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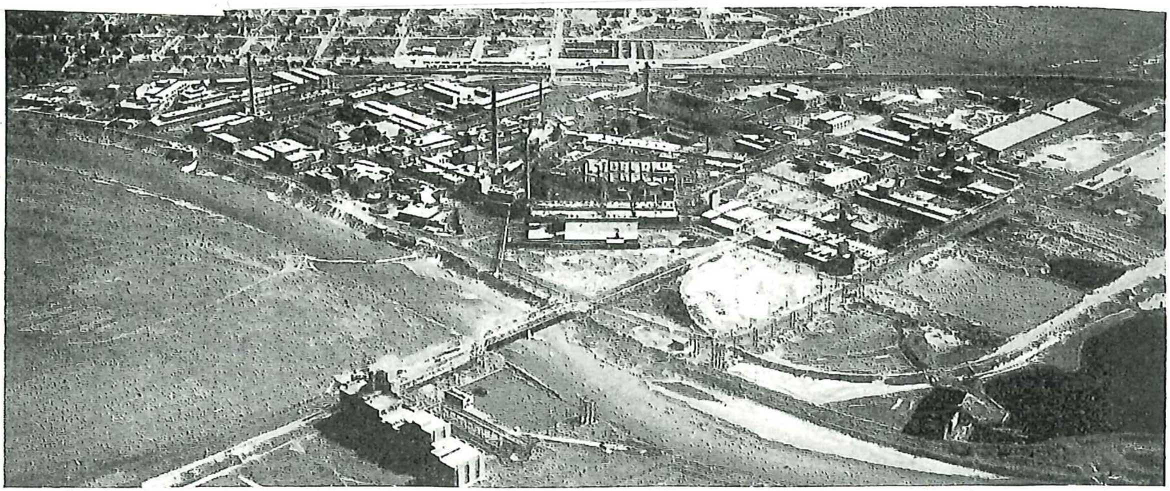


Plant of Dow Chemical Co., Midland, Mich.

Coordinated Effort Solves Dow's Control Problems

By THEODORE R. OLIVE

Associate Editor, Chem. & Met.

ASK ANY Dow Chemical man what his company's outstanding depression achievement was and he will probably tell you, as one of them told me when I recently visited Midland: "It wasn't a chemical process or a chemical engineering discovery, although there were several of those. Rather, it was the continued development and coordination of a versatile and capable organization, which not only was maintained during the depression, but was actually increased." Others may say, with the writer, that this is but a manifestation of Dow custom, and that the real, current accomplishment has been in measurement and control; but there, none the less, in a few words you have the tradition of cooperative achievement and the pride in the company that are the essence of the Dow spirit.

And there is another phase of this spirit, largely the result of the remoteness of the plant from markets and sources of fuel and equipment. This is a consciousness of self-sufficiency, and a will to create what is needed without dependence on others. It is this factor that is responsible for Dow's machine shop, enormous for a chemical plant; and responsible for the fact that Dow engineers are never completely satisfied with their plant equipment and processes, but always on the search for something better. This was parent to the philosophy you find throughout the plant. Not: "How much will a certain development cost?" but "How long will it take?"

It was one of these dissatisfactions with the best that was currently available that led, directly or indirectly, to four out of six of the company's chemical and engineering achievements of the depression period. The dissatisfaction was with the methods then known for rapid and extremely accurate analysis of chemical solutions; and the result, the development under John J. Grebe of new and very efficient electrometric analyzers depending upon oxidation potentials, metallic pH electrodes and conductivity measurements. These investigations were carried on independent of anything being done outside, much of which they anticipated.

Today the company employs more than a hundred of these electrometric analyzers. The greatest number are used in routine analysis, but many are employed with recorders and a considerable number with complete controllers of a type later to be discussed.

What the Achievements Were

Two of the company's depression achievements cannot be traced to electrometric analysis. These were the development of fabricating methods for magnesium Dowmetal alloys, together with markets for the product; and the widespread use in its own plant, and sale of, the Dowtherm heat transfer fluids.

Two more of the achievements depend on electrometric control from start to finish. One is Dr. C. W. Jones' process for the recovery of iodine from natural waters and oil well brines, which made the United States iodine-independent and resulted in the formation of

According to Grebe (1937) this is a rewritten version of the much longer paper by Grebe, Boundy and Cermak from Trans. Am. Inst. Chem. Eng's, 29 (1933).

Dow's subsidiary, the Jones Chemical Co., at Long Beach, Calif. The other is the sea-water bromine project at Kure Beach near Wilmington, N. C. The plant now under construction is to be operated by the Ethyl Dow Chemical Co., owned jointly by the Dow Chemical Co. and by the Ethyl Gasoline Corp. Dow developed the process and is building the plant for the new corporation. Here, with a raw material carrying only about as much bromine as is present in the sewer waste at Midland, was a real problem for automatic electrometric control. Nothing could be done, it was found, without the control. It is probable that, without it, nothing ever could have been done.

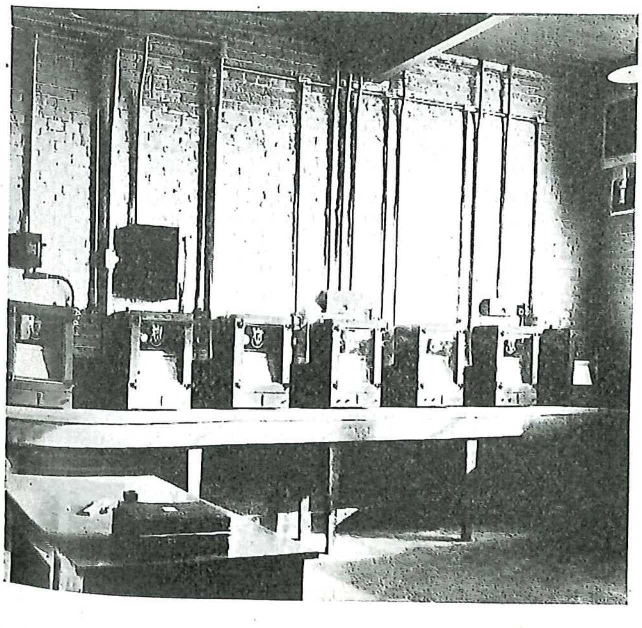
First Aid for Oil Wells

In the last two achievements, electrometric analysis played in the one case an indirect, and in the other a frequent and necessary part. As a result of the electrometric study of impurities in waste brine at Midland, and of a similar study of the action of inhibited HCl on metals, a most unexpected series of happenings occurred. The first was a successful attempt to rejuvenate some of the company's exhausted brine wells by means of inhibited HCl, which left the casings untouched, but attacked the calcareous binder in the sandstone formation. When these results came to the attention of engineers of the Pure Oil Co., the latter sought to try the method with oil wells. Further experiments again showed success, and a technique was evolved which included "blanketing" the well bottom to prevent the acid from striking down; methods for dissolving paraffin and other plugging materials; and methods for speeding the rejuvenation by applying pressure to the acid. Dowell Inc., the service subsidiary which handles these processes, is covering the country's oilfields with its special trains and tank trucks. A record of over 1,500 wells treated, most of them with astonishing results, attests to the vigor of this child which electrometric analysis begot.

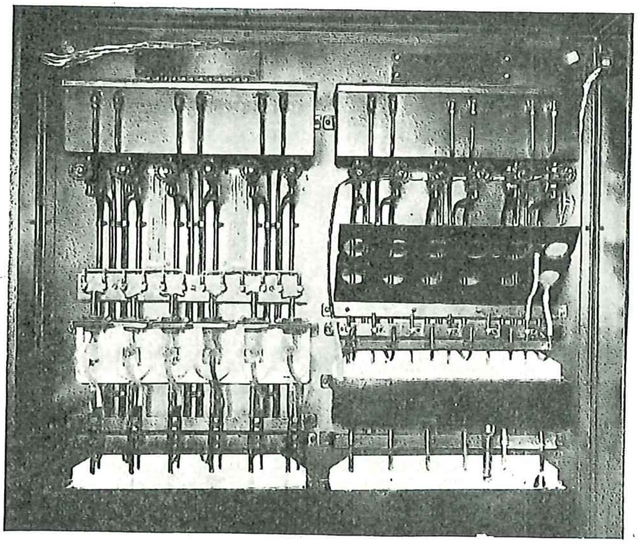
Then, lastly, there is the automatic control achievement, not entirely one of the depression, for its roots go deeper than that, but nevertheless completed and an outstanding success since 1929. Mr. Grebe and his associates have described its principles very completely in a recent paper,* and it is by drawing heavily on this source, and on conversations with Mr. Grebe, that the present author has sought below to set forth his own, simplified version of this fundamental development. Although many commercial controllers do some of the things the Dow control accomplishes, and one (since 1930) has done most of them, the Dow analysis of the problem has put control science in such shape that the advances of the next few years should easily eclipse all those that are past.

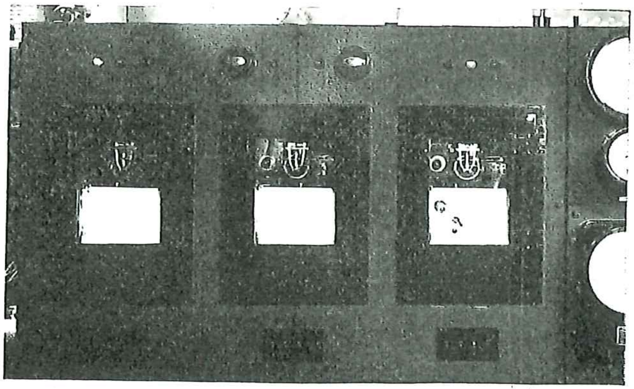
Primary to the automatic control problem was the development of the methods, already cited, for electrometric analysis; for it was to control processes so analyzed that the automatic equipment was evolved. That does not mean, however, that the new methods were useful only with electrometric detecting and indicating equipment, for they are equally suited to the control of temperature, pressure, fluid flow, liquid level, density and other chemical process variables. With any rapid and accurate means for detecting and measuring a variable, the Dow equipment will translate the measurements into control.

Bromine sewer loss recorders and temperature, pH and oxidation controllers



Above: Conductivity cells for boiler water and steam carry-over; Below: Boiler water purification, pH and softening control instruments





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*John J. Grebe, Ray H. Boundy and Robert W. Cermak, "The Control of Chemical Processes." A.I.Ch.E., June, 1933.

Before we come to the control proper, there is a good deal of fundamental reasoning to be followed:

First, a definition or two: the Dow principles are intended primarily for the control of continuous processes, as distinguished from the much simpler batch processes. Any controller that will hold the correct conditions in the former can easily maintain the latter. In any continuous process there is some instantaneous *demand* which may vary widely from minute to minute. In order to maintain the optimum conditions in the process, this demand must be matched accurately, and as quickly as possible after any change, by a change in the *supply*. Measuring the demand, then, and following with the regulated supply is the function of the controller.

At the start of the Dow investigation an analysis of existing controller types was made to see in what manner these instruments matched supply to demand. There were, it appeared, two fundamental types: (1) Controllers, generally called floating or throttling, which attempted at all times to equalize supply and demand; and (2) other instruments, usually known as "on and off," which controlled all or a part of the supply between maximum and minimum rate limits so that the average of the supply, but not its instantaneous values, would equal the demand. The first type was again divided into two: one capable of reaching a supply rate exactly equal to the demand under all conditions; and the other suffering from an inherent "drooping characteristic" which, for every demand rate except one, would arrive at an equilibrium below or above (for higher or lower demand) the desired equilibrium or control point. For many purposes this shift was too small to be of consequence, but it was none the less a bar to perfect action with this type of controller.

what is this?

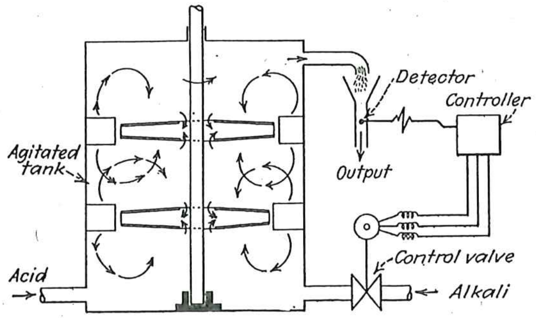
This is P

"droop" = offset

The "on and off" controller, it was found, possessed this drooping characteristic to a much smaller degree—usually negligible—but with increasing deviation from some single demand rate for which the instrument was set, the fluctuations in the controlled conditions increased widely in magnitude. While the average result would remain very nearly at the set point, the instantaneous values, except in systems with large inventories and low lag, were usually too diverse for delicate control. Hence this controller too, for most of the Dow processes, was found to be below the necessary standard of accuracy and attention was turned toward the first of the floating controllers, the one which would permit no shift in the control point, no matter how the demand might vary.

In the development of a controller of this sort, the first step was to analyze the "lags" met in continuous processing, for it is the lag in the controller's "knowledge" of what is happening to the demand that causes most of the difficulty. If the lag is sufficiently small, there is almost no problem, for the supply can follow every demand change without hesitation. However, despite the best efforts of equipment designers, it is rare that the lag can be brought to negligible proportions and it is rare that the controller can "know" of a change until some fairly considerable time after it has happened.

Fig. 1—Layout of apparatus for neutralization control problem



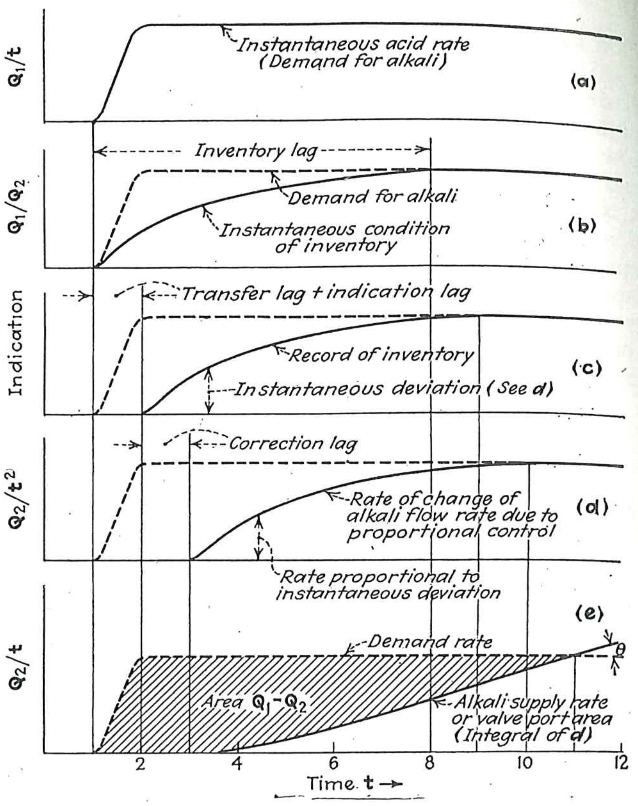


Fig. 2—Curves showing the rate of action and result of a proportional controller

For purposes of illustration, assume a continuous neutralization in which an acid is fed continuously into an agitated tank (Fig. 1) and there neutralized by a controlled flow of alkali. The "independent variable" is the number of acid units that enter per unit of time—*i.e.*, the rate of acid flow and its concentration—and the "dependent variable," the number of alkali units required to effect neutralization. The lags include the following:

1. *Capacity or Inventory Lag*—This represents the time required for a new demand to become established. In every control problem there is some capacity or inertia which cannot be entirely eliminated. Capacity is inherent, of course, in batch processes; in continuous processes, more or less of it is necessary for various practical reasons. For example, since controllers cannot follow changes instantly it is usually necessary to have a storage capacity in which to average the inaccuracies in supply brought about by demand variations. Capacity is often required to give time for the completion of a reaction, or to permit completion of mixing. The practical effect of the inventory lag is to delay the controller's "knowledge" of the extent of a change in demand when such a change occurs as in Fig. 2*a*. Even with instantaneous mixing in this neutralization problem, it is obvious that the condition of the inventory (Fig. 2*b*) will change gradually from the old, balanced state to the new unbalanced state and that the time required to reach the state determined by the new demand will be the time required to displace the contents of the tank. Where wide flow variations are encountered the inventory lag itself will vary and special control means must often be used, but in most problems it is sufficient to assume that this lag remains constant for all variations in demand. It is on this assumption that "rate" or "anticipating" controllers are based.

2. *Transfer Lag*—In addition to the time required to establish the new demand condition, the detecting element will often require an appreciable time to measure the condition.

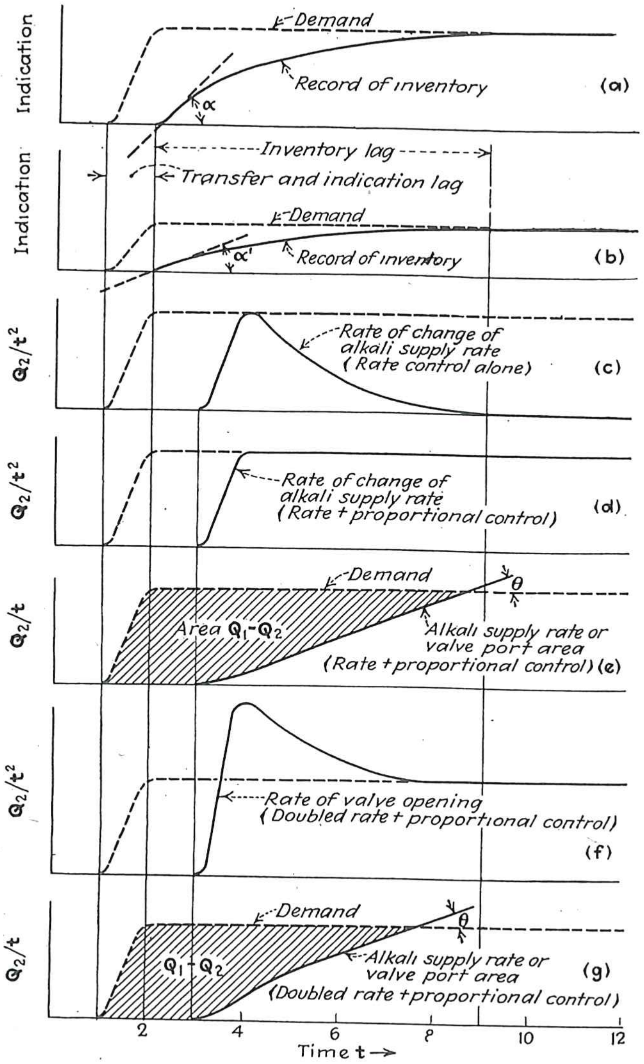


Fig. 3—Rate of action and effect of combined rate and proportional controllers

Part of this time may be in bringing the material to the detector (as in imperfect mixing or where the detector is separated from the tank by a sample line) or part in the inertia of the detector itself (as in the heat capacity of a thermometer bulb and its protective casing). This last may also be considered as part of the capacity lag.

3. *Indication Lag*—Even when the detecting element has responded to the new condition, an appreciable time is usually required for the instrument to deflect to the new position.

4. *Correction Lag*—Further time is needed to convert the measurement into a change in the rate of supply.

These four principal lags appear in every problem. One or more of them may be too small to cause trouble, but their possible effect must always be taken into consideration. Obviously each one should be made as small as possible.

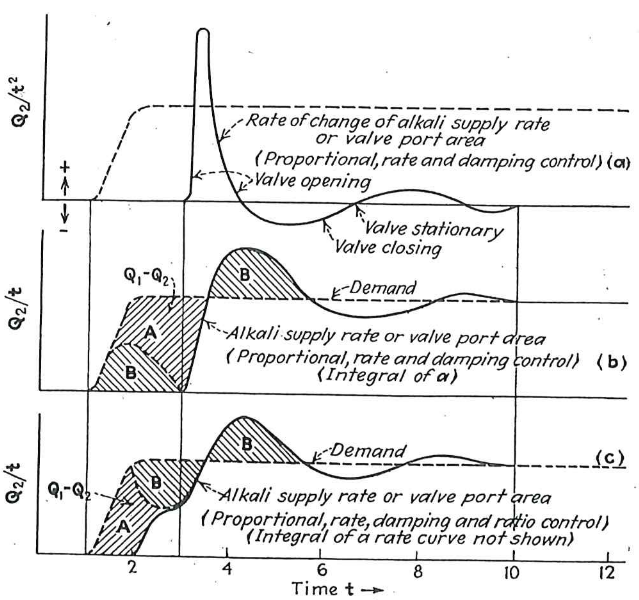
Now that we understand the lags involved, we can analyze the four control principles which can be used to circumvent them. For the sake of having a name by which each of these can be known, they will be referred to as (1) proportional control; (2) rate control; (3) damping control; and (4) ratio control.

P *Proportional Control*—The first requirement of a controller is that it shall have a definite and invariable control point that cannot shift with each change in demand. When it has become stabilized, the controller must, under all circumstances, pass a supply equal to the new demand. Such a definite control point will be attained if the instrument is able to change the rate of flow through the valve or other device controlling the supply at a rate which is proportional to the instantaneous deviation. Without lag it is obvious that such a controller would follow the demand exactly and instantly. For many purposes, such a control is entirely satisfactory, although any considerable lag will cause it to "hunt" (oscillate either side of the control point) unduly. Fig. 2 shows the effect of this "proportional" control. Here Q_1 represents the demand rate and Q_2 the supply rate, for example, in gallons per minute. In curve (*a*) there is a sudden increase in demand. Over a period of time equal to the inventory lag this alters the inventory as in (*b*). After a lag equal to the sum of the transfer and indication lags, the beginning of this change is noted by the instrument as in (*c*). The control valve then operates at a rate proportional to the changing conditions as in (*d*), but after still another lag, the "correction lag." The operation of the valve is such that its rate of opening (increase in port area) is proportional at each instance to the deviation noted at the corresponding instant by the detecting mechanism. The result of this action is portrayed in curve (*e*), which is a plot of the port area (or alkali supply rate) at any instant. Mathematically, this is a rate-of-supply curve obtained by integrating curve (*d*), which is a rate-of-change-of-a-rate-of-supply curve. The shaded area, $Q_1 - Q_2$, is the area of lack of control. Mathematically, it represents the difference between the definite integrals of the rate of demand and rate of supply curves between $t = 1$ and $t = 11$. It is therefore, the quantity by which Q_2 fails to equal Q_1 during this interval.

One further factor of importance appears from curve (*e*). This is the rate (θ) at which the supply is increasing at the instant when it equals the demand. The larger the angle of θ, the greater will be the hunting tendency of the controller, since the more it will overshoot before the trend can be reversed by the effect of the accelerated alkali flow rate. It will be noted, of course, that the curves will not be exactly as shown since the effect of the changed alkali flow rate will begin to make itself felt at the control valve at about $t = 5$.

Rate Control — Another sort of control can now be analyzed which, added to the proportional control, will D "short-circuit" the inventory lag, and materially reduce the area of lack of control without increasing the tendency of the controller to hunt. First, however, we shall consider it separately. It was mentioned above that in most cases the

Fig. 4—Effect of adding damping control (and in c, ratio control also) to the type of controller of Fig. 3f



transfer lag can be assumed to remain constant. The effect of this will be seen from a consideration of Figs. 3*a* and *b*, where it is apparent that the slope (rate of change) of the inventory record at the beginning of the change is an indication of the point to which the inventory will go at $t = 9$. Hence the change can be anticipated long before it has been established. It is only necessary to operate the control valve at a rate proportional to the rate of change of the indication (α or α'); in other words, to open the valve rapidly when the deviation is increasing rapidly (α), or to open it more slowly when the rate of deviation is slower (α'). If a rate-operated controller of this type were operated alone the effect would be as in Fig. 3*c*. Very rapid opening of the valve would result but without the addition of proportional control, the final opening of the valve would not bear any necessary relation to the new value of the demand. Consequently, a superposition of the two controls is needed, giving a rate of valve opening as in curve (*d*), which is the result of adding together the two rates shown in Fig. 2*d* and Fig. 3*c*. If we integrate the effect of the combined controls, *i.e.*, of a controller which changes its valve port area at a rate proportional to both the *deviation* and the *rate of deviation*, the resulting control appears as in Fig. 3*e*, in which the area of lack of control, $Q_1 - Q_2$, has been much reduced without increasing angle θ, the hunting tendency.

Combining a proportional and rate controller, then, eliminates the effect of the inventory lag and decreases the area of lack of control. $Q_1 - Q_2$ can be still further reduced by increasing the effect of the rate controller relative to the proportional control, as in Fig. 3*f* where the rate of valve opening is greater than that indicated by the new demand. This magnified sensitivity of the rate control may be as much as 10 to 1. The resultant curve shows $Q_1 - Q_2$ still further reduced, without any increase in the hunting tendency, θ. However, some tendency to hunt still exists and the addition of a third control effect to damp out the oscillations is often desirable.

Damping Control—What is needed, obviously, is a controller which will operate at a very high rate at the start, so as to offset the supply deficiency as far as possible, but which will then, automatically and without waiting for any indication of the result of the increased supply, cut down the valve opening to a point nearly equal to the new demand. Such a controller could not counteract all of the deficiency, $Q_1 - Q_2$, since some of the inventory would have passed from the mixing tank, but it should be able to supply an extra slug of alkali, thus bringing the remaining inventory to the right value, and immediately reduce the caustic rate to the new demand. The rate of action of such a control is as in Fig. 4*a* and the integrated effect as in (*b*) where the "overshot" area, *B*, in considerable parts offsets $Q_1 - Q_2$, leaving only the area *A* as the lack of control. In such a controller there must be a damping action which lags behind the control action while at the same time it is less than and opposed to the latter. Its effect is gradually to reduce the existing rate, even to the extent of reversing the movement if need be. The magnitude of the damping action is inversely proportional to the length of time the valve has been acting in whichever direction it is moving at the moment, and approaches zero after a time equal to the total lag.

Unclear what this is. Already have P and D-action. This seems to be some ad-hoc correction.

Ratio Control—Still one more control effect, ratio control, can be added to the foregoing methods in those cases where changes in flow are so great as to make the anticipating feature of the rate control ineffective. In this case some sort of meter is placed in the primary flow (acid) line so that it can immediately detect flow changes and almost immediately make a rough correction of the secondary flow (alkali) rate. The other control features then handle the final correction in the usual manner. The integrated result of such a combination appears in Fig. 4*c*.

Once the foregoing principles had been worked out by Dow engineers, they drew up the designs for a number of different controllers which would operate according to these effects, and actually built several of them. One design, described below, was so simple that it was finally adopted as the standard method. In the first place, it was necessary to build a valve that could be opened and closed at any desired rate within wide limits and which furthermore would give equal changes of flow for equal increments of operating time. This was accomplished with a straight-line-flow valve operated through a gear reducer and belt drive by means of a 450-r.p.m. constant-speed, induction, capacitor motor. This motor would operate forward or reverse, and would not coast upon being de-energized. The method chosen for changing the rate of valve operation was to energize the motor in one direction or the other at recurrent intervals of 2 seconds and to maintain the contact during each interval for a period proportional to the desired rate of operation.

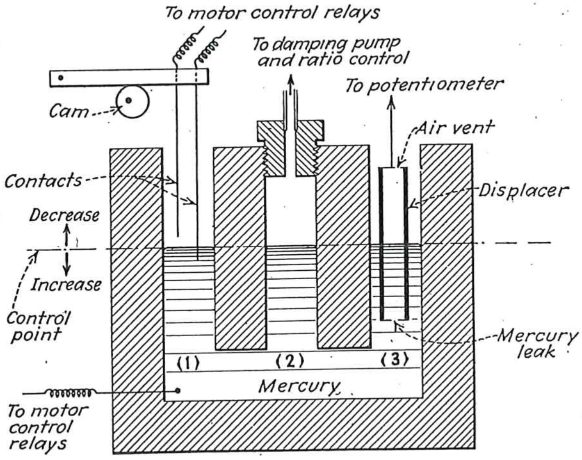


Fig. 5—Dow control block which may be operated by any form of detector that translates condition of the inventory into position of the mechanism

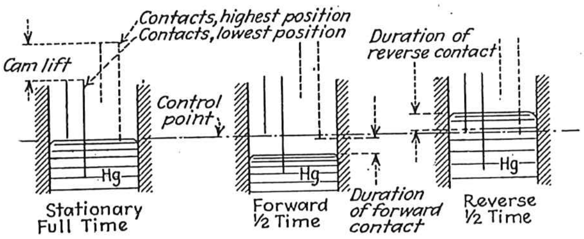


Fig. 6—Illustrating the effect of mercury height on the duration and direction of valve operation

The contact device which translated the indications of the instrument into control impulses of suitable length and direction was a non-conducting W tube containing mercury (Fig. 5). By adjustment of the mercury level in leg (1) the valve could be made to remain stationary or to run forward or backward at any rate from zero to full time. This was accomplished as follows: Note the two contact points in leg (1). Their difference in length is very slightly less than their vertical travel due to the rotation of the cam. The cam cycle is 2 seconds, which determines the contact intervals referred to above. Now, these contacts are so connected with a pair of relays, one of which operates the motor forward, and the other reverse, that when both contacts are out of the mercury, the motor runs ahead. When both contacts are in the mercury, the motor runs in reverse. When the long contact is in and the short contact out of the mercury the motor

Strange: I-action is not clearly described in this paper, except on p.522 when they talk about "drooping".

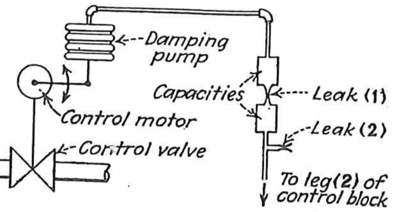


Fig. 7 — Diagrammatic layout of control motor, damping pump, capacities and leaks

does not operate at all, a condition which obtains at the control point. If the mercury level is above the control point, the motor will run backward for a time during each 2 seconds proportional to the negative unbalance of the mercury column; and when the mercury is below the control point, the motor will run forward, for a time proportional to the positive unbalance. These relations are shown in Fig. 6.

It is now possible to show how the mercury height is adjusted to control the direction and duration of valve operation. If only proportional control is to be used, the tubular displacer in leg (3) is wide open at the bottom instead of having the small mercury leak shown in Fig. 5. This displacer is connected to the indicating mechanism (for which Dow preferably uses a null point L & N potentiometer) so that the displacer is raised when the demand increases, and lowered as it decreases. Hence, for every deviation of the indication, there is a definite mercury level and, in effect, a definite speed of valve operation, forward or reverse. The desired proportionality is secured by selecting a suitable wall thickness for the displacer.

Rate control is added by using a mercury leak instead of an open bottom in the displacer. Then, when the displacer is raised or lowered, the immediate effect in leg (1) is to produce a much larger change in the mercury level. How much this increased change will be will depend on the rate at which the mercury passes through the leak, and this in turn will depend on the rate at which the indication changes and the displacer is moved. After the displacer has stopped at a new position, the mercury level will gradually equalize, inside and outside the tube, and the resultant level in leg (1) will be the same as that due to the proportional control alone.

For still greater lag than can be handled by the preceding methods, damping control is necessary. This is accomplished by connecting an air pump (piston or bellows) as in Fig. 7 to the middle leg of the control block and operating it from the stem of the control valve or from something that has a proportional movement, such as a Selsyn motor. The bellows is so operated that the air pressure or vacuum produced by its movement opposes the tendency of the rate and proportional controls. For example, when the demand is increasing and the mercury level in leg (1) is below the control point, the damping pump produces a pressure in leg (2) which will tend to raise the mercury in leg (1) and thus decrease the rate of valve opening. In order that the damping effect may lag behind the movements of the valve, two capacities with an adjustable leak between them (leak 1) are introduced into the line connecting the pump to leg (2) of the control block. A second leak (leak 2) is provided to neutralize the effect of the damping control after a period of time equal to about twice the time lag.

When ratio control is to be added, the method may be very similar to that of the damping control, or it may make use of a venturi through which the primary material is passed and into the throat of which the secondary material is fed. A greater primary flow, provided the venturi is correctly proportioned, will automatically increase the rate of secondary flow in the proper ratio. By the other method, the flow meter in the primary liquid line operates a pump to create a vacuum with increasing flow or a pressure with decreasing flow in leg (2) of the control block. The change in level that results in leg (1) thus causes the control to operate to correct the supply roughly before the indication has had time to change. The pressure or vacuum is relieved through leak (2) after a time, as in the case of the damping control.

These control effects then are used by Dow whenever automatic control is needed. Where slow changes only take place in a low-lag system, the proportional control alone would usually be satisfactory, but it is never used alone since the addition of the mercury leak in the displacer involves no increased expense or complexity. Many applications with small lags could be handled with a combination of proportional and rate control, but it has been found more economical to add also the third effect, damping control, to each installation.

Thus, in every case, as soon as a change is detected, the valve quickly moves to anticipate the new condition. Before the effect of the change can be detected, the valve rate is decreased and its movement usually reversed to bring it near to the opening required by the new conditions. As this is accomplished practically without hunting, and with an invariable equilibrium or control point, this instrument has solved numerous difficult problems, many of which were impossible with other means. Today the company looks forward to the eventual feasibility of using the new commercial instruments now being developed, but in doing so, it will not lose sight of the outstanding contributions that Dow engineers have made to this evolution.

Effect of Tube Diameter in Cyclonic Dust Collectors

By EVALD ANDERSON
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IT HAS OFTEN been demonstrated on the basis of theoretical considerations that the separating effect in cyclonic apparatus should increase as the tube diameter is decreased. Thus, Marcel A. Lissman, in a recent article (*Chem. & Met.*, Oct., 1930, p. 630), calculates the separation factor in cyclones of various diameters for an initial velocity in the outer vortex of 60 ft. per second, wherein he shows that while in a 10-ft. cyclone the force on a certain size particle in the outer vortex was 22 times the force of gravity, the same force in a cyclone, 4 in. in diameter, was 672 times gravity. In other words, the force on a given particle for a given gas velocity in a 4-in. cyclone was about 30 times as large as the force on the same size particle with the same gas velocity in a 10-ft. cyclone.