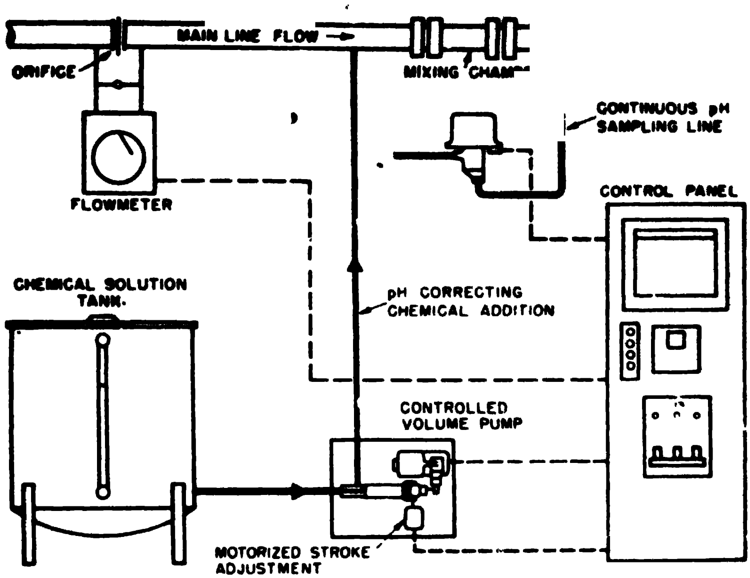

Figure 14-29. pH control with Milton Roy pump. (*Courtesy of Milton Roy Co.*)

the length of stroke in connection with the pH measurement. Thus pH and rate of flow are measured by separate controllers, which both use the pump as final control element, one by regulating the motor speed, the other by regulating the length of piston stroke.

An interesting combination between flowmetering and pump control is offered in the Treet-O-Control by B-I-F Industries, Inc., illustrated in Figure 14-30.

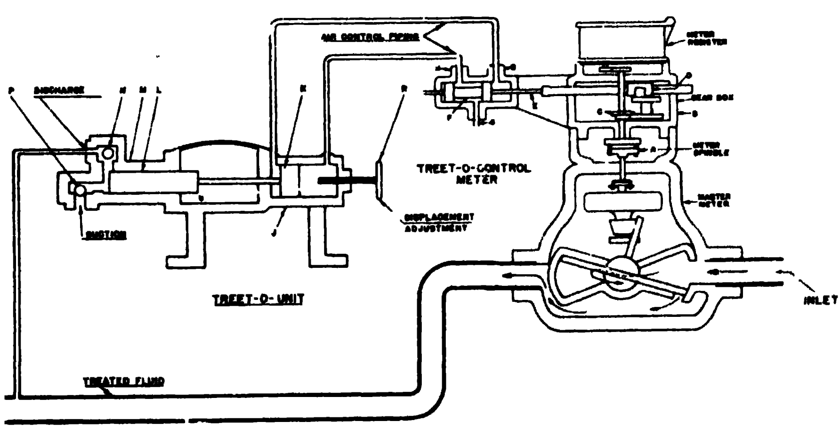

Figure 14-30. Treet-O-Control system. (*Courtesy of B-I-F Industries.*)

The purpose is to add a secondary fluid to a treated fluid in a fixed proportion to the rate of flow of the latter. A positive-displacement meter of the nutating disc type (see page 147) is used to measure the fluid and to provide the signal for the Treet-O-Unit, which pumps the secondary fluid into the main line.

A unit volume of fluid passing through the Treet-O-Control meter turns the meter spindle *A* through one revolution. Gear box *B* mounted above the meter contains reducing gears *C* and crank mechanism *D* to convert the rotation of the meter spindle into a reciprocating movement of the valve rod *E*, which operates pilot valve *F*. Compressed air, steam or hydraulic oil under pressure is admitted as operating fluid to the valve body at point *G*. When the pilot valve *F* on the Treet-O-Control meter has moved to the right, operating fluid passes through the connecting pipe *Q* into the impulse motor *J* moving piston *K* and plunger *L* to the right until the piston strikes the adjustable stop *R*. Secondary fluid is drawn through suction valve *P* of measuring cylinder *M* by plunger *L*. As the flow of fluid through the Treet-O-Control meter continues, the meter spindle *A* makes another revolution, reversing the pilot valve now admitting operating fluid into control line *H*. This forces piston *K* and plunger *L* to the left, and the plunger now forces secondary fluid through the discharge valve and into the main line.

The displacement adjustment screw, *R*, determines the length of travel of the piston and plunger assembly. This permits adjustment of the ratio between the treated fluid and the secondary fluid. Once the ratio between the two flows is set, it is maintained for all rates of flow of treated fluid within the range of the meter.

Glossary

A number of terminologies have been released by various societies. Others are in preparation. The difficulty of providing a practical terminology of common validity has not yet been solved. Recently, the Scientific Apparatus Makers Association (SAMA) published Tentative Standard RC 18-12-1960, "Markings for Adjustment Means in Automatic Controllers." The definitions and terms used therein have a wholesome touch of realistic attitude. It is only to be regretted that the limitations of the project did not permit the Standard to cover the total scope of terminology for measurement and control as such. Some of the SAMA definitions have been used in the text and in this glossary; others are from the somewhat obsolete but still excellent ASME Standard 105 of the American Society of Mechanical Engineers, and the rest are the author's additions. The purpose has been to use and, at the same time, unify the language used by all those able men who are in daily contact with the instruments for measurement and control that make our industrial productivity possible.

Automatic Control System is any operable arrangement of one or more automatic controllers connected in closed loops with one or more processes.

Automatic Controller is a device which measures the value of a controlled variable and operates to correct or limit the deviation of this controlled variable from a selected reference.

Cascade Control is the adjustment of the set point of one or several automatic controllers by the action of another automatic controller. The controller which adjusts the set point must be in closed loop with the controller of which the set point is adjusted.

Closed Loop. The complete signal path in a control system; represented as a group of units connected to a process in such a manner that a signal started at any point follows a closed path and comes back to that point. The loop includes automatic controller, process, measuring means, etc.

Control Agent is that process, energy, or material of which the manipulated variable is a condition or characteristic.

Control Point is the value of controlled variable which, under any fixed set of conditions, the automatic controller operates to maintain. In positioning-type controller action, the control point may lie anywhere within a predetermined range of values of the controlled variable. The control point may then differ from the set point by the amount of offset.

Controlled Variable is that quantity or condition which is measured and controlled.

Controlled Variable Signal is the signal transmitted by the measuring means which is a function of the magnitude of the controlled variable.

Dead Time is any definite delay between two related actions.*

Deviation is the difference between the actual magnitude of the controlled variable and a selected reference.

Deviation Signal is the input into the automatic controller. It is a signal of the deviation of the controlled variable from a selected reference.

Differential Gap, applying to two-position controller action, is the smallest range of values through which the controlled variable must pass in order to move the final control element from one to the other of its fixed positions.

Final Control Element is that portion of the control loop which directly changes the value of the manipulated variable.

Floating Action is that in which there is a predetermined relation between the deviation and the speed of a final control element.

Floating Band (applying to proportional-speed floating controller) is the range of values of the controlled variable which produces a change from minimum to maximum floating speed.

Floating Rate (applying to proportional-speed floating control action) is the ratio of the speed of the final control element to the deviation.

Floating Speed (applying to integral or floating action) is the rate of motion of the final control element.

Gain is a term describing the strength of proportional-position action. It is the ratio of the change in output signal (in percent of rated output signal span) to the change of deviation signal (in per cent of controlled variable span) that produces it, as a result of proportional-position action only.

Load Change is any disturbance that acts on a process from outside the closed loop and tends to alter the controlled variable.

Manipulated Variable is that quantity or condition which is varied by the automatic controller so as to affect the value of the controlled variable.

Measuring Means consists of those elements of an automatic controller which are involved in ascertaining and communicating to the controlling means the value of the controlled variable.

Multiposition Action is that in which a final control element is moved to one of three or more predetermined positions, each corresponding to a definite range of values of the controlled variable.

Offset is the steady-state difference between the control point and the value of the controlled variable corresponding with the set point.

* A more accurate definition would read: dead time in a single capacitance is the time that elapses between a step input and the beginning of change in the output. It is also defined—in particular with regard to multiple capacitances—as the total time required to change through 63.2 per cent of the total change minus the time constant, with the change being the result of a step input.

Process is the production equipment to which an automatic controller is applied.

Proportional Plus Rate Action is that in which proportional-position action and rate action are combined.

Proportional Plus Reset Action is that in which proportional-position action and proportional-speed floating action are combined.

Proportional Plus Reset Plus Rate Action is that in which proportional-position action, proportional-speed floating action, and rate action are combined.

Proportional-Position Action is that in which there is a linear relation between the magnitude of the deviation signal and the magnitude of the output signal.

Proportional-Speed Floating Action is that in which there is a linear relation between the magnitude of the deviation signal and the rate of change of the output signal and/or final control element position.

Rate Action is that in which there is a linear relation between the rate of change of the deviation signal and the controller output signal.

Rate Time (applying to proportional plus rate controller action and proportional plus reset plus rate controller action) is the time interval by which the rate action advances the effect of the proportional-position action upon the final control element.

Rate time is commonly expressed in minutes. It is determined by subtracting (1) the time required for a selected motion of the final control element, due to the combined effect of proportional-position and rate actions, from (2) the time required for the same motion due to the effect of proportional-position action alone, with the same rate of change of the controlled variable in both cases.

Ratio Control is the control of a secondary variable by making its magnitude follow a primary variable at a set ratio.

Repeats Per Minute is the magnitude in which reset rate is expressed. It is the number of times per minute that the proportional-position response to a given deviation signal is increased by virtue of reset action.

Reset Action is identical with proportional-speed floating action. Its usage however differs: a proportional-speed floating controller is limited to this one action. If this action is combined with proportional-position action, then it is referred to as reset action.

Reset Rate (applying to proportional plus reset controller action and proportional plus reset plus rate controller action) is the number of times per minute that the effect of the proportional-position action upon the final control element is repeated by the reset action.

Self-regulation is an inherent characteristic of the process which aids in limiting deviation of the controlled variable.

Set Point is that magnitude of the controlled variable which the controller is set to maintain.

Set Point Signal is a signal received by the controller as a measure of the set point value.

Single-speed Floating Action is that in which a final control element is moved at a single speed.

Two-position Action is that in which a final control element is moved from one of two fixed positions to the other. ("Open-and-shut action" and "on-off action" are synonymous.)

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