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Trans. Am. Inst. Chem. Engrs., 29, 211-256 (1933).

THE CONTROL OF CHEMICAL PROCESSES

By JOHN J. GREBE, RAY H. BOUNDY, ROBERT W. CERMAK*

Introduction

Automatic measurement and control have become increasingly important factors in modern chemical industry. Precision has supplanted the guess work and wasteful "rule of thumb methods" and has decreased materially the effect of the so called "human equation" in the chemical field. There is perhaps no other field where accurate control is as essential as in the chemical industry; nor is there any other industry which has such a variety of variables that must be controlled.

The accurate measurement and control of the variable factors of chemical processes will pay dividends in a direct and obvious manner if their existence is justified economically. Chemical processes can not operate without control, but a careful analysis of economic factors is necessary in order to determine whether manual control should be replaced with automatic controls.

In the manufacture of pharmaceuticals the purity, uniformity and appearance of the product are of paramount importance. None of these factors can be consistently maintained at a high standard without careful control of the manufacturing and finishing processes. Since control is essential in a process, it follows, that the more accurate the control, the better the operation of the process, and the finer the product resulting. Usually more damage is done to equipment by starting and stopping, and by wide fluctuations from the proper control range, than from continuous normal operation.

During the period 1924 to 1929 control problems kept arising at the Dow Chemical Company which could not be satisfactorily solved with any control mechanism commercially available at that time. To illustrate, it was desired to neutralize an organic base RONa with concentrated sulphuric acid to a pH of 6.4 to 7.0 continuously and automatically. Practical construction made it necessary to carry a three minute inventory of the reaction mixture in the reaction tank.

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The titration curve of this organic base is shown in Fig. 1. By drawing horizontal lines along the allowable control limits and dropping vertical lines from their point of intersection with the titration curve

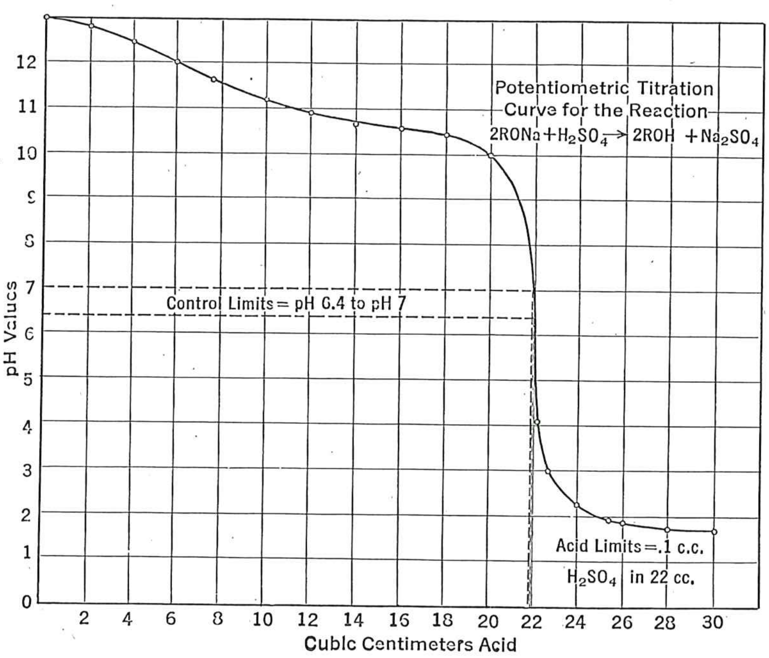

FIG. 1.

to the X axes, we find that the variation of the acid, when the control is within the correct limits, cannot be more than .10 cc. in a total of 22.0 cc. or one part in 220. If the unit is to stay in control, the acid valve cannot vary more than this amount during the total time lag, which was about three minutes. This gives 220 × 3, or 660 minutes (11 hours) required for the valve to open from an "off" position to proper control. Improvement could have been obtained if part of the acid had been by-passed, or if a non-proportional valve had been used, but since the flow and the concentration of the organic base was apt to vary as much as 100 per cent in a few minutes this would have been impracticable. To be successful this control would have had to start with the valve completely shut and be in control in less than five minutes. This was impossible with any control commercially available in 1928.

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a fundamental study
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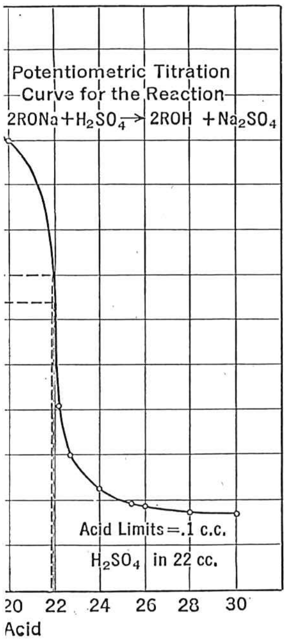

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Such problems as these led the Dow Chemical Company to make a fundamental study of the theory of controls and to develop a control mechanism which would fulfill their own requirements.

Factors Requiring Measurement and Principles of Operation

The following chart is a classification of the various measurements with which one is apt to have contact in the chemical industry. The chart also shows the various apparatus or equipment available to make these measurements properly. Wherever possible, comments are made as to whether the instruments are suitable for indicating, for recording, for integrating, for automatic control, or for various combinations of these functions. Also, notation is made of the various ranges or limitations which the methods under discussion may contain.

There seems to be no hard and fast rule in regard to the choosing of the proper principle of measurement as to whether it is chemical, mechanical, or electrical in nature—each has its own particular advantages and also its peculiar disadvantages. In addition, each of the three principles of measurement has a limited field in which it alone is dominant. For example, in the field of ion concentration and liquid composition measurements, chemical methods, or adaptations of them, are the only ones it is possible to use. In the measurement of practically all other variables the particular principle of measurement seems to be rather a "toss-up" between the mechanical and the electrical.

The apparatus used in mechanical methods of measurement is, as a general rule, more portable, inasmuch as it requires no source of electric power and is somewhat more simple in construction, and therefore requires less maintenance. However, mechanical methods of measurement require apparatus which is difficult, if not impossible, to operate at a distance from the detecting device.

The electrical systems, as a whole, are more accurate than the mechanical, and have the added advantage of being easily adapted to remote operation, it being merely necessary to lengthen the lead-wires connecting the detector and the indicating mechanism. To offset these advantages, is the necessity of providing a dependable source of electric power.

Time Measuring Instruments

	Class	Operating Principle	Remarks
Mechanical	Escapement Type *a.* Pendulum *b.* Balance Wheel	An oscillating member with a definite period allows a definite movement of an indicating mechanism at each oscillation. So long as the inertia of the oscillating system remains constant, the period also remains constant	Indicating, recording, controlling
Electrical	Synchronous Motors and Clocks	The speed of the synchronous driving motor is dependent upon the frequency of electrical impulses received from the power line	Indicating, recording, controlling
	Governor Controlled Motors	When the motor speed exceeds the governor setting, the governor opens all or part of the motor circuit reducing the speed—the opposite action takes place on a decrease in speed	Indicating, recording, controlling
	Vibrating Crystal	A piezo-electric crystal of definite thickness is held firmly between two metallic plates across which there exists a definite e.m.f. The crystal will vibrate at a frequency dependent only upon the thickness of the crystal and its temperature	Laboratory use primarily. Used in broadcasting stations for controlling and indicating frequency

Speed Measuring Instruments

	Class	Operating Principle	Remarks
Mechanical	Tachometer	Usually a weight or weights thrown outward by centrifugal force against spring tension and indicating the speed directly upon a calibrated dial	Indicating, recording, controlling. By means of gears almost any range may be covered
	Vibrating Reed	A series of reeds of various vibrational frequencies rigidly supported at one end upon the machine. Vibration of the machine causes a sympathetic vibration of the proper reed	Indicating. May be made for almost any range
	Speed Indicator	An indicator which shows the number of revolutions of a shaft. When used in conjunction with a clock the speed can be computed	Indicating. May be made for almost any range

TEMPE

	Class	
Thermometers	Liquid in Glass	E
	Mercury in Steel	E
	Pressure	T
	Bimetallic	T
	Gas Thermometer	E
Pyrometers	Electrical Resistance	V
	Thermoelectric	
	Optical	S
	Total Radiation	.
	Fusion	

TEMPERATURE MEASURING INSTRUMENTS

	Class	Operating Principle	Remarks
Thermometers	Liquid in Glass	Expansion of liquid into capillary	Non-recording, non-controlling, delicate. Range −100 to 550° C.
	Mercury in Steel	Expansion of mercury in steel capillary	Can be used for controlling, non-recording. Range −38 to 360° C.
	Pressure	Thermal expansion of a gas, a liquid or vapor pressure of a liquid	Indicating, recording, controlling. Range −150° to 600° C.
	Bimetallic	Turning moment produced by differential expansion of two metals	Indicating, recording, controlling. Range −150° to 600° C.
	Gas Thermometer	Expansion of enclosed volume of gas	Non-recording, non-controlling. Range −272° to 1600° C.
Pyrometers	Electrical Resistance	Variation of resistance of a wire coil with temperature changes	Indicating, recording, and controlling. Very exact. Range up to 1100° C.
	Thermoelectric	E.m.f. set up when two dissimilar metals are placed in contact	Potentiometer or millivoltmeter may be used as detecting device. Indicating, recording, controlling. Range, base metals −100° to 950° C. Noble metal −100° to 1400° C.
	Optical	Standard calibrated filament is brought up to same luminosity as unknown body and lamp current is noted	Range 700° to 3000° C. Indicating, recording, controlling
	Total Radiation	A body when heated gives off radiant heat in the form of light by which its temperature can be estimated	Range 550° to 2400° C. Indicating, recording, controlling
	Fusion	Small pyramids or cones of various mixtures which fuse at definite predetermined temperatures	Indicating. Range 600° to 2000° C.

Pressure Measuring Instruments

	Class	Operating Principle	Remarks
Manometers	U-tube	Balancing pressure by means of an equivalent column of some liquid	Indicating. Used for pressures up to 15 lbs. per sq. in.
	Draft Gage	Inclined tube communicating with relatively large chamber	Indicating. Down to .01″ of water
	Inverted Bell	Balancing pressure by means of weights at end of lever or torsion of spring	Range ±5″ of water. Used as indicator, recorder, controller
Pressure gage	Bourdon Tube	Pressure tends to straighten out a hollow tube bent in circle and having pressure on inside; vacuum tends to coil it up	Indicating, can be used for controlling and recording. Used for any commercial pressures
	Diaphragm	Thin flexible metal sheet with pressure on one side. Pressure tends to bulge diaphragm	Indicating, can be used for controlling and recording. Used to large degree in ammonia gages
	Bellows	Corrugated metal cylinder with pressure on inside. Pressure tends to elongate the bellows. Vacuum tends to shorten bellows	Indicating, recording, controlling. 29″ mercury vacuum to 1600 lbs./sq. in. pressure

Fluid Flow Measuring Instruments

	Class	Operating Principle	Remarks
Liquids	Orifice or Venturi	A constriction in a line creates a definite back pressure for a definite flow	Indicating, recording, integrating and controlling. Range not limited
	Weir	Liquid is held back by dam which has notch through which liquid flows. Depth of flow through notch is measure of flow	Indicating, recording, integrating, and controlling. Range not limited
	Propeller	An impeller or wobbling disk is interposed in the line. Flow of liquid causes motion of impeller or disk	Integrating primarily. Rarely indicating .15 f.p.s. to 20 f.p.s.
	Bucket Type Meters	Liquid fills buckets to definite weight or level which then dump and repeat cycle	Integrating primarily. Rarely indicating
	Pitot Tube	Special L-shaped tube is used with connections for measuring static and velocity pressure. Difference between impact and static pressure is measure of velocity	Primarily indicating. Limited by pressure measuring instrument used

Fluid Flow M

	Class	
Gases	Orifice or Venturi	Co d fl
	Propeller or Vane Type	A l o s r
	"Wet" Type Meters	A a u s a t r c
	"Dry" Type Meters	A a r r i
	Pitot Tube	Sp
	Electrical Heat	H
	Electrical Resistance	A

Fluid Flow Measuring Instruments—(*Continued*)

	Class	Operating Principle	Remarks
Gases	Orifice or Venturi	Constriction in a line creates definite pressure drop for each flow	Indicating, recording, integrating and controlling. Limited only by size
	Propeller or Vane Type	A light, easily rotated propeller or impeller, is placed in gas stream. Motion of gas causes rotation of vanes	Integrating primarily. Rarely indicating. 1 to 50 f.p.s.
	"Wet" Type Meters	A series of chambers sealed against leakage by some liquid. The gas displaces the sealing liquid in the chamber and rotates the frame carrying the chambers which is connected to a set of calibrated dials	Primarily integrating. Rarely indicating
	"Dry" Type Meters	A series of flexible bellows operate a valve which is alternately filled and exhausted by means of the gas, thus operating a series of calibrated dials	Primarily integrating. Rarely indicating
	Pitot Tube	Special L-shaped tube is used with connections for measuring static and velocity pressure. Difference between impact and static pressure is measure of velocity	Primarily indicating or recording. Up to 10,000 f.p.m.
	Electrical Heat	Heater is placed in stream with one temperature-measuring device upstream, one, downstream. Temperature difference between two devices is measure of velocity of gas flowing	Indicating, recording, controlling
	Electrical Resistance	A coil of definite resistance is placed in the line and heated by an electric current. The gas on passing cools the heater element, changing its resistance—this is then a measure of the flow	Indicating, recording. Has automatic control possibilities. Not commercially available

Weight Measuring Instruments

Class	Operating Principle	Remarks
Platform Scales	A platform is connected by a system of multiplying levers to a lever carrying a movable weight. The weight upon the platform is counter-balanced through the lever system by the movable weight	Indicating, recording and controlling. Up to 900,000 lbs.
Spring Balance	A platform is either suspended or supported by direct tension or compression in a flexible spring. The weight increases either the tension or compression in the spring in direct proportion to its weight	Not used extensively because of inherent inaccuracies. Up to 200 lbs.
Torsion Balance	Two platforms are balanced against one another and any movement is resisted by torsion of a flexible member	Not used extensively. Up to 10 lbs.
Chemical Balance	Two pans suspended from a movable cross arm having knife edge bearings. The weight in one pan is counter-balanced by an equivalent weight in the opposite pan	Indicating. Up to 10 lbs.

Volume Measuring Instruments

	Class	Operating Principle	Remarks
Liquids	Tanks	Merely a tank of sufficient size calibrated in the desired units	Not applicable to automatic control. Merely indicating. Limited only by tank size
Liquids	Standard Measures	Containers holding definite volumes of a liquid such as quart, gallon, etc.	Not applicable to automatic control. Merely indicating. Limited by convenience and portability
Gases	Gasometer	An inverted bell submerged in a suitable liquid	Intermittent operation
Gases	"Wet" Type Meters	A series of chambers sealed against leakage by some liquid. The gas displaces the sealing liquid in the chamber and rotates the frame carrying the chambers which is connected to a set of calibrated dials	Primarily integrating. Rarely indicating
Gases	"Dry" Type Meters	A series of flexible bellows operating a valve by which they are alternately filled and emptied by the gas pressure. This movement operates a set of calibrated dials	Primarily integrating. Rarely indicating

Specific

	Class	
Liquids	Hydrometer	D
Liquids	Westphal Balance	S
Liquids	U-tube	A
Gases	Orifice	A

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	Remarks
by a vers able n the nced n by	Indicating, recording and controlling. Up to 900,000 lbs.
nded nsion xible eases pres- irect	Not used extensively because of inherent inaccuracies. Up to 200 lbs.
nced any tor-	Not used extensively. Up to 10 lbs.
m a iving The nter- alent an	Indicating. Up to 10 lbs.

RUMENTS

	Remarks
t size units	Not applicable to automatic control. Merely indicating. Limited only by tank size
e vol- uart,	Not applicable to automatic control. Merely indicating. Limited by convenience and portability
ed in	Intermittent operation
ealed e liq- s the mber rying con- rated	Primarily integrating. Rarely indicating
oper- they and ssure. a set	Primarily integrating. Rarely indicating

Specific Gravity Measuring Instruments

	Class	Operating Principle	Remarks
Liquids	Hydrometer	Device usually of glass, having a large body, a graduated stem and weighted to float upright in a liquid. The hydrometer sinks to the point where the buoyant force of the liquid equals the hydrometer weight	Indicating. Can be made recording and controlling and for almost any specific gravity
	Westphal Balance	Small weighted glass sinker of definite volume suspended by a fine wire to the beam of balance. The sinker is buoyed up by a force equal to the weight of the liquid displaced; this is measured by weights placed upon the beam	Primarily indicating
	U-tube	A U-tube filled with a liquid of definite gravity and having a definite amount of the unknown immiscible liquid in one leg. The total weights of the two legs of the U-tube tend to balance and thus give an indication of the specific gravity of the unknown liquid	Primarily indicating
Gases	Orifice	A constant volume of gas is drawn through an orifice and a manometer is used to measure the pressure drop. The pressure drop across the orifice increases with specific gravity of the gas	Primarily indicating

Liquid Level Measuring Instruments

	Class	Operating Principle	Remarks
Mechanical	Gage Glass	A long glass tube is attached to the outside of the tank or chamber. The liquid maintains the same level in the glass as in the tank	Indicating. Limited only by length of tube and pressure it will stand
	Float	A hollow chamber sufficiently light floats upon the surface of the liquid and changes its position accordingly	Indicating, recording, controlling
Electrical	Inductance	The liquid is contained in an annular space surrounding one leg of the closed core of a transformer. The liquid forms a short circuited secondary, causing a greater current to flow in the primary coil	Indicating, recording, controlling
	Resistance	A resistance wire is supported inside a tube in such a way that the liquid, as it rises, short circuits more of the wire. The change in resistance of the wire causes a change in the current flow which is measured by a calibrated ammeter	Indicating, recording, controlling
	Contacts	A series of wires of various lengths dip into the liquid chamber and make contact with the liquid. The contacts serve to short out definite resistances, allowing a greater current flow which is measured on a calibrated ammeter	Indicating, recording, controlling

HUMID

	Class
Mechanical	Wet and Dry Bulb
	Hygroscopes
	Condensation
Electrical	Thermal Conductivity

NSTRUMENTS

	Remarks
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arious liquid ontact ntacts ite re- reater meas- meter	Indicating, recording, controlling

HUMIDITY MEASURING INSTRUMENTS

	Class	Operating Principle	Remarks
Mechanical	Wet and Dry Bulb	Two thermometers, one measuring air temperature and other measuring depression due to saturation. Dry air absorbs moisture from the wet bulb and thus cools it to a definite temperature, depending upon humidity of air	Indicating, recording, controlling. Range 0 to 100 per cent
	Hygroscopes	A material is used which is sensitive to humidity changes such as catgut or wood. This is in contact by means of a lever system with a calibrated dial. The material shrinks or expands depending upon the humidity and so operates the dial to indicate the humidity directly	Indicating, recording, controlling. Range 10 per cent to 90 per cent
	Condensation	A cup with a highly polished surface is used partially filled with water, then filled with ice water until the air in contact with the cup is cooled below the dew point and the dew collects upon the surface of the cup	Indicating. Range 0 to 100 per cent
Electrical	Thermal Conductivity	Two suspended wires are heated, one surrounded by dry air and the other by the air in question. Wires are connected in two arms of Wheatstone Bridge circuit. Changes in thermal conductivity change the resistance of the wires with respect to each other and so unbalance the bridge circuit	Indicating, recording, controlling. Range 0 to 100 per cent

Composition Measuring Instruments

	Class	Operating Principle	Remarks
Gas	Heat Conductivity	Two suspended wires are heated—one surrounded by a standard gas and the other by the gas in question. The wires are connected in two arms of a Wheatstone Bridge. Changes in thermal conductivity change the temperature and necessarily the resistance of the wires with respect to one another and so unbalance the bridge circuit	Indicating, recording, controlling. Depends only upon having sufficient difference between thermal conductivity of gases being determined
	Orifice	A constant volume of gas is drawn through an orifice and the pressure drop is measured across the orifice. The pressure drop across the orifice increases with molecular weight of the gas	Indicating, recording. Depends only upon having sufficient difference between molecular weights of gases
	Combustion	The gas is made to pass over a platinum catalyst containing a thermocouple. The platinum catalytically ignites the gas, the combustion evolves heat which is measured by the thermocouple	Indicating, recording. Used primarily for determining combustibility of a gaseous mixture
	Absorption or Adsorption	One of the gases can be absorbed or adsorbed by passing through some medium. The gas composition being known before and after passing through the medium the amount of the one gas can be determined	Indicating, recording

Composition

	Class	
Liquids	Titration	A
Ion Concentration	Colorimetric	A
	Conductivity	A
	Various Electrodes *a.* Quinhydrone *b.* Gas *c.* Glass *d.* Metallic	V

COMPOSITION MEASURING INSTRUMENTS—(*Continued*)

	Class	Operating Principle	Remarks
Liquids	Titration	A definite quantity of the unknown is neutralized to a certain point by a standard solution. The amount of standard solution required varies with the amount of unknown in the sample	Can be used for continuous indication record
Ion Concentration	Colorimetric	A definite amount of an indicator is placed in a definite quantity of unknown and the color is compared with known color standards. Under set conditions a definite pH will give a very definite shade of color to the solution	Can be made indicating and recording by the use of photocell, though not commercially available. 0 to 14 pH
	Conductivity	A sample is allowed to flow into a conductivity cell of calibrated resistance—the resistance of the sample is measured by means of a bridge. The presence of various ions changes the conductivity of the solution and the exact amount can be determined from the calibration	Can be made indicating, recording and possibly controlling
	Various Electrodes *a*. Quinhydrone *b*. Gas *c*. Glass *d*. Metallic	Various types of electrodes are used in conjunction with a potentiometer	Can be used for indicating, recording and controlling. 0 to 14 pH

Type of Equipment Required for Various Installations

Much could be said about the choice of equipment and the relative merits of various makes of apparatus for any one installation. We prefer, however, to reduce this to the simple statement that, wherever possible, a null point instrument should be preferred over any other type. The trend of instrument design in the past few years toward potentiometers and other balanced systems of measurement serves to prove this point. In general, the instrument installation develops with a process, starting with ordinary indicators which are then either replaced or augmented by recorders, with or without signal lights or alarms. When the process has been sufficiently developed so that further investment in equipment is justified, automatic control instruments are installed to maintain as accurately as possible the conditions which have been determined as desirable.

A brief history of the development of special automatic control equipment for the processes of the Dow Chemical Company over the past nine years may be of interest. It illustrates the development of apparatus capable of more accurate and more rapid control than any available on the market. Recently the standard of accuracy and responsiveness described below has been approached by commercial units, and we believe that there will be no further need for developing improved types of control apparatus for our own purposes. Our work will concentrate on the application of the controls now available to as many processes and apparatus as will justify their use.

Our earliest work in 1924 on special electrometric control was directed specifically to the use of oxidation potentials, conductivities and ion concentration measurements. Readings were taken with potentiometer recorders having signal contacts suitable for high and low alarm. These were used with home-made valves designed to give a definite proportional increase of flow for each turn, and were operated at a fixed speed of control in either direction, depending on whether the reading was high or low. Wherever there was any appreciable time lag in the system, " hunting " was sufficiently serious to make good hand operation better than automatic control. This was soon modified by operating the valve at a higher rate of speed when the reading was far off than when the reading was near the correct value. One more addition was then made to the contact system to make the control inoperative whenever the reading was returning to the right value on the recorder.

This was quite successful in controlling a neutralization reaction that was impossible to regulate by hand. One of this type of apparatus functioned satisfactorily for seven years until it was replaced by the more improved apparatus described below. Every effort had been made to reduce the time lag of this particular neutralization apparatus to the shortest possible period. Since the time lag depended on lime being gradually dissolved and an appreciable period of violent agitation, the overall time lag could not be reduced below 20 seconds, and the inventory amounted to two minutes flow in order to save evaporation expense, the lime was handled in as thick a slurry as possible, which caused many rapid fluctuations in the flow in spite of a good piping layout.

For some of our installations in which the inventory and the time of reaction, as well as the lag in the sampling line could not be reduced sufficiently it became evident that more accurate control was required. Efforts were therefore made to increase the speed of the motor operating the control valve in direct proportion to the amount by which the reading was off from the correct value. A rather simple apparatus for accomplishing this purpose was developed which was based on the principle of energizing a constant speed motor at frequent intervals, each impulse being for a length of time proportional to the amount by which the reading was off.

Special slow speed (450 r.p.m.) squirrel cage induction capacitor motors were obtained in order to make the drive very reliable and to eliminate any necessity for magnetic brakes or dynamic braking to prevent coasting. These have been exceptionally successful and economical.

Early in 1928 we faced the problem of controlling a plant which was not designed for easy control, but in which the accuracy of two neutralization steps was very important. The total time lag of two minutes could not be reduced without major changes. Again a search was made of all the commercially available apparatus that might serve for this purpose without success. Various methods were tried to overcome the poor control results. Introducing slugs to make a more rapid change of the inventory when the reading changed from high to low, and a method of damping the action of the control so as to start out fast and gradually slow down each time the indication changed in direction, were attempted. Each apparatus was sketched, and tried in its essentials, to make use of the rate of change of the reading to anticipate the condition which would be obtained when the entire inventory was changed according to the new

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rates of input. This should make it possible to counteract the unbalanced condition almost as soon as the transfer lag and apparatus lag would permit. Efforts were also made to improve the apparatus originally installed to proportion the flow of the two ingredients according to their volumes, but concentration changes limited the advantages gained by this step.

This work made it clear to us that only by correlating every possible control effect in the proper proportion and sequence could difficult problems of control be overcome and easy problems of control be satisfied with exceedingly responsive and accurate results.

The results of this work led to the design of a "control block" attached to a standard recording potentiometer in which contacts are made every two seconds to cause the control motor to operate in the desired direction for a period of time which is determined by (1) the amount by which the reading is off, (2) the rate at which the reading is moving away from the right value, thus eliminating the effect of inventory lag, and (3) the time during which the control has been operating, in the direction it is operating at that moment, within a period of time measured by the time lag.

This simply means that when a change in the reading calls for action on the part of the control to open a valve, the motor is free to operate the control very fast according to the amount called for by the proportional and rate, or anticipatory control. This corrects the condition at once and the control is gradually slowed down until the recorder has had time to detect the change due to the correction. If, however, during this time the first two control effects still call for more, the controller will operate faster and in general cause a correction which will return the reading to the right value without any "hunting." If, however, the ratio between the various lags does not hold constant due to variations in total flow or the like, it is best to increase the sensitivity of the control and tolerate one or two cycles of "hunting" under the most unfavorable conditions.

By the correct combination of these three control effects we regularly observe that when big increases occur in the demand, that the control mechanism, after having opened the valve rapidly, actually is closing it to a more nearly correct value while the reading is still going away from the right value and calling for more. Also when the reading is approaching the correct value rapidly, the rate of control causes the motor to operate as though the reading had already overshot.

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Normally the combined action of the rate control and the damping control have closed a valve sufficiently after a period of opening to have come to a nearly stable setting when the reading returns to the right value. All of the above is accomplished by raising and lowering the level of mercury in a contacting cylinder of which a detailed description is given in Appendix B.

To further reduce the difference between the amount of any ingredient called for, and the amount supplied within the time during which it can be averaged in the process, it is necessary to short circuit the various lags involved in controlling the process by the end point or final conditions, and to proportion the flow of the ingredients as closely as possible. In fact, in many instances, such as combustion controls in power plants and the like, the bulk of the control effect can be taken care of by proportioning apparatus. These in themselves require, for best operation, the application of proportional, rate, and damping control to the lags to which even this apparatus is subject. Proportioning or ratio control depends primarily on flow meter devices and constancy in composition.

Having developed and built a number of these control blocks as attachments to a standard recording potentiometer, we found it most economical to use it on every control job regardless of its nature. The improved result obtained, and the ruggedness of the control mechanism depending on only one 110 volt A.C. service connection always paid for the apparently higher first cost. In the last two years our development work has narrowed down to improve the details particularly on the various detector devices for recording changes in the various factors requiring measurements enumerated above.

Recent development in the line of air operated controls which compensate for the change in control point with demand, and also include both proportional and rate control effects, have changed our minds in regard to the possibility of accomplishing good control with fluid operated mechanisms under difficult conditions. It is expected that further developments will be made by the instrument manufacturers so that before very long we will be able to buy on the market satisfactory equipment for all installations using either electrical drive or fluid operated valves.

Appendix A

Theory and Development of Control Devices

Automatic continuous control devices in general are of two types. Those which maintain the reading of a given test indicator at exactly the same point, regardless of fluctuations in the demand, and those which have built into them a drooping characteristic so that for any rate of flow, or for any demand, there is a different indication when the control is at the equilibrium. In many instances there is no harm in allowing for such a damping range or drooping characteristic, and where such is the case air-flow or liquid flow devices have been used to advantage because of the great simplicity of a diaphragm valve. However, where greater accuracy, more positive control, and a reduction in the inventory, or a reduction in the fluctuations is desired, it is necessary to go to a differential control which is so adjusted as to maintain the given indication at a fixed point regardless of load, or fluctuations in demand.

Apart from the two types of continuous control above referred to, there are other control devices used in industries which are less perfect and can not be classed with continuous controls. Foremost among these is the "on and off" control applied to electric heating equipment, oil burners, chemical controls, and the like. These controls also have a drooping characteristic giving a different temperature or other indication for each demand. In the case of electrical heating units it would be inefficient to use series resistance and too expensive to use voltage control in most cases. It requires no argument to convince a person that "on and off" control is undesirable wherever it can be avoided.

It is not the use of a furnace which limits its life, but the fluctuations in temperature and the starting and stopping. Again in a machine it is not the normal torque which will cause high maintenance or wear, but the abnormal addition of sudden acceleration and deceleration and the like. A chemical process which is worth controlling must work better at some particular condition than in a range of conditions, so that if it is at all possible the control should be such as to maintain one fixed condition rather than to fluctuate between high and low limits. The evils of "on and off" control have been reduced by a great many compromises. For example, instead of controlling all the oil or all the electrical circuits, one small part is controlled so that fluctuations are small but requiring manual

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supervision. Where the inventory is very large and the time lag very short "on and off" controls can be made consideraly better than otherwise, but even then under these very favorable conditions a more perfect control would maintain exactly the right value and in general be well worth its installation. It should be cheaper to do the job the best we know how than to improvise an "on and off" control.

To analyze control problems it is primarily essential to understand what the time lag of every step in the control is, and how it will affect the operation. All controls are alike in these fundamental conditions, whether they be temperature, pressure, level, humidity, flow, or speed controls. In all of these cases there is a certain demand which may fluctuate, a device for indicating or recording this demand, or the result of the demand, and devices for regulating the supply to take care of the demand.

A very simple illustration may help to explain what is meant by time lag. Let us take, for example, the very common and easily understood example of the equipment used for making hot water with atmospheric pressure steam. The water temperature is to be controlled to 110° F. while the steam has a temperature of 212°. The heating surface provided for the steam is sufficient to take care of the maximum demand, since this demand may continue for some time so that even a five minute storage is relatively small. Assume now that the temperature control mechanism uses the vapor pressure of a fluid to operate a diaphragm or bellows on the steam control valve. This controller may be at equilibrium condition for a given flow of water and steam at this moment. The demand for water is now doubled and immediately the average temperature of the water in the tank decreases due to the higher rate of flow of cold water into it. Heat is then absorbed from the detector of the control element which gradually reduces its temperature and pressure. During this time the temperature difference will increase, which will again increase the rate of heat transfer between the detector and the water, and the steam valve begins to open up more and more. After some time, possibly five minutes in all, and after the temperature of the water has gone below the value that it ought to reach according to the drooping characteristic of this control, the temperature of the detector has reached the point where it will cause a supply of steam equal to the demand.

It is easy to review then the various lags involved in this control.

First, there is the lag due to the time required for the colder water entering the tank to reach the detector element. Then there is the lag in the temperature of the water around the detecting element due to the fact that the inventory of the tank is sufficient to warm the cold water coming in, to some extent. Then there is the lag due to the heat capacity of the detecting element which in this case might well amount to two to three minutes. Next there is the lag between the detecting element and the control valve which in this case is very small and may not seriously affect the control characteristics. It will be noticed that even if the first lag due to the time required to bring the new temperature condition of the water to the detector were eliminated it would still take a considerable portion of time to make the detector respond due to its heat capacity. In order not to have cold water during this time it is desirable to have sufficient storage to carry over the period of lack of control. However, this storage again affects us adversely in that it reduces the temperature difference available to transfer the heat to the detector element. This again calls for more capacity. As a result it is our custom to stand for the radiation and the expense of large hot water storage tanks, even though there is plenty of steam and heating surface available to take care of the instantaneous demand, all because of the inherently poor characteristics of the control mechanism; and then the temperature of the water does not remain constant.

It is possible to assemble a control system using equipment now available on the market which would take care of this condition and give very good control on an instantaneous heater. However, this control mechanism may cost more for initial capital and maintenance than the tank which is saved, and in addition it requires a greater intelligence to understand such a control mechanism than the simple type which was used. On the other hand by the use of the principles described in the following discussion, the control can be made equally simple and almost as cheap and still take care of the demand accurately.

The curves drawn on the accompanying chart will serve to illustrate the development of the theory.* If, for example, as shown in

* The curves illustrating the development of anticipatory control combinations must be considered as first approximations which deal only with the first impulse of any new change. It is assumed that all the actions following that first impulse would occur without any further changes during that time due to the control mechanism itself. This is done in order to avoid complicated transcendental functions, which even at their best could not give a com-

Fig. 2, Curve 1, the demand suddenly increases from one value to another it may be shown on a graph plotting the demand against time. In this case the demand runs at a steady value up to $t=4$, at which point it increases very rapidly and finally stopping at the new value of demand at $t=5$, and continuing from there on at that same value. In practically every case there is some inertia, some capacity, some storage effect which will cause the condition inside of the apparatus being controlled to follow the demand gradually along an exponential curve such as shown in Curve 2. This illustration shows the case in which the capacity of the system is such that the new demand having been in effect for a period of ten time units will finally have brought the analysis, or the indication of the inventory close to the new value as due to the increased demand. In other words the time lag due to the capacity or storage effect is 10 time units. This condition is indicated or recorded by the detecting device after it has existed, but the time lag between these two steps may vary over wide ranges depending on local conditions. In some cases the pressure or the temperature will follow within .001 of a second of the condition actually existing in the apparatus. In other cases a long sample line may have to be run so that the lag between the instantaneous condition in the tank or storage and the recorder or indicator may be as much as two minutes. In Curve 3 this lag was assumed to be equal to two units of time, so that the record of the analysis would start at $t=6$ and be complete at $t=16$.

A very commonly used method for controlling, which has wide applications and in many instances is satisfactory under the conditions, is a proportional control which causes the mechanism governing the supply to operate at a rate which is proportional to the amount by which the indication differs from the right value. However, there is no control device which would not have in it some slight lag between the time the reading is indicated or recorded and the time that a corresponding amount of control impulses is exerted by the control mechanism, so Curve 4 shows the rate of control due to proportional control according to the record as shown in Curve 3. It starts at $t=7$. The integrated effect of this proportional control or the difference in the valve opening or the like between the beginning of this control period and the end, is shown on Curve 5, which starts at $t=7$ and

plete and perfect analysis. It is obvious that if the conditions for control are properly met for any one increment of time, they will take care of themselves all the time regardless of what new changes may occur.

increases at a rate proportional to the amount by which the reading is always from the right value. Such a control, because of the faculty of operating at a rate proportional to the amount by which it is off, often solves control problems which are very difficult and

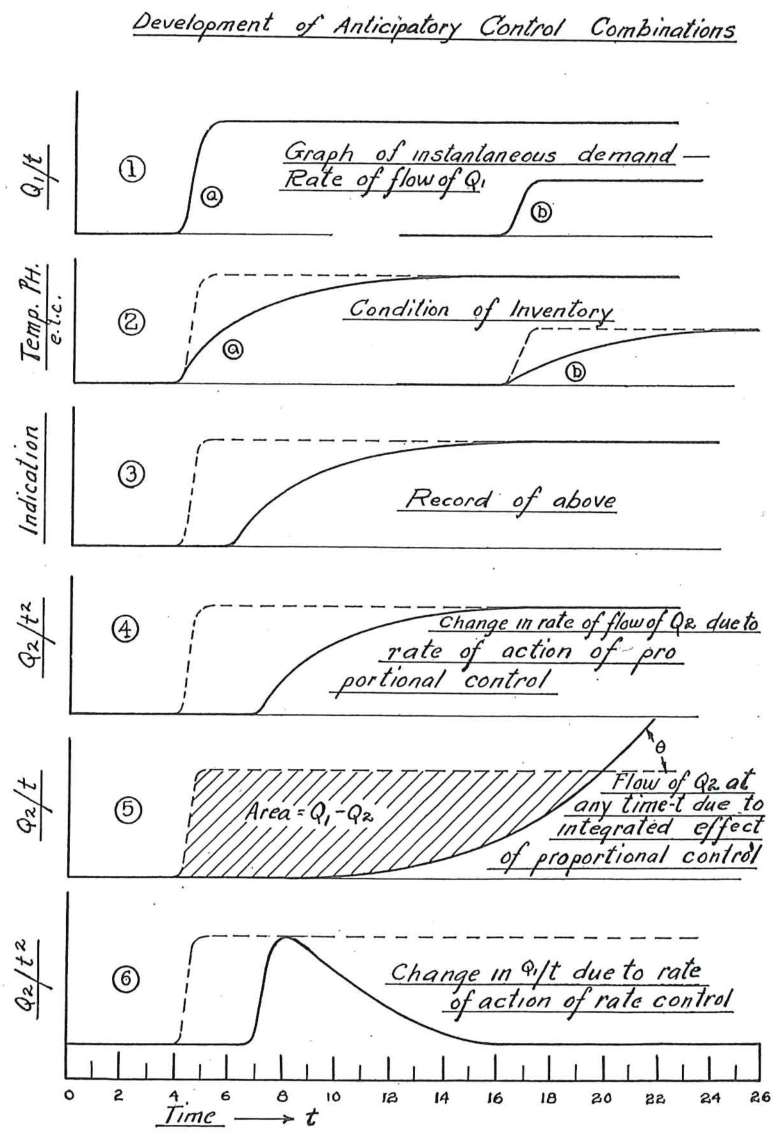

FIG. 2. CURVES 1–6.

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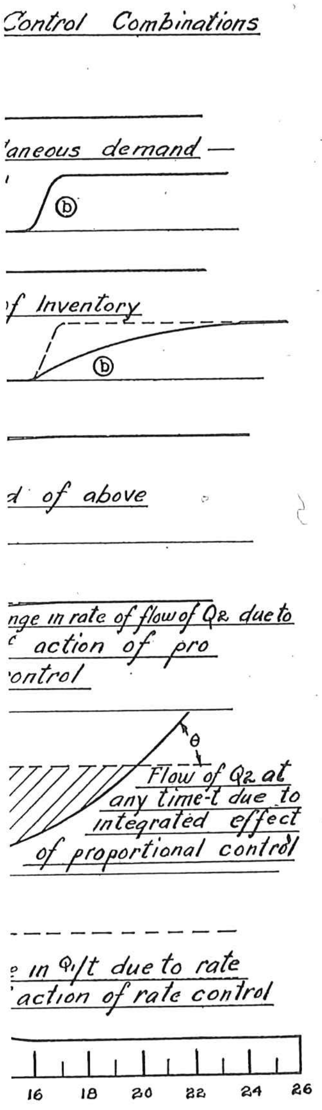
troublesome with an "on and off" control. Curve 5 shows by the shaded area between $t=4$ and $t=20$ the integrated effect of the difference between the demand and the supply during the interval between the first increase in demand and the time at which the control mechanism had brought the rate of flow of the supply equal to the rate of flow of the demand. Now it is obvious that the record would not be exactly as shown, since after the period of time between $t=4$ and $t=7$ the effect of the increased supply will make itself felt in the analysis and also on the record at the time $t=9$ which allows for the time lag between the instantaneous rates of flow and the record. And yet it is easily understood from the curve showing the integrated effect of the proportional control that the rate at which this curve crosses the value of supply for the given demand will determine its tendency to hunt, since it will be working to produce an oversupply until this flow has corrected the condition of the inventory and recorded the correct value. For a period of time, therefore, the control mechanism has been opened too much and it is bound to hunt, though by keeping the slope of the line in Curve 5 sufficiently small, this oscillation may not be troublesome.

Yet when one considers the area representing the difference between the total flow of demand and supply, it is easily seen that it is far too large for best control conditions.

It will be noticed that the slope of the beginning of the curve in Curve 3, as it is being recorded, is an indication of the value to which the indication will go if nothing is done to control the supply. For, as shown in Curve 2*b*, when the change in the demand is only half as large this slope can only be half as high, since the time required to change the inventory to the new value representative of the instantaneous flow is fixed by the capacity. In fact when the total flow is roughly the same, the slope of this line, or the rate by which the indication is moving away from the right value, is an accurate indication of the value to which the test would go if nothing were done with the controls.

It should, therefore, be possible to devise an apparatus which would cause the controls to work as though this ultimate value had already been reached; in other words to fully anticipate the reading which will exist after some time. Such a device would eliminate the effect of the time lag due to the storage capacity, the inertia, the time of reaction, and the lag in the detecting device, especially where it consists of a temperature indicator having an appreciable heat ca-



pacity of its own and a protecting tube to separate it from the material to be tested. In other words just as soon as possible after the demand has changed to a new rate, the control should act according to that new rate of demand with only the straight time lag due to the time required for the new demand to be first noticed at the detector and the time required for the detector to indicate or record this condition.

There are a great many different forms of apparatus that will accomplish this purpose. It may be done with levers and dash-pots. It may be done with electrical devices, using a dynamic brake or the like. It may be done with air pressure devices with a leak, and it may also be done as we have chosen; by moving a piston through mercury and permitting the displacement to vary according to the time during which the piston has been displaced due to a leak in the bottom of the hollow cylinder acting as a piston. Combinations of these devices can be developed indefinitely. We actually tried out about five before we found what we believe is the simplest and cheapest combination for the greatest variety of applications.

Curve 6 gives the graph showing the rate of action due to the anticipatory control. It will be noticed that if this curve is added to the proportional control the rate of action of both the rate control and the proportional control combined will be as shown in Curve 7; starting at $t = 7$ and almost immediately operating the control mechanism at a rate proportional to the change in the instantaneous demand. The integrated effect of this control is shown in Curve 8 and it is noticed that the area representing lack of control has been reduced considerably without increasing the slope at which the line showing the total flow of supply intersects the new demand line.

Curve 9 shows the effect of causing the rate control to be overly sensitive in relation to the proportional control. This causes the control to act, not according to the new demand, but faster than the new demand would indicate by a factor which may be any convenient figure up to approximately 10. Under these conditions the proportional control would be very slow and the effect of the rate control very large so that the control mechanism would be able to reach the new supply rate still faster without increasing the angle at which the line representing the rate of flow of supply intersects the new demand line. This again reduces the area representing the lack of control, but it will be noticed, as shown on Curve 10, that regardless of what is done it is impossible to counteract the effect of the area

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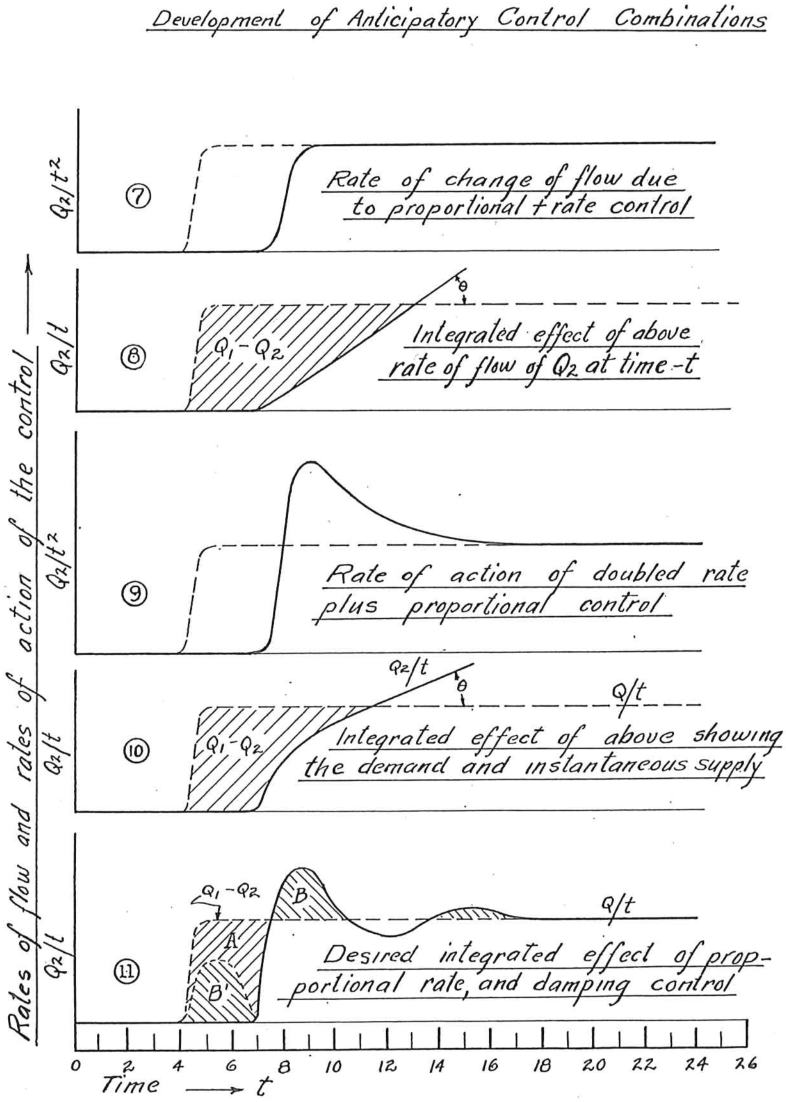

FIG. 2. CURVES 7–11.

However, in order to make a control which is applicable everywhere, and especially to the many problems in our own chemical controls, it is necessary to counteract this area of lack of control as much as possible in order to get the best effects. This requires that in response to the new demand, beginning at $t = 4$, which is detected at $t = 7$, the control mechanism should increase the supply to a very high value immediately, after which automatically and without waiting for any impulses from the indicating device, the supply would be reduced again to a definite fraction, so that the final supply will be near to the new value of the demand. The area *B*, shown in Curve 11, which is a graph of the integrated effect of the rate control, proportional control, and the new control, which we are looking for, shows that *B* can be made smaller than $A + B$ and yet be capable of counteracting the remaining effect of the lack of control. Some of this effect, Area *A*, has passed on beyond the controlled inventory and therefore can not be counteracted.

In the case of a turbine this is equivalent to causing the governor to give an over supply momentarily to take care of the new demand and in addition supply the momentum which was lost on the part of the rotor before the governor was able to call for more. Then immediately without waiting for the governor to shut off, this supply is cut down to the more correct value, so that the governor acts only on the differential that may remain after this cycle of operation.

In the case of a tank in which acid and alkali are being mixed, this extra slug would change the inventory remaining in the tank to the right value so that the continuous flow which will follow will be able to keep up with the new demand. It will be noticed that the differential of Curve 11, or the rate of action required by the control mechanism, is in the form of a damped oscillation as shown on Fig. 12 at $t = 7$.

The rate control plus the proportional control cause the control mechanism to open up the valve or the like at a very rapid rate overshooting the mark, but while the rate control and the proportional control are still calling for more, because this effect can not have reached the recorder since not enough time has elapsed for that, another control must cause the control valve to operate in the other direction to reduce the total flow from the "over-shot" value. It will be noticed that when the curve indicating the instantaneous supply crosses the demand line after having supplied the area *B* on Curve 11, it is moving in the opposite direction at a very slight angle to the new demand line indicating very stable control conditions.

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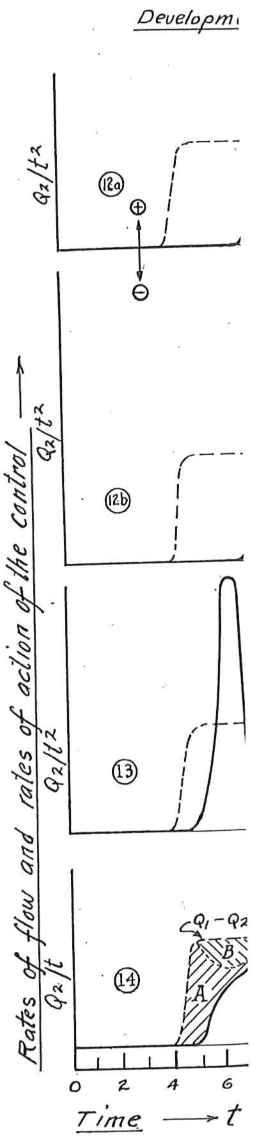

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Curve 12 shows the rate of action required on the part of the control mechanism. It will be noticed that it calls for a damping action which lags behind the control action and is opposed to it. In other words, if the control valve has been moved for a given time,

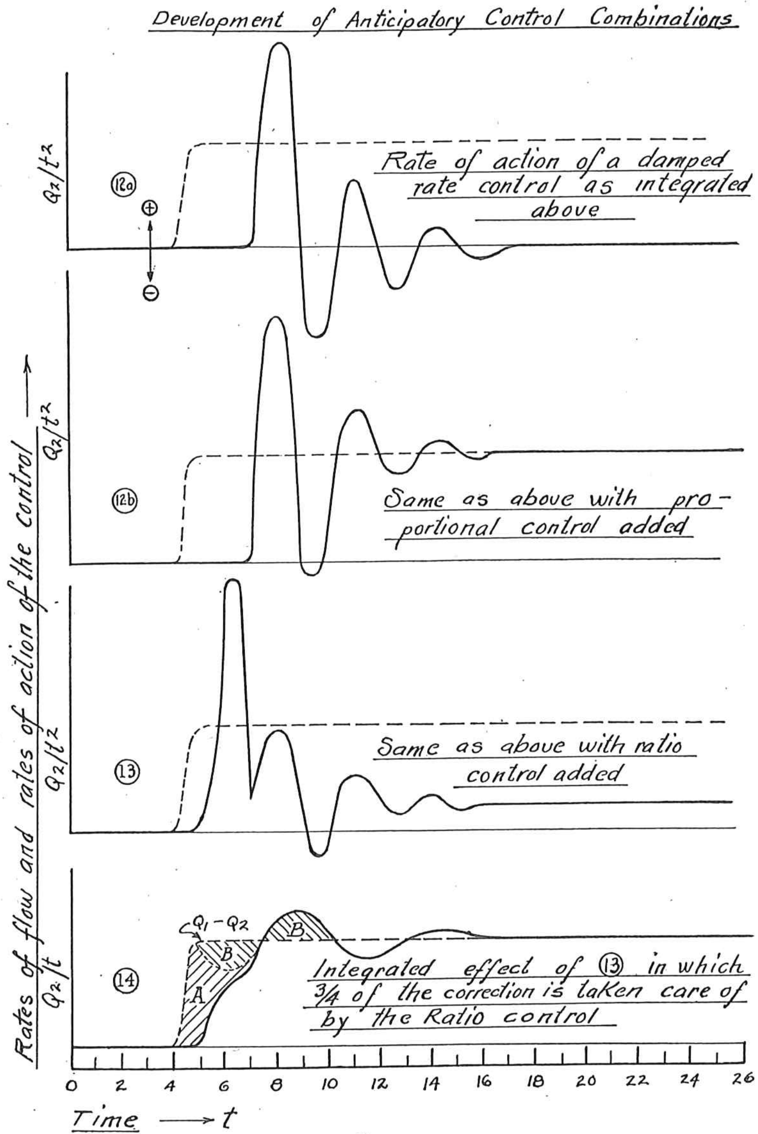

FIG. 2. CURVES 12a–14.

which in this case is one time unit, this damping control should reduce the speed of motion in the same direction and finally call for a motion in the opposite direction, and again when the mechanism has moved in the opposite direction, the damping control must call for a second reversal of the control mechanism in the first direction, etc. Each time the amount of motion must be reduced so that within a few cycles there is no effect due to the damping control. Devices which will act in this way can also be made in a great variety of ways. However, it is essential that they either be connected to the valve or mechanism controlling the supply or to another device whose motion is proportional to that of the control valve. It is very necessary not to confuse the motion of the mechanism which causes the valve or the other control to change in position with the actual motion of the final control mechanism.

One simple way in which the damping control may be actuated is to have the control valve operate a diaphragm, a piston, or bellows. The fluid which is displaced by it will cause the control to work in the opposite direction when its pressure is applied to the mercury surface. There must be a leak from this system and a storage capacity and orifices must be built into the system so that the effect of this pressure produced by the motion of the control valve can not be felt at the other end until after some time has elapsed and the valve has moved for a definite time. At the same time the leak permits some of the pressure to escape continually so that the effect of the pressure can not call for a reversal of the mechanism to the full amount, but only a fixed fraction of its total motion.

The foregoing discussion makes it clear that for a perfect control all three of these effects are absolutely necessary. The proportional control is necessary, since without it there would be no definite zero point to which the mechanism could control. It is true that in some extreme cases of large inventory and short time lag, an " on and off " control would be satisfactory, but even this control could not be as good as a proportional control which would take its place and if this is simple and cheap enough, there is no reason for not using the best. The rate control is also necessary, since it is the only way in which the reading, to which the indicator should go, but can not go on account of the inventory, can be anticipated by the control mechanism. A proportional control with damping can to some extent take the place of the rate control, but even this can not under any circumstances give the desired result of anticipating the reading on the

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On our control mechanism, the rate control with its anticipatory function is applied, by simply boring out the piston actuating the proportional control and providing it with a small leak. More detailed description is given in Appendix B.

The damping control is very essential wherever the time lag of the recording mechanism is appreciable, nor is there any other method by which the desired effect of over-shooting by an amount proportional to the new desired value can be accomplished satisfactorily. Again this action is very simple to install in the case of our control mechanism by merely connecting a sylphon bellow to the control valve or the like, which causes an air pressure or suction to be applied on the surface of the mercury in the control contact cylinder. A leak provides for the dissipation of the force at a definite rate, so that the effect of the damping control can only be felt for a definite period of time. The relation between the volume of air on either end of the resistance in the line and an additional orifice, when necessary, determines the time interval after which the damping control will take effect. This must be adjusted for each installation after the equipment is installed, since conditions will vary from one load to the next. In fact, the adjustment of the ratio between the rate control and the proportional control, the duration of the rate control, the time lag in the damping control, as well as its proportionate effect and finally the speed of the control mechanism, all must bear the proper relation. These adjustments may appear to be difficult to make so as to get the best results. They do require a thorough understanding of the problem and experience in the manipulation of the various factors, and yet that is no more than to be expected, since every development and refinement or improvement requires the intelligence to understand it. These controls, however, are so responsive that there is no harm in cutting the speed of control to one-half the maximum practical value so that even if an adjustment should go off in an undesirable direction by 100 per cent it should not cause serious hunting.

A simple set of rules to follow for the first adjustment of the various control effects on a new installation is given as follows:

1. Let the proportional control effect be just equal to the maximum speed of operation. In other words when the reading goes far off and remains far off, the motor should run continuously due to the proportional control effect.

2. Determine the total capacity lag of the equipment with a stop watch, making a sudden change and finding out the length of time required for it to be recorded. Adjust the leak of the rate control so that it will drain the total content of the piston for full deflection in the time determined above. Operate the control mechanism with these two control affects and check the ratio between the anticipatory rate effect and the proportional control. It will probably be too large so that iron rods may be placed into the piston to displace some of the mercury.

3. Connect the damping control and adjust the leak so that the pressure or vacuum is relieved in about twice the time interval of the time lag. Adjust the resistance between the bellows and contact cylinder so that it takes a time equal to one-half the lag for the pressure to be effective in the control cylinder.

4. Operate the control mechanism with all three control effects and make minor adjustments. Increase the speed of control to as high a value as possible and again check up on the various adjustments. Having adjusted the mechanism to work properly at as high a speed as possible, reduce the speed to about one-half this value, if there is no urgent need for the high speed.

The best proof of the effectiveness of these ideas is their practical operation. It is interesting to note that while the apparatus described was being developed, the men working on the apparatus, who have been experienced with control devices, were astounded at its uncanny wisdom in controlling and stabilizing the rapidly fluctuating conditions.

Having described these conditions at length we may now go to another phase of the control which is also desirable in many instances, and permits an increased speed in the response to changes in demand. This fourth control effect is a proportioning device, which causes the supply to be roughly proportioned to the demand immediately upon the change in the demand. It consists of some sort of a flowmeter which is sensitive to changes in flow of the primary material. This change is caused to produce a suction or a pressure in the same air line through which the damping control functions. The action is limited by the air leak in this system which will bring the air pressure to normal after the change in the rate of flow has stopped. And so, for example, if the rate of flow of the uncontrolled acid should suddenly decrease, the control mechanism will cause the control motor to cut down the amount of alkali immediately, by an amount which is roughly proportional to the amount by which the acid flow has decreased. While this control is still acting, any change in the analysis of the solution may begin to make itself felt on the acid adjustment according to the other control effects. It will be seen, however, that the lag between the change in the primary flow and a rough proportionate change in the controlled flow has been reduced to a much smaller value, so that the total fluctuation from the right value due to the change in acid flow has been reduced considerably.

The effect of this mechanism is shown on Curve 13. This type of control is used quite generally in the industries, and is incorporated with particular refinement in the modern combustion control systems. In other words a complete combustion control should increase the flow of air, coal, and water immediately upon an increase in the demand for steam in as accurately proportioned quantities as is reasonably possible. A fine adjustment actuated by the CO_2 concentration and the water level or other devices capable of indicating the quantity of water is then desirable. On a decrease in the demand for steam, the coal should be decreased first, and thereafter the air, and still later the water.

As will be noticed even this proportioning control is very easy and simple to apply to the control device which we have developed. The main requisite is some sort of a flow meter which will change a volume and create a suction or pressure corresponding to the changes in the flow.

Normally a control will be installed to work with the proportional and rate control functioning. Where greater speed of response is required, and where the time lag in the system is comparatively large, a damping control will be used in addition, and where the lag is too large for these three effects, the proportioning flow meter devices will be used.

It will be noted that neither the proportioning or ratio control nor the damping control, which are actuated by devices outside of the indicator or control cabinet, can possibly destroy the benefit of the proportional and rate control if they should be damaged or made inoperative.

A special effort has been made to obtain a final control mechanism that will be as fool-proof as possible. As it is now developed it consists of an electric motor, a reduction gear, and a pulley and belt arrangement. Limit switches are eliminated by the use of stops which take the tension off the belt when it has reached the limit of travel in either direction. The motor is especially designed to operate at a very slow speed. To eliminate inertia we have used a speed as low as 450 r.p.m. The responsiveness of such a system is remarkable and we can expect that the motor will last as long as a transformer, since it is totally enclosed, ball-bearing, without brushes or contacts of any sort. The motor can be stopped and started twice each second or faster, and the amount of travel in either direction is determined by the length of time during which it is energized. A single pole double-throw switch is all that is required for the reversal; which means that only two single pole relays are required. The starting torque of the motor, even though it works through a high ratio reduction gear, is two-ft. lbs., so that very positive control is insured regardless of the resisting force that might have to be overcome.

Appendix B

Description of Apparatus and Results Obtained

The following sketches of the control unit, developed by the Dow Chemical Company, are only diagrammatic, but will serve to illustrate operating principles without the complication of complete drawings.

Figure 3 is a sketch of the control unit when used only for proportional operation. It is an insulating U-tube partially filled with mercury. A cylindrical piston is immersed about half way in

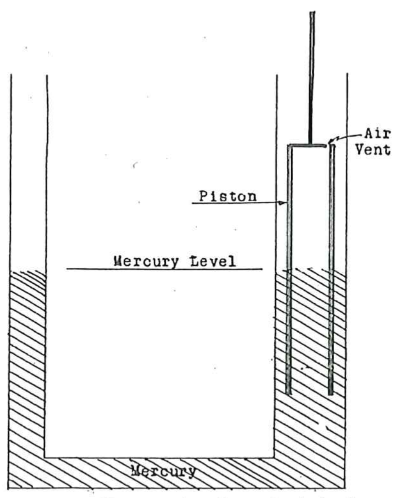

Fig. 3. Proportional control device.

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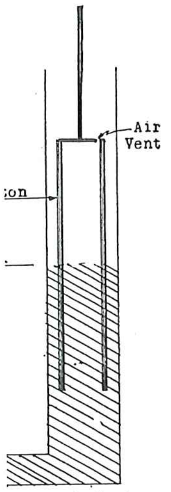

control device.

the mercury. The free end is directly coupled to the controller in such a way that when the indication is increasing the piston is raising and vice versa. Due to their thickness the walls of the piston displace mercury, and, therefore, the mercury level in the U-tube varies with movements of the piston. It will be much simpler at this point to assume that if the mercury level is as shown in the small arm in the diagram, the control is at neutral and the controlled motor is stationary, and that if the mercury rises the motor runs ahead at a speed proportional to the height; or if it lowers the opposite is true. Later it will be shown how this is accomplished. One can readily see that *the mercury level will be changed in proportion to any change of the piston,* and, therefore, the speed of the control motor will vary in direct proportion to changes of the piston. It is interesting and important to notice that any amount of proportion may be obtained by modifying the dimensions of the walls of the piston. This change will in no way effect the action of the unit when used in combination with rate or damping.

In Fig. 4 rate has been added to the proportional control. The only change necessary was the addition of a small orifice on the bottom of the piston. Now if the piston is moved we instantly get a large change in mercury level because the effect has been exactly the same as if the piston were solid. The mercury level in the piston

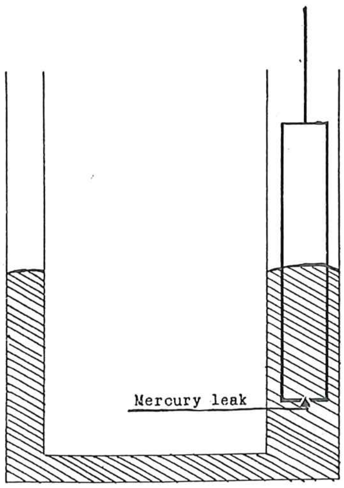

Fig. 4. Proportional and rate control device.

then gradually comes to the same level as that outside by leakage through the orifice, and the final mercury level is the same as if only proportional control had been used. In this manner we get an action that depends entirely upon the rate and direction of which the indication is moving. Should the indication stop moving, the rate control will, after a lapse of time, cease to act, but when it moves, rate always anticipates the stopping point and acts accordingly. Thus it is easily possible for rate control to reverse the control motor before the indication has crossed the control point.

The combination of rate, proportional, and damping, as well as the wiring diagram, are sketched in Fig. 5. Damping is obtained by adding a third arm to the U-tube and connecting this arm to an air pump which is directly connected to the control motor. This pump creates a pressure if operated in one direction, and a vacuum if run in the other.

Two adjustable air leaks and an air inventory are introduced in the air line this way:

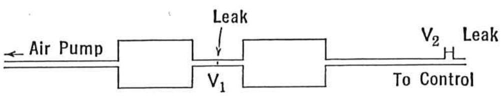

FIG. 4A.

Assume that a sudden change has caused deviation of the indication from the neutral point. The control motor starts to operate rapidly, and when, due to rate and proportion, it has changed the valve to its approximate new position, air has leaked through V_1 and built up pressure enough in the container to change the mercury level sufficient to stop the motor. Air gradually leaks out of V_2 at a rate just sufficient to prevent the motor operating for a period equal to the time lag. If, however, any further change should take place in the meantime, the control is still in readiness to operate. V_1 and V_2 must be adjusted experimentally in order to just take care of the time lag. It is possible to add proportioning control to the damping mechanism in practically the same way. It is not best done that way, however, as will be seen later.

The wiring diagram is shown in Fig. 5 also. The common 110 V. line is grounded to the mercury. Two contactors are continuously moved up and down in the smaller arm of the U-tube by a cam as shown. The long contact makes electrical connection through the mercury and a normally closed relay so that as long as it is in

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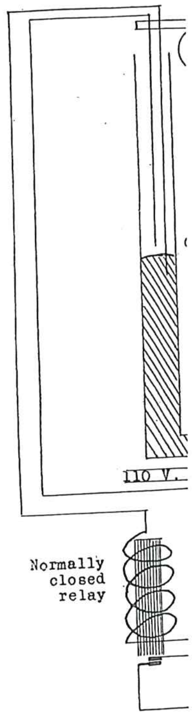

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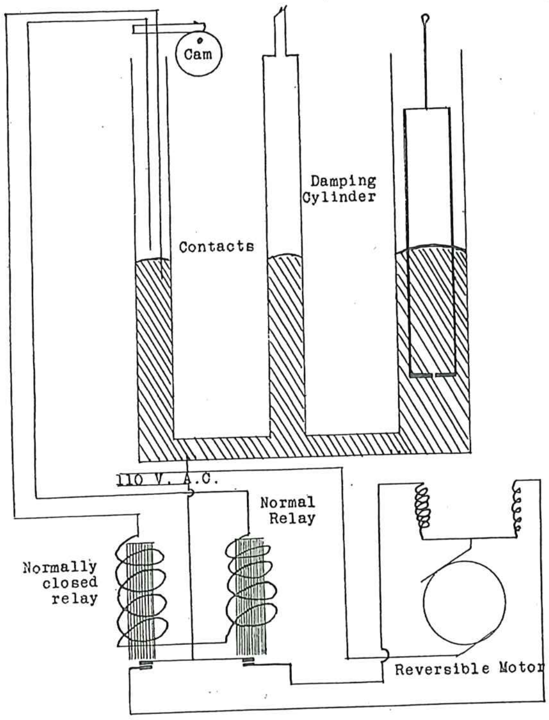

FIG. 5. Complete control device with wiring diagram.

mercury, a circuit is completed through the normal open relay and the motor reverses. The vertical distance between the two contacts is almost the same as the lift of the cam. The important point is that as long as the long contact is in contact with the mercury, and the short one out, the control motor does not operate, and when both are out the motor runs ahead. But if both are in contact with the mercury the motor runs in reverse.

Figure 6 follows a complete cycle of the cam through the positions neutral, full time ahead, and full time reverse. Neutral position is shown in the first series. The long contact (b) is never out of the mercury, nor does the short one (a) ever touch it. Therefore the control motor does not run. Control motor action ahead is sketched in the second series. b' is never in the mercury, so that the motor is allowed to run full time ahead.

In the last series a^2 is in contact full time, and the motor runs in reverse.

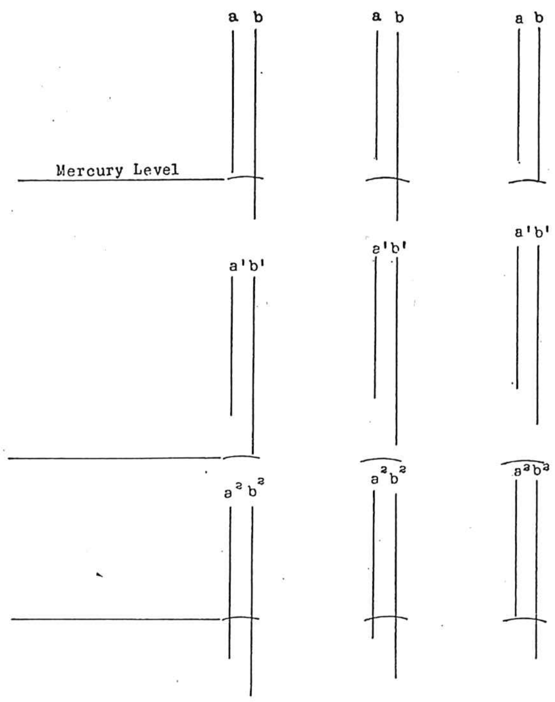

FIG. 6. Contact system of control device.

In order to test both the theory and the operation of the complete control units, a laboratory control was operated over a period of three months.

The apparatus consisted of Leeds & Northrup standard zero to one volt potentiometer equipped with our own control unit, a Dumore series reversible motor connected through a 100 to 1 gear reduction to the control valve, electrodes for giving pH value indication, a sylphon bellows for the damping pump, and general laboratory equipment.

The diagram of the complete assembly is given in Fig. 7. City water at a pH of 10 flowed from a ¼″ pipe into a venturi tube into the throat of which was introduced the necessary acid to control the

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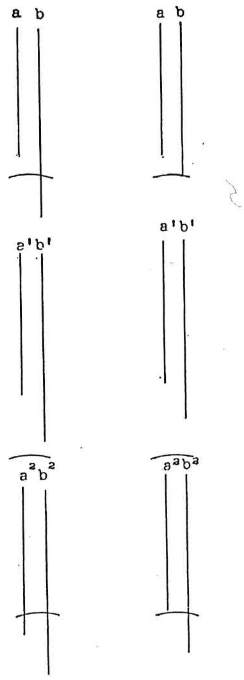

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pH at about 3.0. The venturi served a double purpose. The acid was mixed thoroughly with the water and proportioning control introduced by means of it. Due to the aspirator effect of the venturi the higher the velocity of water through the venturi the greater the suction on the acid feed line. The first venturi constructed was so

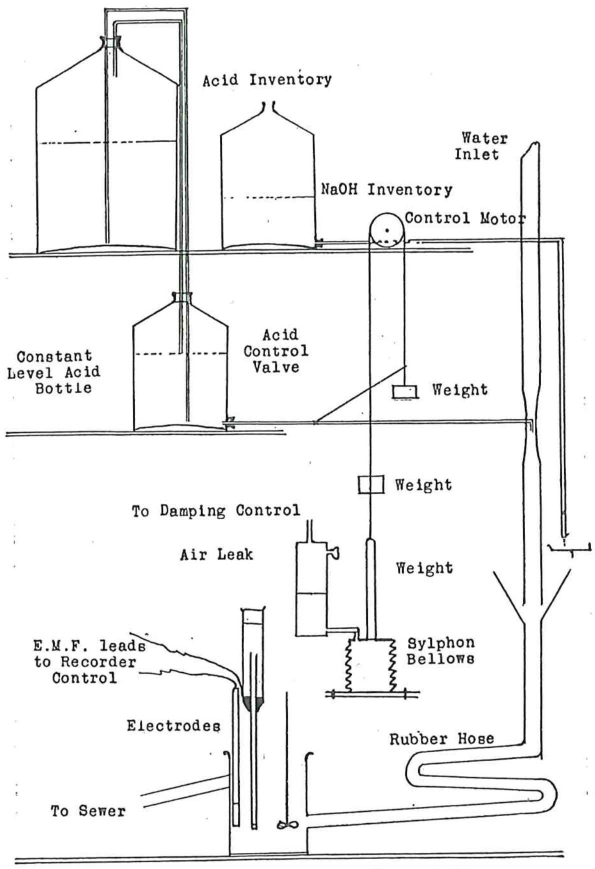
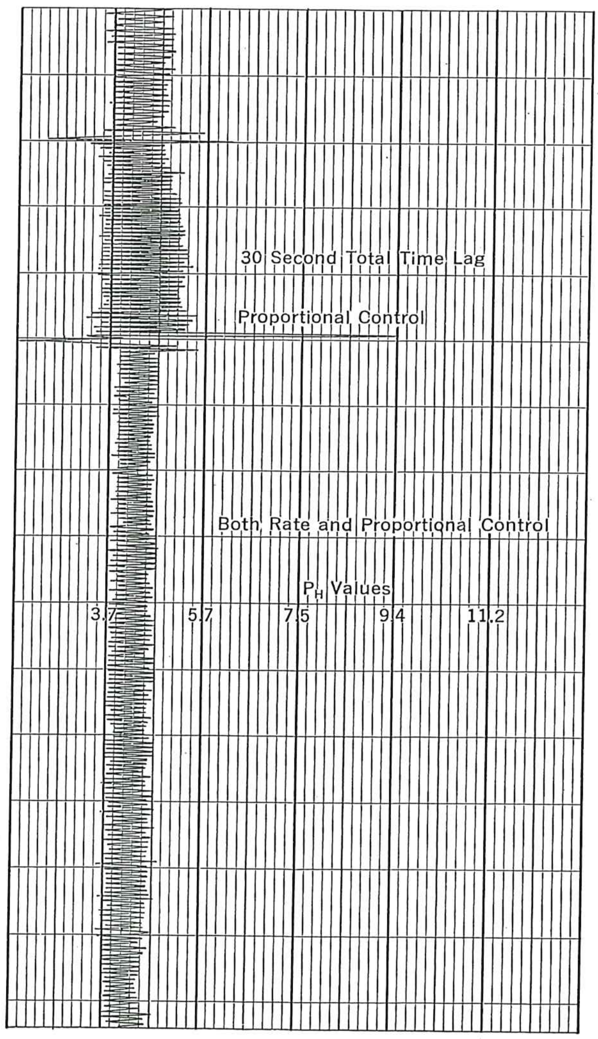


FIG. 7. Laboratory control apparatus.

nearly the correct proportion that the water flow could be changed 100 per cent above or below normal without changing the indication more than .10 of a pH value. From the venturi the mixture flowed into a funnel, through a rubber tube into a beaker containing a stirrer and electrodes, and then to the sewer. The length of the rubber hose could be varied from zero to 50 feet to obtain various time lags

Variations in the size of the beaker, of course, changed the inventory lag. The control valve was an ordinary ⅛″ pyrex stopcock. A study of the diagram (Fig. 7) will give a better idea of the apparatus than any further description. H_2SO_4 of approximately 1.210 gravity was used. The automatic NaOH dump made it pos-



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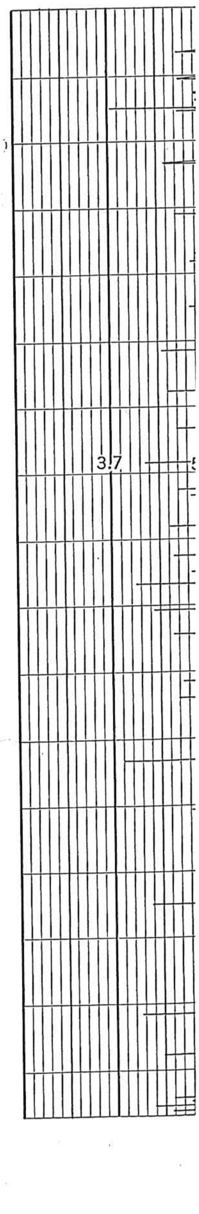

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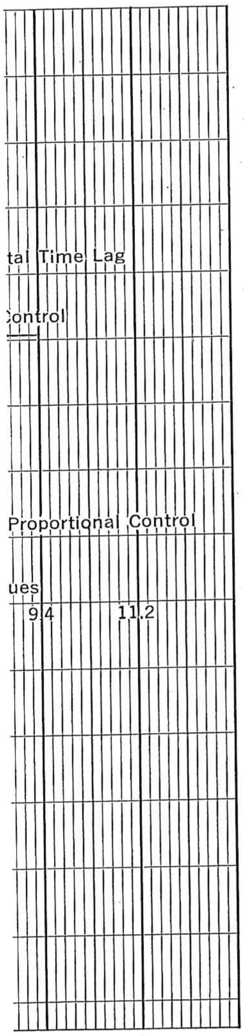

sible to throw the control completely off every few minutes in order to study how quickly equilibrium was reestablished.

The control records (Figs. 8, 9, and 10) show better than words how perfect the control action really was under the different conditions indicated on the chart.

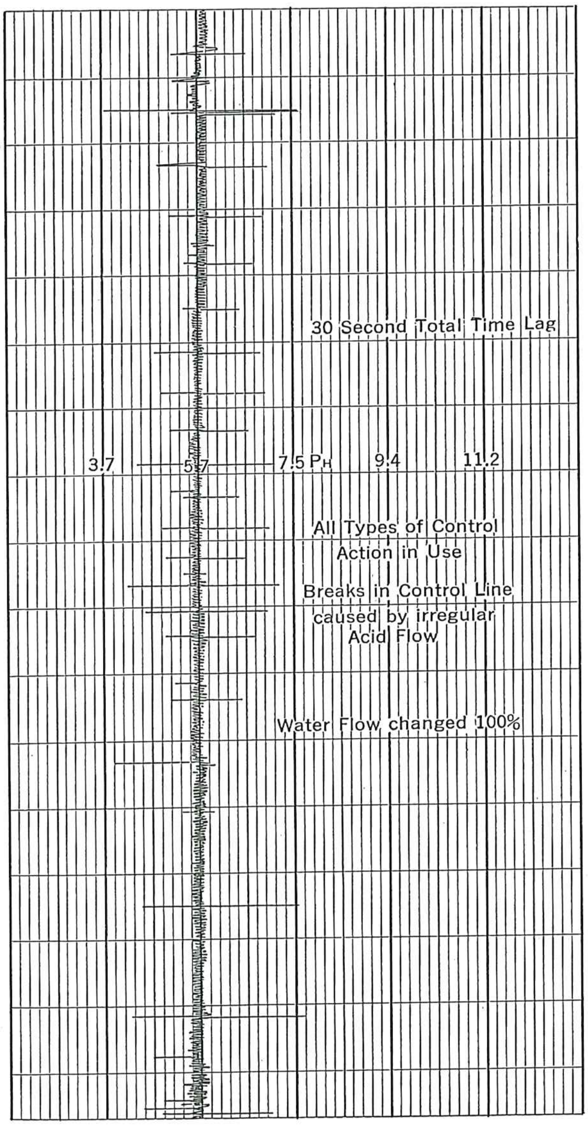

FIG. 9.

The titration curve of Midland City water is reproduced in Fig. 11. Analysis of it by the same method as used on Fig. 1, shows that the city water should be considerably more easy to control than the organic compound (Fig. 1). This is true in practice.

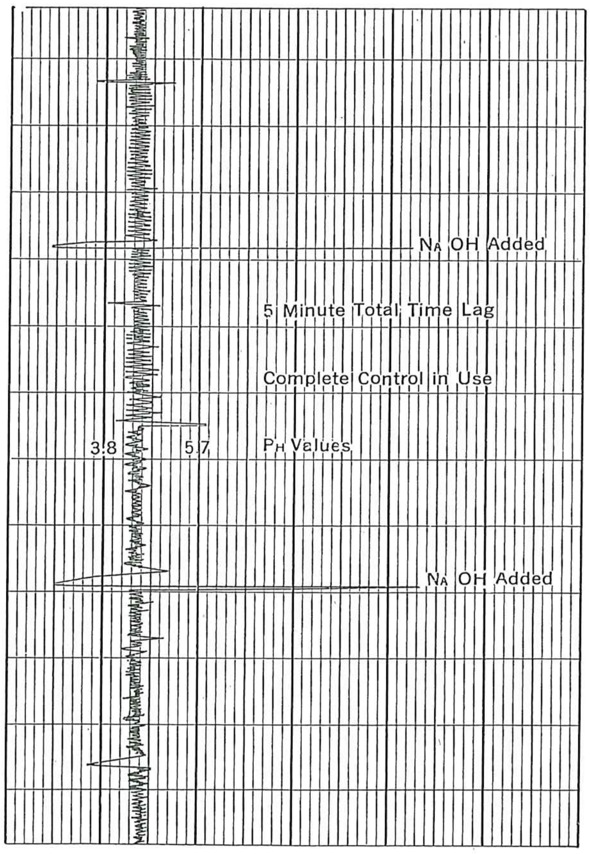

FIG. 10.

After the experience with the laboratory control, as well as many actual plant installations, some conclusions as to better control design may be drawn.

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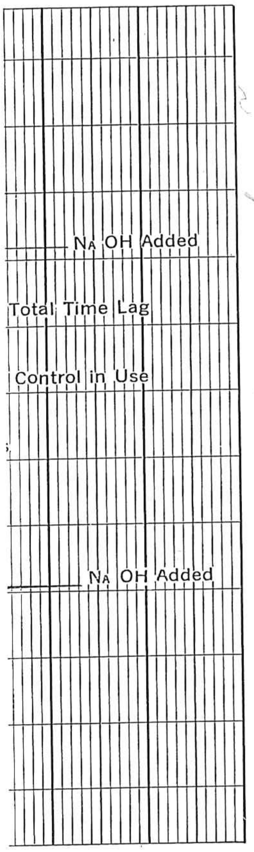

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y control. That is by far the new plant. Yet it is the hard-

est point to impress upon the designers of such plants. The controls in a plant properly designed for automatic operation are always simple and easy to operate. Controls to accomplish exactly the same purpose in an old fashioned or improperly designed plant are always difficult. No control, regardless of how perfect, can take the place of proper plant design. The effect of time lag can be compensated for, but never eliminated in a control. That can be done only in plant construction. When the number of controls in one plant are quite large, it is good practice to centralize the controls in one room. This makes maintenance easier. It also makes it possible for one operator to watch all the controls all the time while his assistant takes care of work outside the control room.

A good control must be simple, inexpensive, and mechanically rugged. After the installation and a few preliminary runs, a laboratory assistant should be able to take complete charge of the equipment. The overall time lag must be cut to an absolute minimum. Invariably when this is done, the plant itself is smaller, more compact, and cheaper to build and operate.

Each control job is an individual problem, and must be worked out individually. The method of attack is usually quite similar. First a good indication must be developed. Second, a thorough analysis of time lag made. If the plant is already in operation the indicator should be installed and the control operated manually in order to determine the various time lags involved. If the plant is being designed a theoretical study of time lag can be completed and every effort made to reduce it to a minimum. Knowing the time lag it is possible to decide what types of control action are necessary and to design the mechanism accordingly.

The control of chemical neutralizations are unusually difficult, due to the fact that the indication does not change in equal increments when equal quantities of the reagent are added (Figs. 1 and 11). But as long as there is some change the variations in amount can be compensated for by modifying the cam that lifts the control piston. Its slope should be very small at the neutral point, where there is a large change with only a small amount of reagent and should be exceedingly steep where the change is small.

In the laboratory control overall time lags as high as five minutes could be handled very nicely. In this case the inventory lag was two minutes.

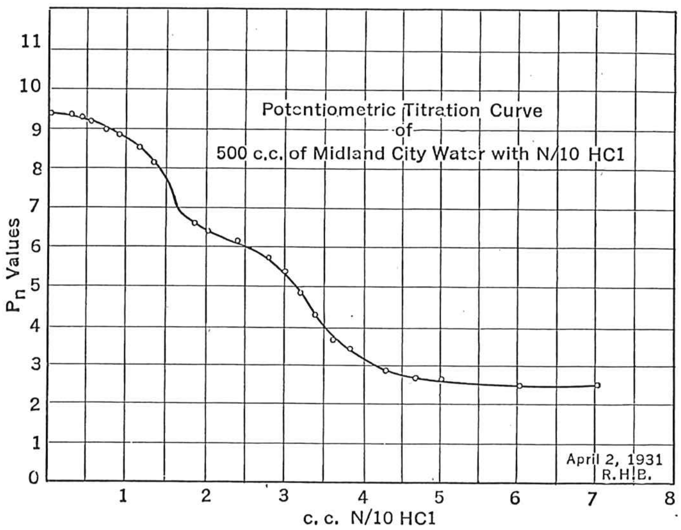

FIG. 11.

DEFINITIONS

1. Inventory Lag

The mixing tank contains a definite inventory of liquid mixture at all times. When liquid of unbalanced proportion enters this tank, the effect (assuming instantaneous mixing) is a change in the composition of the tank content.

The greater the volume of liquid in the tank, the less will be the amount of this instantaneous change.

If the inflow of unbalanced liquid continues unchanged for a sufficient time there will ultimately be established in the mixing tank a liquid of new and abnormal and fixed composition. The time interval from the beginning of change to the establishment of the final new composition under the above conditions is the "inventory lag."

2. Transfer Lag

Since the detector is assumed to be located outside the mixing tank there will be a time interval during which the changing liquid flows from the tank to the detector. This is "transfer lag."

3. Apparatus Lag

After the change has been detected a certain time interval will occur during which the change is recorded and the corrective mechanism carries out its function. This is the "apparatus lag."

4. Reaction Lag

Time is required for many chemical reactions to go to completion. This lag may be treated either as inventory or as transfer lag, depending on the design of the equipment and the type of reaction.

Summary of Oral Presentation of the Paper and Demonstration of the Apparatus

"Open and Shut Control" refers to the operation of a controller which starts and stops the controlled flow whenever the reading is low or high. This is sometimes modified by the use of by-passes separately controlled.

"On or Off," or "Opening or Closing" refers to the operation of a control mechanism which operates to close or open a valve, at a definite rate, depending on whether the reading is high or low.

"Proportional Control" refers to a control apparatus which increases or decreases a flow at a rate proportional to the amount by which the reading is off from the right value. This permits the control apparatus to work fast when the reading is far off, and to slow down as the reading becomes more correct, thus increasing the speed of control without increasing hunting.

"Hunting" refers to the periodic oscillations around the desired control point due to over-shooting.

"Rate Control" or "Rate of Deviation Control," also called "Anticipatory Control," is a mechanism which causes corrections to be made at a speed which is proportional to the rate at which the reading changes. If the reading goes off slow, the corrections are made slowly. If the changes are rapid, the corrections are made much faster. Also when the reading is coming back to the right value at a rapid rate, the controller will actually operate as though the reading were already on the opposite side of the control point. It is obvious that if a reading comes back very rapidly that it will overshoot. "Rate Control," by counteracting this tendency to overshoot before it reaches the desired control point, reduces hunting and makes a quicker response possible. "Rate Control" is used where "Inventory (Capacity) Lag" does not permit the full effect of any change to be detected immediately on the recording instrument. By the use of Rate Control the delay due to inventory lag is reduced or eliminated entirely.

"Damping Control," or "Damped Impulse Control," refers to a control apparatus which will start correcting a condition at a very rapid rate and then slow down the controlled flow and waits for the effect of this change before continuing to operate rapidly to correct a condition. This would be the equivalent of an operator opening a steam valve wide when he finds that the temperature of a heater has dropped in order to make up for the fact that he knows that the actual temperature must be considerably lower than what the indicator has had time to show. He then closes the valve some, and leaves the setting somewhat higher than it was previously and waits to see what further correction will be required when his instrument has had time to record the corrections which have been made. "Damped Impulse Control" should be capable of increasing the flow very rapidly, then decreasing it to a more nearly correct steady value, even though the instrument showing the changes is still going away from the right value. This counteracts the effect of "Transfer Lag" and "Apparatus Lag" makes possible the correction of a condition before the recording instruments have had time to fully record what has occurred.

"Ratio Control" is the method of control in which the primary ingredients to be balanced are measured separately and then roughly proportioned so that changes are corrected before they have had the chance to show the full effect in the mixture or inventory, so that the remaining discrepancies to be corrected for by the actual conditions of the final inventory are reduced. This is best illustrated by a combustion control in which the fuel and air is metered and proportioned, the final adjustment being made according to the CO_2 concentration. It is also illustrated by a furnace for which extra heat is turned on whenever the door is opened, with the knowledge that the increased rate of heat loss will require an increased rate of heat input in order to keep the temperature from fluctuating too far before the temperature control can make up for this sudden change.

A good control for a very difficult problem should include the last four named control principles, which are: Proportional Control, Rate of Deviation Control, Damped Impulse Control, and Ratio Control. No control problem has been found to our knowledge which can not

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be analyzed and met in terms of these four fundamental control principles. The particular apparatus designed to carry out this work are merely illustrative of the way these control effects can be carried out. We believe they illustrate the easiest way in which we could modify apparatus which were obtainable on the market to accomplish the desired results. We believe, however, that much better control instruments will be built by the instrument manufacturers.

You will notice all the while that I have been stumbling over words. When we get together with other men who have been working on automatic control we find it very difficult to get down to a common language. The conceptions back of it all are the same, they cannot be any different, we believe, but to make it clear to each one just what we mean when we use a certain word is rather difficult; so if there is anything we can do about that, and if the Institute can do anything about getting instrument manufacturers together to define and set standards for control, let us do it.

Discussion

Secretary LeMaistre: Gentlemen, Mr. Dorr has been called away and has asked me to take his place for a few minutes. Discussion on this paper is now open.

J. J. Grebe: Does anyone have any pet problems, or any troubles that he might want to have analyzed, or any questions in connection with the paper or the apparatus that you have seen demonstrated here? It really has not been demonstrated, I will admit, for the time is rather short to go through with it, and if you desire to go into further details, just step up after the meeting, and you can go into the mechanics of it if you wish.

T. H. Chilton: Would you take a minute to explain in a little more detail what you mean by rate of change control?

J. J. Grebe: The rate of change control is that part of the control mechanism which analyzes the change in flow or the change in reading, or the rate of change on the record, to determine what the instantaneous input into the inventory is. You know that when you throw the acid off one hundred per cent that the whole inventory is going to take a little time to get a hundred per cent excess in acid. This mechanism analyzes, from the change recorded, what the final reading should be and then acts accordingly, immediately.

T. H. Chilton: You mean if the reading changes by two hundredths of a millivolt in one second you would get a certain response, but if you change four-hundredths you would get twice the response?

J. J. Grebe: That is right, twice the response, or even more, in fact you can multiply that by four at times because of the conditions. Is there any desire to see some of the illustrations of records that we were able to obtain in the laboratory? We have a number of slides which we have not shown. (Many indicate a desire to see them.)

(Slide showing Fig. 11.) There is the potentiometric titration curve of the Midland City water.

(Slide showing Fig. 7.) Here is a demonstration set-up which we made some years ago, similar to this demonstration set-up, where we have a constant flow of water and a fairly constant flow of acid if no setting is changed. This control valve on the acid was operated mechanically by this control motor. Caustic is added intermittently by a little trip bucket to upset the entire equilibrium. We would add more or less time lag in here by having rubber hose in there, giving us as much as five minutes of lag. In other words, it took five minutes before this detector was able to find out what had been done. Then it would pile into it and work so fast to counteract that change, that within a few minutes the approximately correct reading had been obtained. It would then wait until the indication would come along to show how nearly it was right, and then make the final correction.

(Slide showing Fig. 8.) Here is the result that one can expect to get by using Proportional Control. And then, when we add to that the Rate Control, so that the two are acting together, we have then the inventory counteracted completely, and only the transfer lag to be taken care of.

(Slide showing Fig. 9.) This slide shows what happens when all of the types of control are added. We were using the Proportional Control, the Rate Control, the Damped Impulse Control and the Ratio Control or Metered Flow Control. Each of these breaks in the line are the result of putting in a bucket of caustic to upset the equilibrium, and you notice how quickly the conditions were restored again, showing less than a tenth of a per cent variation.

(Slide showing Fig. 10.) Here is what happens under the best conditions with a big time lag.

Now there is no way of taking that transfer lag and eliminating it entirely. You notice here we have obtained about the best results you can possibly wish; the area under this curve, showing low, is approximately equal to the area indicating high, and further on it would average out to be approximately right, but there is nothing you can do any faster than this, because it takes you that long to find out what to do next.

Are there any other questions?

Chairman Dorr: The next paper is "The Measurement and Control of Hydrogen Ion Concentration in Industrial Plants" by Mr. George A. Perley.

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