PRINCIPLES OF
INDUSTRIAL PROCESS CONTROL

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A Division of Minneapolis-Honeywell
Regulator Company

-9282-

New York: JOHN WILEY & SONS, INC.
London: CHAPMAN & HALL, LIMITED

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PRINTED IN THE UNITED STATES OF AMERICA

FOREWORD

The last thirty years have been a period of great progress in the field of automatic control and automatic regulation. Automatic positioning controllers or servomechanisms are now used in the rapid and accurate control of airplanes, guns, and other fighting equipment.

Automatic control of industrial processes has been of equally great importance in speeding up the production of the many materials necessary in the fighting of a modern war. To mention one example, the synthetic-rubber program would have been impossible without the use of a multitude of automatic temperature, pressure, flow, and liquid-level controllers.

In applying automatic control to industrial processes, however, there are certain fundamental principles which apply to the operation of a process when under automatic control, as well as to the functioning of a servomechanism and its positioned element. This book is primarily devoted to the description and explanation of these fundamental principles.

The author has done an admirable job of drawing together the many loose ends in the literature on automatic control. The complete control system is divided into four elements; the measuring means, the controller mechanism, the final control element, and the process. The pertinate quantities are carefully defined, and appropriate lag coefficients and time constants are used in a treatment of the dynamic characteristics of control systems. Experimental lag coefficients are given for many industrial measuring elements. A number of controlled response curves are given and are used to illustrate the effects to be expected when adjusting a controller on the job. The theory of automatic control is considered with principal emphasis on the controlled and uncontrolled process response curves. The reaction rate-lag method is used to calculate controller settings and reaction rates, and lags are given for a number of representative processes. The cycling period method of setting the reset rate and rate-time controller adjustments is carefully stated and illustrated.

Advancing technology in the industrial field is coming to depend more and more upon precision in processing, introducing standards which would have been thought impossible a few years ago. It is true, therefore, that automatic control of industrial processes is in many cases indispensable; in others it is growing in acceptance because of the advances it makes possible in uniformity of product, reduction of production costs, and improvement in quality.

N. B. NICHOLS

CAMBRIDGE, MASSACHUSETTS
May 15, 1945

PREFACE

This book is an introduction to the science of automatic control. In order to obtain a working knowledge of the principles of automatic control it has in the past been necessary to refer to a variety of sources. The literature on the subject is widely distributed, and, in addition, it does not completely cover the many phases of industrial process control. Analysis is restricted to more or less highly developed theories applying to particular problems. Since the appearance of Professor W. Trinks' *Governors and the Governing of Prime Movers* in 1919, instrumentation and automatic control have progressed to the development of sophisticated control mechanisms and methods without a parallel development of a generally useful foundation of theory.

The purpose of this book is to treat, in a logical manner, the important laws of operation of industrial automatic control systems and to provide a practical background of theory. Details of measuring devices and controlling mechanisms are brought out only when they are necessary to the analysis of principles and characteristics of operation. The importance of proper measurement is emphasized because of its great influence on automatic control.

Primarily, the book is intended for the student in chemical, metallurgical, mechanical, or electrical engineering. The growing importance of this subject to modern industrial processing has been acknowledged by the addition of courses in instrumentation and automatic control to the curricula of engineering colleges and technical schools. For the student, this early emphasis on automatic control is vital since a process designed and constructed with proper consideration for its control is most likely to be successful. Secondarily, the book may serve as a reference for the industrial user of automatic control equipment.

ACKNOWLEDGMENTS

To Mr. R. B. Werey, consulting engineer, I would like to express my gratitude for the many helpful suggestions and for supervision of the preparation of illustrations. His careful review of the initial copy contributed much to the exposition of complex details.

Mr. N. B. Nichols of the Radiation Laboratory, Massachusetts Institute of Technology, prepared the Foreword and reviewed the manuscript from the technical standpoint. I am greatly indebted to him for his constructive criticism and for his contributions to the mathematical and scientific analyses.

The review of Messrs. J. J. Grebe and R. W. Cermak, Dow Chemical Company, was genuinely helpful in broadening the scope of the material. The encouragement and inspiration of Messrs. G. M. Muschamp and L. M. Morley of the Brown Instrument Company made possible the writing of the book, and Mr. C. B. Sweatt of the Minneapolis-Honeywell Regulator Company sponsored the project.

The suggestions of Mr. J. G. Horn, Mr. W. H. Wannamaker, and other associates of the Brown Instrument Company are gratefully acknowledged. Access to the data files of the Brown Instrument Company aided greatly in the preparation of concrete examples and applications. Much credit is due Mrs. D. P. Eckman for her typing of the manuscript and consideration of grammatical details.

Donald P. Eckman

Philadelphia, Pa.
March 27, 1945

CONTENTS

SYMBOLS

C	CAPACITY
c	CONTROL POINT
D	DAMPING FORCE
e	BASE NATURAL LOGARITHMS
F	FLOW
f	FLOATING RATE
G	SPECIFIC GRAVITY
g	ACCELERATION DUE TO GRAVITY
h	HEAD
J	MASS
L	LAG
N	REACTION RATE
P	FINAL ELEMENT POSITION
p	PRESSURE
q	RATE TIME
R	RESISTANCE
r	RESET RATE
S	SPRING FORCE
s	PROPORTIONAL BAND
T	TEMPERATURE
t	TIME
U	TORQUE
V	VOLUME
W	ENERGY
θ	VARIABLE (TEMPERATURE, PRESSURE, FLOW, LEVEL)
π	PI = 3.1416
ϕ	PHASE OR LAG ANGLE
ω	ANGULAR VELOCITY OR PERIOD

CHAPTER 1

THE ART AND SCIENCE OF CONTROL

Automatic control, by virtue of its value to industry, is rapidly assuming importance as one of the newer sciences. It is emerging, however, from the adolescent state of an art dependent upon rule-of-thumb procedures to an exact science based on analytical methods. Fundamental laws and principles are being recognized, and as their significance becomes more widely understood scientific analysis is gradually supplanting the less reliable methods of the past.

An understanding of basic principles is of great value in the analysis of automatic control problems because these principles may be applied to any problem regardless of variations in physical or mechanical details. The control engineer can then recognize the vital factors and readily sift out the unimportant details. The automatic control problem is thereby reduced to its essential components and further analysis is simplified.

Automatic control of industrial processes is but one division of a broad and complex field which includes such diverse subjects as speed governing, temperature control, automatic airplane piloting, automatic machine operation, artillery fire control, and hundreds of other associated subjects. Industrial process control includes the control of temperature, fluid flow, pressure, liquid level, air conditioning, and any other variable quantities of an industrial process.

Electrical circuits and vibrating systems have many elementary characteristics in common with controlled processes. Characteristics similar to those of electrical capacitance, resistance, oscillatory circuits, and other electrical phenomena are found. The forced vibration of a mechanical system and the control of a process variable require almost identical analyses. Industrial process control, therefore, has many analogies in other scientific and engineering fields.

Automatic control is used for the prime purposes of efficiency and economy. It eliminates the element of human error and provides a continuous steady response in counteracting changes in the balance of the process. Automatic control pays for itself in savings of fuel, processing materials, and labor, and in the increased value of the product because of greater output or increased quality.

Automatic control must be properly applied to obtain successful detail, consists of solving directly for controller requirements from empirical equations. Quantitative analysis of the controlled system by these means makes possible the selection of the mode of control.

The reaction curve for the controlled system, as shown in Fig. 7–18, is derived from the characteristics of the process, the measuring means, and the controlling means. Usually enough accuracy can be obtained with the design data for the process. Thus the reaction curve can be derived without having the actual process at hand. The reaction curve can, of course, be obtained by test of the actual controlled system.

The reaction curve can be approximated by a *reaction rate* N and a *lag* L. A line drawn tangent to the point of inflection of the curve intersects the time axis at a distance from zero. The time shown on the curve is called the lag L of the controlled system. The slope of the line is the maximum rate of change of the measured variable and is called the reaction rate N of the controlled system. The per cent change in valve or other final element position to produce the reaction curve is called ΔP.

Several values of these factors have been determined for various applications and are listed in the table below.

PROCESS	CONTROLLED VARIABLE	CHANGE ΔP	REACTION RATE N	LAG L
Ammonia absorber	Temperature	83	16	8.7
Fractionating column	Temperature	42	6.3	7.5
Wet bulb	Temperature	50	2.5	4.5
Oil-tube still	Temperature	25	8.2	3.1
Superheater	Temperature	25	24	2.1
Dry bulb	Temperature	16	9.3	0.77
Milk heater	Temperature	4	25	0.67
Water flow	Flow	33	47	0.12
Column vent	Pressure	4	2.1	0.08
Canning retort	Temperature	17	7.2	0.03

The lag factors in the table give a particularly good picture of the wide variations encountered in controlled systems. It must be noted that the data are representative of one specific application and should not be assumed correct for other applications of similar nature.

The adjustments for the proportional mode can be estimated by solving a set of empirical equations. These relations are derived from a study of the stability of controlled systems.

For the proportional mode of control the proportional band can be determined from

$$s = \frac{100NL}{\Delta P} \qquad [7\text{–}15]$$

where s = proportional band in per cent.
N = reaction rate in per cent of scale per minute.
L = lag (from reaction curve) in minutes.
ΔP = per cent of change in the valve position required to produce the reaction curve.

For the proportional-reset mode of control the adjustments can be determined from

Ziegler-Nichols

$$s = \frac{110NL}{\Delta P} \qquad [7\text{–}16]$$

$$r = \frac{0.3}{L} \qquad [7\text{–}17]$$

where r is the reset rate. For the reaction curve of Fig. 7–18 the proportional band should be 55 per cent and the reset rate 0.3 per minute.

For the proportional-reset-rate mode of control the adjustments can be determined from

$$s = \frac{83NL}{\Delta P} \qquad [7\text{–}18]$$

$$r = \frac{0.5}{L} \qquad [7\text{–}19]$$

$$q = 0.5L \qquad [7\text{–}20]$$

where q is the rate time. For the reaction curve of Fig. 7–18, the proportional band would be 41 per cent, the reset rate 0.5 per minute, and the rate time 0.5 minute.

Obviously, if after solving the above equation the proportional band is found to be less than 3 or 4 per cent, two-position control may be possible. It is an interesting problem to solve the equations for the processes listed in the table above.

The Ziegler-Nichols method has limitations common to most empirical methods. The approximation of a reaction curve by a time lag and a straight line is not invariably valid. For example, if the process reaction curve indicates large transfer lag the difference between the settings required by a relatively sensitive and an insensitive measuring means may be quite significant.

This method does not provide the optimum settings for all types of load changes but for only the one particular type used in determining the reaction curve. This is hardly serious, since the only requirement is that the controller be adjusted for the worst conditions. This

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CHAPTER 10

AUTOMATIC CONTROL SYSTEMS

Most control systems include only a single measured and controlled variable. It is obvious that in many applications the introduction of other variables into the control system is necessary for the more complete accomplishment of the purpose of automatic control. The control system must then be made responsive to changes in more than one variable.

When the controller is forced to counteract the effect of changes in two, three, or even more uncontrolled variables in the process, the quality of control is dependent upon the rate and magnitude of changes in these variables. Operation can be improved by arranging the control system so that several variables are controlled.

Pressure changes in the control agent are often the cause of difficulty, and *metered control* is used to introduce either pressure or flow as a second measured variable in the control system. Often the balance of the process or the operation under control is dependent upon a proportion or relationship between two variables. When this requirement exists, the control system must be arranged so that one of the variables is controlled in a fixed relationship to the other. In some instances the second variable introduced into the control system may be time; that is, a measured variable must be controlled to a certain magnitude with time. Proportioning of variables in this manner is accomplished in *ratio control* and *time-variable control.*

It is also necessary in many processes to protect either the process equipment or control system from the effects of excessive temperature, pressure, or other variable. An auxiliary controller is often connected into the control system to limit its operation so that excessive temperatures or pressures may be avoided. The control of sudden reactions in the process is often accomplished in a similar manner. *Limit control* and *series-proportional control* are methods by which auxiliary variables are introduced.

It is possible to indicate only the general principles involved in multivariable control systems since these systems are nearly always arranged to meet the requirements of a specific application. By ingenuity in composing standard arrangements and by the tailoring of special control mechanisms to individual needs, many variables may be correlated into a single, extensive control system.

Metered Control

Many processes are controlled by regulating the flow of a heating medium such as steam, fuel gas, or fuel oil for supplying heat to a process. Variations in flow of the control agent not dictated by the controller cause supply changes. Such variations in flow are caused by changes in pressure differential at the valve, which, in turn, result from changes in pressure of the fuel supply, and changes in downstream pressure caused by clogging of fuel burners, and so on. These changes are difficult to counteract since they must carry through the process before they are detected by the controller. Supply changes sometimes occur suddenly or over a wide range, and deviation may become excessive before a new balance of conditions can be established.

Supply changes must be corrected before they enter the process if adequate control is to be maintained, especially where the process has large transfer lag or dead time. For example, in the heating furnace of Fig. 10–1, the rate of flow of fuel oil is determined by a controller which measures a temperature in the furnace. Ordinarily the control valve would be set directly by the controller. Suppose, however, that a flow controller is installed in the oil line and its control point automatically regulated by the master temperature controller. With pneumatic controllers, for example, the output pressure of the master controller is connected to a receiving mechanism in the flow controller. The control point is made to move over the scale of the flow controller in response to the output pressure of the master controller. We now have a system in which the master controller can call for any rate of flow within the limits of the flow controller. This flow is maintained at the desired value by the separate control action of the flow controller.

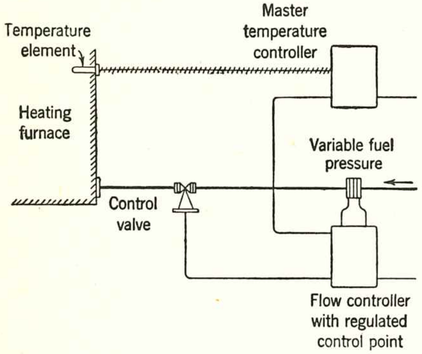

Fig. 10–1. Metered Control System Employing a Secondary Flow Controller.

The flow controller insures a constant rate of flow of control agent regardless of changes in pressure differential across the control valve. Variations in oil pressure cause a change in flow which is immediately corrected by the flow controller without any action by the master controller and without upsetting the control of temperature. At the same time, the master controller adjusts the valve position in order to control the magnitude of the master variable. This control action is accomplished through the flow-controller mechanism.

The above-described system of metered control is extensively applied in averaging control of liquid level as illustrated in Fig. 10–2. A liquid-level controller regulates the control point of a flow controller. Pressure changes in the vessel and downstream from the control valve frequently make the control of liquid level in the tank difficult. By means of metered control the effect of these pressure changes can be eliminated. Both liquid level and outflow can thereby be made more stable and consistent.

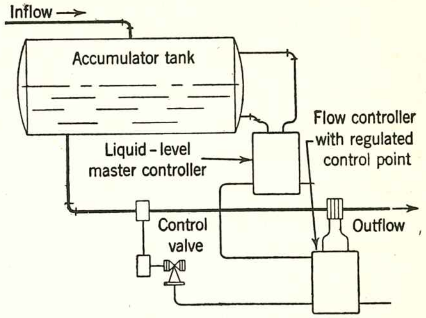

Fig. 10–2. Metered Control System Employing a Secondary Flow Controller for Averaging Liquid-Level Control.

A system of metered control which accomplishes similar results is shown in Fig. 10–3. Instead of a flow controller, a pressure controller regulates the pressure of the control agent. This system is useful only when the control agent is a fuel gas or steam. If the hand valves or other orifices at the burner remain in fixed positions, the pressure is directly proportional to flow. The pressure controller serves to change the gas or steam input by varying the downstream pressure of the

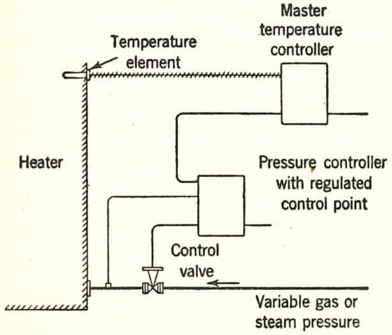

Fig. 10–3. Metered Control System Employing a Secondary Pressure Controller.

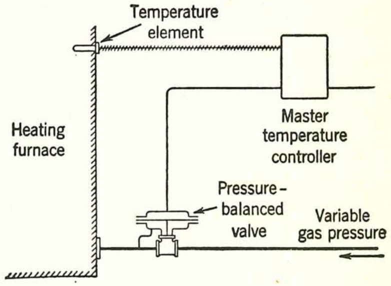

Fig. 10–4. Metered Control System Employing a Pressure-Balanced Control Valve.

control valve. The action of the pressure controller is, of course, identical to the action of a flow controller.

A third method of accomplishing metered control is shown in Fig. 10–4. A pressure-balanced valve corrects for variations in gas pressure. The valve is so constructed that the output pressure of the controller is applied to one side of the diaphragm and the downstream gas pressure is applied to the other side of the diaphragm. The pressure-balanced valve is actually a self-operated pressure regulator whose control point is regulated by the master controller. Any change in gas pressure is counteracted by the pressure-balanced valve and is not allowed to pass into the process.

The master controller must use whatever mode of control is required by process characteristics. Nearly always, however, this is the proportional-reset mode since metered control is applicable where load changes of appreciable magnitude are involved. A flow controller with regulated control point adopts the mode of control best suited to the control of flow: sometimes proportional, but more often proportional-reset, control. A pressure controller with regulated control point is more often a proportional controller.

Metered control does not maintain any fixed relation between the master variable and the control agent which is manipulated by the master controller. The flow or pressure is set to any magnitude required by the master controller in order to maintain control of the process. In this manner, the flow of the control agent is related through the process to the master variable. Actually the secondary flow or pressure controller is equivalent to a control valve in an ordinary control system.

In metered control it is necessary to consider characteristics such as controller scale shapes and valve characteristics. The problem involved is similar to that of the control system analyzed in a previous chapter where valve characteristics were related to magnitude of process loads. In metered control the problem is more complicated because of the greater number of factors.

Supply changes are corrected by the secondary controller; demand changes, by the master controller. For a load change caused by supply, only the valve characteristic is important since the magnitudes of both master and secondary variables remain essentially unchanged. In metered control with a flow controller, considering supply changes only, a linear or semi-logarithmic valve characteristic is satisfactory.

For a load change caused by demand, the characteristic of the secondary controller scale is important. The magnitude of changes in flow is governed by both the characteristic of the secondary controller scale and the characteristic of the mechanism which adjusts the secondary

control point. This mechanism usually has a linear relation between master variable and setting of secondary control point in inches of secondary controller scale. The secondary controller scale may be either linear or square root, depending upon the type of flowmeter. A square root scale, however, is not greatly different from linear between 40 or 50 and 100 per cent of scale. An approximately linear relation between flow and master variable is satisfactory as long as process load does not change over an extremely wide range.

RATIO CONTROL

In many applications, especially in the control of continuous processes, it is desirable to ratio or proportion one variable with another. For example, the flow of two fluids must often be proportioned in order to maintain a suitable mixture.

Ratio-flow control systems are arranged as shown in Fig. 10–5. The primary instrument here is not a controller but a transmitter. The control point of the secondary controller is set in direct relation to the magnitude of the primary flow. For that reason it is important that the primary transmitter have a linear relationship between its measured variable and transmitted pressure or other output impulse.

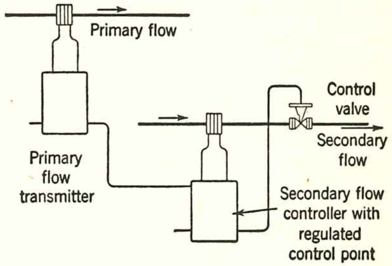

Fig. 10–5. Ratio Control System for Two Flows.

As the magnitude of the primary variable changes, the control point of the secondary controller is automatically moved to a new value so that an exact ratio is maintained between primary and secondary variables. The secondary controller controls the magnitude of the secondary variable to the value called for by its control point.

The mechanism which adjusts the control point of the secondary controller should include zero and range adjustments, permitting variations in ratios and magnitudes of the two variables. Basic ratios are established by the ranges of the primary transmitter and secondary controller. The basic ratio may be selected by proper sizing of the orifices. For example, if each flowmeter has the same range, and the ratio of primary to secondary is to be 0.5, then the control-point range must be 200 per cent. In other words, the control point of the secondary controller must move over full scale for only 50 per cent of full-scale change of the primary variable.

The primary transmitter and the secondary controller must have identical scale characteristics; otherwise an exact ratio cannot be maintained. For example, a square root scale on the primary transmitter would not match a linear scale on the secondary controller. For that reason both primary transmitter and secondary controller must use either the square root or linear scale. In order to maintain the desired ratio accurately, the secondary controller must have proportional-reset control. Reset response is necessary in order to maintain the secondary variable at the shifting control point as closely as possible.

Ratio-flow control systems may also be employed to proportion several secondary variables to one primary variable. For example, it is possible to set the magnitude of two or more secondary flows in relation to a single primary flow by connecting the primary transmitter to the mechanisms for adjusting the control points in two or more secondary controllers.

Ratio-flow control is also accomplished by other means, one of which is to place volumetric meters in both the primary and secondary flow lines. A differential-gear mechanism connects the two meters, and a control valve in the secondary line is positioned by the difference in rotational speeds of the two meters. Proportioning pumps are also arranged so that the ratio of two flows depends upon the speed and capacity of each pump.

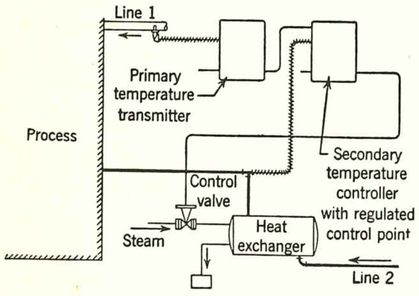

Fig. 10–6. Ratio Control System for Two Temperatures.

Ratio control may be applied for variables other than flow. For example, it may be necessary to maintain a ratio of heat flows as shown in Fig. 10–6, such that the total heat flow in both feed lines remains constant. Assuming that the rate of flow in the feed lines is constant, the temperature of the feed in line 2 is maintained at a ratio of the temperature of the feed in line 1 by controlling the heater in line 2.

When the temperature of the feed in line 1 increases, the primary temperature transmitter lowers the control point of the secondary temperature controller. This, in turn, partly closes the steam valve to the heater in line 2 and lowers the temperature in line 2. The heat balance of the process is thereby maintained more exactly.

Ratio control also has applications where a controlled relation exists between temperature and pressure. In the handling of vapors, hydrocarbons for example, pressure as well as temperature determines its state. A specified state may be obtained by measuring the temperature of the vapor (primary variable) and maintaining pressure (secondary variable) at a specified ratio.

The important factor of process reaction rate should not be ignored in ratio control or in any other correlated systems. Suppose, for example, that we wish to maintain temperature as a ratio of pressure in a ratio-control system. Pressure is measured and used to determine the magnitude of the temperature. However, as pressure changes ordinarily occur at a fast rate, the control point of the temperature controller would be moving at a relatively fast rate. If the temperature process has a slow reaction rate, as it usually does, the maximum rate of change of temperature might be so small that the temperature could not follow the moving control point closely enough to maintain the desired ratio. In ratio-control systems it is obvious that the secondary variable must have a reaction rate equal to or greater than the primary variable; otherwise the ratio cannot be accurately maintained.

It should be noted that ratio control is altogether different from metered control even though the control systems have similar outward appearances. In ratio control a definite ratio exists between the primary and secondary variables at all times, and there is no reaction of the magnitude of the secondary variable back to the magnitude of the primary variable. In metered control there is no fixed relation between magnitudes of master and secondary variables, and the secondary variable acts through a process to control the magnitude of the master variable. In some applications, the primary variable may be controlled by the addition of a control system to the primary transmitter. This arrangement does not alter the operation of the system.

A pneumatic ratio-control system is perhaps the most common and the most versatile in operation. However, the primary and secondary variables can be combined in one controller and the control point operated mechanically. The principle of operation is the same in this type of system as in the pneumatic system. Electric and hydraulic-type ratio-control systems are also used, however.

TIME-VARIABLE CONTROL

In the processing of metals and chemicals it is sometimes necessary to vary the controlled variable over a definite time schedule. For example, in annealing steel a schedule as shown in Fig. 10–7 may be required. The furnace temperature is raised to 1500° F in 4 hours, held for 8 hours, and lowered to 500° F in 6 hours. This time schedule must be incorporated into the automatic control system.

Time-variable control is accomplished similarly to ratio control. All systems operate on the principle that the control point is moved through the desired time schedule. The control system functions to maintain the controlled variable, temperature in the example above, as close to the moving control point as required.

There are four principal methods for obtaining time-variable control. In the first arrangement an electric motor drive is attached to the control point of the controller in such a manner that applying electric power to the motor moves the control-point index along the controller scale. The speed of the motor drive is selected to fit the particular application. Auxiliary electric timers and interrupters govern the movement of the control point in accordance with the desired schedule.

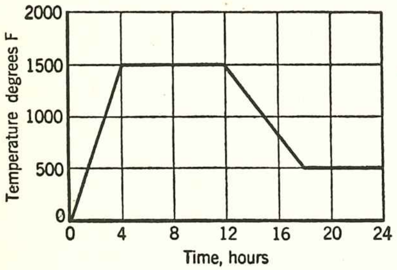

Fig. 10–7. Typical Temperature Schedule for Time-Variable Control.

A second arrangement employs a two-record self-balancing potentiometer. One record is operated in the ordinary manner from the controlled temperature which it is desired to maintain on a schedule. The second record is operated along the desired time schedule rather than being used to record a measured variable. The second record or point is positioned from a variable-voltage source in which the voltage is made proportional to the schedule by means of a shaped cam. By a simple arrangement, the second record is made to operate as the control point of the controller. The controlled variable (the first record) is then controlled to the magnitude dictated by the control point (the second record).

A third arrangement involves a transmitting mechanism whose output pressure is made proportional to the desired schedule. A cam in the transmitting mechanism is shaped to provide the desired time schedule. The transmitting mechanism adjusts the control point of a secondary controller having a control-point setting mechanism. The secondary controller measures and controls the variable to the desired magnitude.

A fourth arrangement provides mechanical means for transmitting the desired schedule to the secondary controller and operating the control point. A cam shaped to the desired time schedule may be located either outside or inside the controller case. In this class we may place all the many simple types of time-temperature and time-pressure controllers of the non-indicating or indicating types found in the control of batch-type operations.

Although there are a multitude of time-variable control mechanisms and systems, the application of one type is illustrated in Fig. 10–8 for time-temperature control of a crystallizing kettle. The time-schedule mechanism contains a cam shaped to provide a schedule as follows: uniform heating rate to 212° F during 2 hours, a holding period of 2 hours at this temperature, and a cooling period with a uniform temperature decrease of 18° F per hour for 3 hours, and then a uniform decrease of 7.2° F per hour for 13 hours. The complete cycle takes 20 hours.

Control of temperature during the time schedule is accomplished with the proportional-reset mode of control by regulating steam to the kettle jacket. It is in applications of this general nature that a large number of simple, non-indicating time-temperature controllers are used.

As in ratio control any number of variables may be connected with the same time schedule. In multiple-zone furnaces, for example, the time-variable control system is usually arranged so that each zone is separately controlled, but all to the same time schedule.

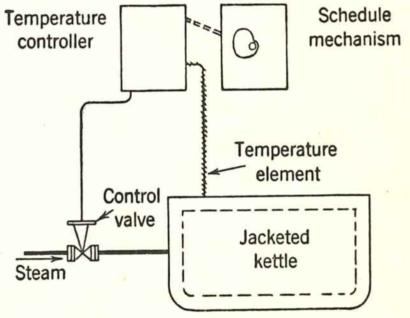

Fig. 10–8. Time-Variable Control System for Kettle Temperature.

In all these systems the controller must maintain the variable at a moving control point much in the same manner as in ratio control. Consequently it is necessary to employ a mode of control which will maintain the controlled variable at the control point within the desired limits. The selection of the mode of control is based upon the process characteristics and the desired quality of control, just as with any control system.

Two-position and single-speed floating control find wide usage in time-variable control of thermal processes where transfer lag or dead time is negligible. Proportional control is suitable only if the proportional band may be made small, thus eliminating any serious offset. The proportional-reset mode is ordinarily best adapted to time-variable control since reset response tends to eliminate offset caused by varying positions of the control point.

Process reaction rate again must be considered if a fast rate of change of control point is required. The control point should not be moved at a rate greater than that at which the controlled variable can change; otherwise deviation of the variable is inevitable. Ordinarily the rate of control-point movement is quite slow as illustrated by the example in Fig. 10–7.

Careful consideration must be given to the final element because of the wide variations in flow required at various positions of the control point. Adequate sensitivity of valve positioning and smooth changes in valve position are necessary if close control is desired. The rangeability of the control valve should be large to provide adequate control of both large and small magnitudes of the controlled variable.

LIMIT CONTROL

Many simple controllers serve in industrial process control as safety devices to protect process equipment from overloads of temperature or pressure. The addition of a second controller to the control system results in a simple type of multivariable control system.

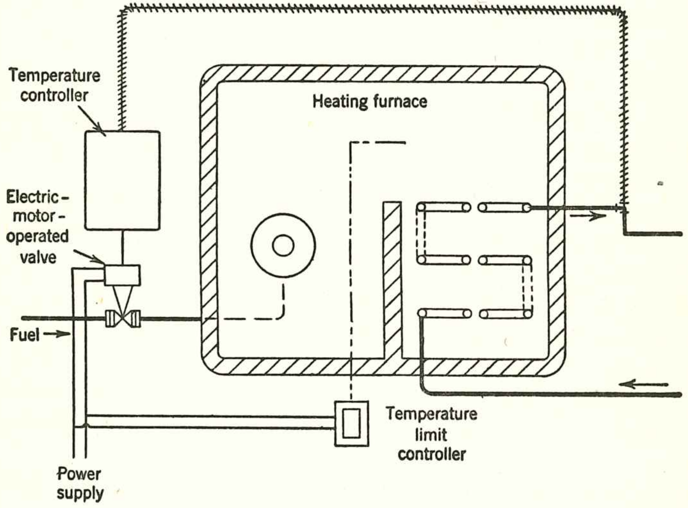

FIG. 10–9. Limit Control System for Preventing Excessive Brickwork Temperatures.

Figure 10–9 illustrates the application of a limit control on a gas-fired heater. At times, excessive gas supply may cause the temperature of the brickwork to rise above the softening point. A second electric two-position controller of the millivoltmeter type is installed with the thermocouple in the brickwork. The control contacts of the limit controller are connected into the control system so that the control valve ordinarily operated by the temperature controller is closed by excessive limit temperatures.

The main controller operates in normal fashion as long as the limit variable remains below the desired point. If the limit variable rises above the safe point, the control of the main variable is automatically cut off until the limit variable returns to the safe level. Note that, during this period, control of the main variable is lost, and deviation of the main controlled variable may occur.

A "lockout"-type limit-control system is shown in Fig. 10–10. Temperature of the heater is controlled by a pneumatic controller and diaphragm valve. At times, however, the feed to the heater may drop below a safe limit and it is necessary to shut off the entire system until the flow of feed can be reestablished. In the present example a flowmeter having electric limit contacts is installed in the feed line. When the flow of feed drops below the set limit, the contact is broken, the electrical locking-type relay is deenergized, and a three-way valve in the temperature controller valve line is opened. The fuel flow to the heater is cut off and a signal given. The system is then completely shut down until it is manually started.

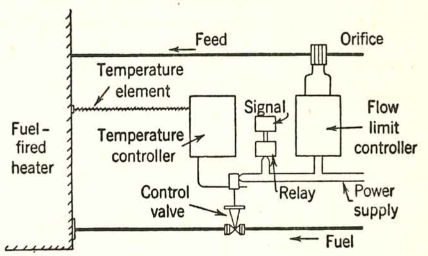

FIG. 10–10. Limit Control System for Closing down Process upon Feed Failure.

When the control system is electrically operated, a limit controller of the electric type is used to remove all power if the control valve is solenoid operated, or to drive a motor-operated valve to the closed position. With pneumatic controllers the limit controller is arranged either to remove all pressure or apply full pressure to the diaphragm control valve.

With fuel-fired furnaces, it is sometimes necessary to connect flame-protecting devices into the control system in order to protect the furnace from dangerous building up of unburned fuel if the flame should go out. The flame device is usually arranged so that the control system is shut down when the flame is out. These installations, in the interest of safety, must be made in an approved manner.

A series-proportional control system is appropriate when the process arrangement requires that the control be accomplished from either of two variables at different times. This type of multivariable system usually, although not necessarily, involves considerations of safety. Series-proportional control may therefore serve a different purpose from limit control.

Let us suppose that the reaction in the chamber of Fig. 10–11 is controlled with a proportional temperature controller. At a certain time the reaction in the chamber causes the pressure to rise rapidly above its normal value. Assume also that during this period pressure is more indicative of process conditions than temperature. For this type of process a pneumatic proportional controller to control pressure is installed in series with a temperature controller, both operating a single diaphragm control valve.

The action of the system normally is such that the temperature controller maintains a moderate output pressure, 8 lb per sq in., for example. The measured pressure is normally such that it is below its control point, and the pressure controller calls for a high output pressure, 12 lb per sq in. or more. However, since the output of the pressure controller becomes the supply to the temperature controller, only 8 lb per sq in. is maintained at the valve.

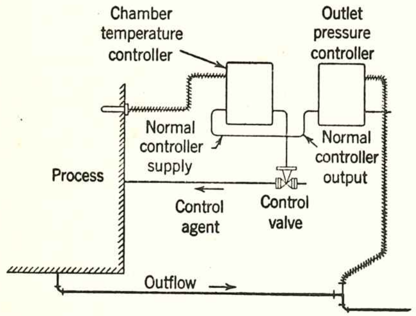

Fig. 10–11. Series-Proportional Control System for Heating Chamber Temperature and Pressure.

During the reaction period, the pressure rises rapidly to its control point and the output pressure drops to a lower value, say 6 lb per sq in. The pressure controller now controls the valve position since the temperature controller cannot produce a higher output pressure than its supply. The controller delivering the lower pressure automatically assumes command of valve position. The chamber pressure is controlled during the reaction period, and when conditions return to normal the temperature again controls the process. By this arrangement the control function is automatically shifted from one controller to the other as required by conditions in the process.

Series control is useful in the control of furnace temperatures where the control function must be shifted from temperature to fuel rate during certain periods and also in air-conditioning control where the control function must shift from temperature to humidity as conditions of the intake air require.

Series-proportional control is not usually accomplished with electric proportional controllers. Greater versatility in series control can be obtained with pneumatic proportional controllers, since the output of one may readily serve as the supply for the other.

Dual Control Agents

In some processes more than one control agent may be needed. The controller must then be arranged so as to regulate two flows into the process instead of one, and the control system includes a single measured variable and two adjusted variables. For that reason, it may be classed as a multivariable control system.

The temperature of plating tanks is controlled by means of dual control agents. The temperature of the circulating water is controlled by admitting steam when the temperature is low, or cold water when it is high. Figure 10–12 illustrates a system where pneumatic proportional control and diaphragm valves with split ranges are used. The steam valve is closed at 8.5 lb per sq in. pressure from the controller, and fully open at 14.5 lb per sq in. pressure. The cold water valve is closed at 8 lb per sq in. air pressure and fully open at 2 lb per sq in. air pressure.

If more accurate valve settings are required, pneumatic valve positioners will accomplish the same function. The zero, action, and range adjustments of valve positioners are set so that both the steam and cold water valves are closed at 8 lb per sq in. controller output pressure. The advantages gained with valve positioners are that standard diaphragm valves are acceptable, settings can be much more accurate, and the action of each valve can be readily adjusted.

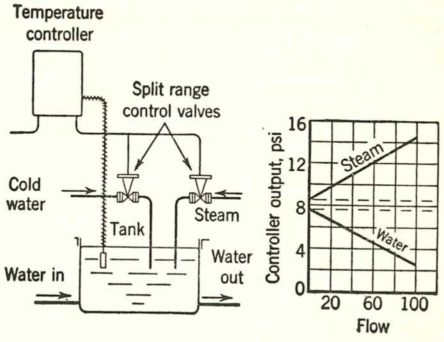

Fig. 10–12. Dual-Agent Control System for Adjusting Heating and Cooling of Bath.

For applications having dual agents, duplex controllers are arranged with two complete control systems operating from a single measured variable. Two standard control valves are used, and settings are made by means of the control point of each system. The system may be either electric or pneumatic.

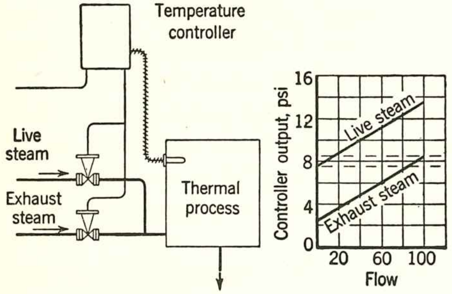

Fig. 10–13. Dual Agent Control System with Two Heating Agents.

Another example of dual control agents, illustrated by Fig. 10–13, is the control of temperature in paper-drying machines. Ordinarily, exhaust steam is utilized for heating, and a valve in the exhaust steam line is set from a temperature controller. Because of varying loads on the steam system, exhaust steam is likely to change considerably in pressure and quality. Then the heat supply of the exhaust steam is supplemented by live steam. Check valves prevent reverse flow.

The connection of the valves is illustrated in Fig. 10–13. The controller pressure is connected to the diaphragms of both valves. The exhaust-steam valve is set to open at 7.5 lb per sq in. and is fully open at $13\frac{1}{2}$ lb per sq in. Both valves are open between 7.5 and 8.5 lb per sq in. controller pressure.

Changes in quality of exhaust steam are automatically corrected by the reset response of a proportional-reset controller. Suppose, for example, that the heat content of the exhaust steam becomes gradually lower. The temperature in the paper machine drops slightly below the control point, and reset response gradually opens the live-steam valve so as to maintain the required heat supply.

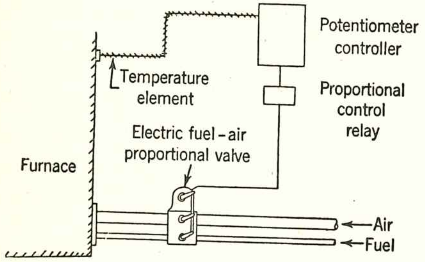

FIG. 10–14. Dual Agent Control System Employing Electric Proportional Control for Adjusting Both Fuel and Air.

The size of each valve should be based upon the relative heating and cooling effect of each agent. The addition or subtraction of heat from the process should be the same with corresponding openings of each valve. The characteristic of each valve should be the same. Linear valve characteristics are preferable since the overall response of the two control agents can more easily be matched.

Dual control agents, and sometimes more than two, are often needed in fuel-fired furnaces burning combinations of oil and air or gas and air. Here again the mechanisms and systems are many and highly individual, but most of them fall into three general classes: those with a single fuel regulated by single valve and with inspirated air; those having a dual or combination valve which adjusts the flow of both fuel and air; and those with metered-ratio control of multiple fuels.

In many simple applications where an exact fuel-air ratio is not required a single fuel is adjusted by a control valve and the air is inspirated with correspondingly greater flow as the fuel flow increases with positioning of the control valve. Also common is a single power unit operating two valves, one in the fuel line and one in the air line. Such an application is illustrated in Fig. 10–14, where electric proportional control is employed for furnace temperature. An electric-motor operator positions both the fuel and air valves, thus maintaining a ratio of fuel to air by virtue of the flow characteristics of each valve. Many of these combination valves are provided not only with a means for adjusting the maximum flow, or valve size, but also with a means for adjusting the flow characteristic to match fuel-air ratio at various settings.

Metered-ratio control is suitable either where exact ratio is necessary, or where multiple fuels are required, or both. For example, many high-capacity furnaces for metallurgical work take three fuels such as oil, gas, and air.[6] The combination of two systems already described provides an interesting problem in the application of automatic control. Metered control will maintain the exact flow of fuel required by the master temperature controller. In addition, exact ratios between fuel flow or flows and air flow must be maintained. Ratio control is thus combined with metered control so that fuel and air are held not only to specified flow rates but also to the desired flow ratio.

When the process can be controlled with a two-position or proportional mode the problem of dual control agents is not difficult. If proportional-reset control is required because of process load changes, proper valve arrangement becomes important to the operation of the control system; smooth changes in flow must be provided by proper selection of valve sizes and proper adjustment of valve operation.

ENGINEERED CONTROL SYSTEMS

Many industrial processes require control systems arranged to correlate widely diversified variables affecting the process. In addition, purely functional operations may be incorporated into the control system, not necessarily for control of selected variables but to make the process more continuous in action. In this way the operation of the process is made almost entirely automatic. These systems range, for example, all the way from simple pressure control of curing molds in rubber and plastics manufacture to automatic control of central power stations. Power plants are an excellent example of such coordinated and engineered systems. They are sometimes completely controlled to the extent that operators are required only to maintain automatic systems and handle emergency conditions.

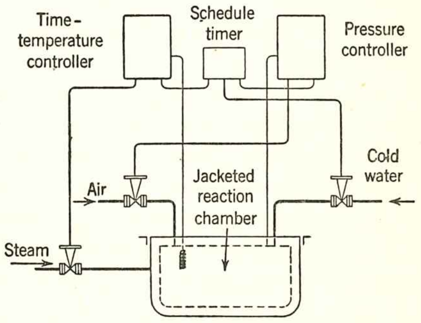

FIG. 10–15. Correlated Control System for Automatic Operation of Reaction Chamber.

Correlated control systems are necessarily different for every application. They must be "tailored" to perform a particular task. A hypothetical case will illustrate what can be done to provide completely automatic operation. The complete unit of Fig. 10–15 is arranged to carry through automatically a complete batch operation.

The purpose of this correlated system is to heat the materials in the reaction chamber through a controlled cycle and, in addition, control the pressure and cold-water injection during predetermined intervals. This program is accomplished by a process timing mechanism and the necessary temperature, pressure, and auxiliary controllers as follows:

1. Operator manually starts timer to begin program.
2. Timer turns on air supply to time-temperature controller, thereby opening the steam valve to the reaction chamber.
3. Temperature controller raises the temperature of the reaction chamber to 180° F at a linear rate of rise during 2 hours.
4. Temperature of the reaction chamber is held to 180° F for 1 hour.
5. One-half hour after the temperature has reached 180° F, the air supply to the pressure controller is turned on by the timer, thereby opening the air valve.
6. For the remainder of the program the pressure is controlled to 20 lb per sq in. gage.
7. At the end of 1 hour at 180° F, the reaction chamber temperature is lowered to 100° F in ½ hour at a linear rate.
8. When the temperature of the reaction chamber has reached 100° F, the cold-water valve is automatically opened by the timer.
9. Timer shuts off the temperature and pressure controllers.

This example represents the action of a typical engineered system where all control functions are coordinated in order to achieve completely automatic operation. The example is by no means as complicated as some actual applications.

The important coordinating function of the control system is provided by the process timing mechanism. These devices contain a series of cams for operating a set of pneumatic or electric switches. The cams are generally driven by an electric motor operated either on a purely time basis or from external sources.

A process timing mechanism is illustrated in the operation of vulcanizers for rubber tire manufacture. The cycle is as follows:

1. Open steam valve.
2. Raise temperature to vulcanizing point.
3. Hold temperature at vulcanizing point for required period.
4. Close steam valve.
5. Open blow-off valve.
6. Close blow-off valve after required period.
7. Open water cooling valve.
8. Open drain valve after required period.
9. Close water cooling valve after required period.
10. Close drain valve.

It may be noted that only during steps 2 and 3 is there any automatic control of an independent variable (temperature). All other steps are merely time functions required to provide a complete processing operation.

Many correlated control systems are built around the time-variable control system with an auxiliary electrical timer for performing the required operation at the beginning and end of the cycle. Self-contained units of this nature are used in rubber, food, glass, and tobacco processing to eliminate manual operations which would otherwise be necessary.

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GLOSSARY OF TERMS USED IN AUTOMATIC CONTROL

The following terms and their definitions have come into use in the science of automatic control. These definitions are offered subject to revision by further issuance and adoption of terminology by the A.S.M.E. Industrial Instruments and Regulators Division Committee on Terminology.

Automatic Control. Automatic maintenance of balanced conditions within a process.

Automatic Controller. Mechanism which measures the value of a variable quantity or condition and operates to correct or limit deviation of the measured value from a selected reference.

Automatic Control System. An automatic controller including primary element and final element in which the action is operated on or influenced by other control mechanisms or automatic controllers external to the first automatic controller.

Automatic Regulator. *See* Automatic controller.

Automatic Reset. *See* Reset response.

Capacity. Change in stored energy or material required to produce unit change in potential or level.

Cascade Control System. *See* Metered control system.

Constant-Speed Floating Mode. *See* Single-speed floating mode.

Control. *See* Automatic control.

Control Agent. Process energy or material of which the manipulated variable is a condition or characteristic.

Control Circuit. *See* Controlled system.

Control Point. Selected reference value of controlled variable which it is desired to maintain.

Control System. *See* Automatic control system.

Controlled Medium. Process energy or material in which a variable is controlled.

Controlled System. Interconnected process, controller, or controllers, and control mechanisms wherein a single designated variable is maintained within limits.

Controlled Variable. Quantity or condition which is measured and controlled.

Controller Adjustment. Manually adjustable characteristic of an automatic controller for varying relationship between controlled variable and controller response.

Controller Lag. Retardation or delay in response of final control element to change in controlled variable at the controller.

Controller Response. Output signal or impulse from an automatic controller.

Controlling Means. Elements of an automatic controller which are involved in producing a corrective action.

Corrective Action. Controller action initiated by deviation and resulting in variation of the manipulated variable.

Correlated Control System. An automatic controller including primary element and final element in which one or more measured variables are controlled in relation to another measured variable or in relation to time.

Cycling. Periodic change of controlled variable from one value to another.

Dead Time. Any definite delay period in the measuring means, controlling means, or process.

Dead Zone. Largest range of values of controlled variable to which the measuring means or controlling means does not respond.

Demand Change. *See* Load change.

Departure. *See* Deviation.

Derivative Mode. Controller action in which there is a continuous linear relation between derivative function of controlled variable and position of final control element. (Linear controller scale is assumed.)

Deviation. Difference at any instant between value of controlled variable and control point.

Differential Gap. Two-position controller adjustment: smallest range of values through which controlled variable must pass in order to move final control element to both its fixed positions. (Linear controller scale is assumed. Expressed in percentage of controller scale.)

Distance-Velocity Lag. *See* Dead time.

Drift. Wandering of controlled variable in which its value aimlessly departs from control point.

Droop. *See* Offset.

Droop Correction. *See* Reset response.

Dynamic Error. Difference between true value of a quantity or condition changing with time and the value indicated by a measuring means.

Error. *See* Deviation.

Final Control Element. Portion of controlling means which directly determines the value of manipulated variable.

Floating Mode. Controller action in which there is a predetermined relation between value of controlled variable and rate of motion of final control element, the direction of motion corresponding to the direction of deviation.

Floating Rate. Proportional-speed floating controller adjustment: rate of motion of final control element corresponding to a specified deviation. (Linear controller scale is assumed. Expressed in percentage motion per minute per per cent deviation.)

Floating Speed. Single or multispeed floating controller adjustment: rate of motion of final control element. (Expressed in percentage motion per minute.)

Hunting. *See* Cycling.

Floating controller: An on/off (two-position) controller for the rate change of the valve. It may also have a neutral position, It works like a on/off I-controller

Inactive Neutral. *See* Differential gap.

Instrument. Mechanism for automatically measuring and indicating the value of a quantity or condition.

Integral Response. *See* Reset response.

Inventory. *See* Capacity.

Lag. Retardation or delay of one physical condition with respect to some other condition to which it is closely related.

Lead Component. *See* Rate response.

Limit Control System. *See* Series control system. Selector

Load Change. Change in process conditions which requires a change in the average value of manipulated variable to maintain the controlled variable at the desired value.

Load Error. *See* Droop.

Manipulated Variable. Quantity or condition which is varied by the automatic controller so as to affect the value of controlled variable.

Master Controller. In a metered control system, that automatic controller which adjusts the control point of another automatic controller.

Measured Variable. Quantity or condition the value of which is automatically ascertained by an instrument or an automatic controller.

Measurement. Act of ascertaining the value of a quantity or condition.

Measuring Lag. Retardation or delay in response of measuring means of an instrument or an automatic controller to changes in measured variable.

Measuring Means. Elements of an instrument or automatic controller which are involved in ascertaining value of measured variable.

Measuring System. *See* Measuring means.

Meter. *See* Instrument.

Metered Control System. An automatic control system in which the automatic controller operates a second automatic controller for adjusting the value of the manipulated variable.

Mode of Control. Systematic method of action of a controller.

Modulating Mode. *See* Proportional mode.

Multiagent Control System. An automatic control system in which two or more manipulated variables are adjusted by a single automatic controller.

Multiposition Mode. Controller action in which a final control element is moved to one of three or more predetermined positions, each corresponding to a definite range of values of controlled variable.

Multispeed Floating Mode. Controller action in which a final control element is moved at two or more rates, each rate of motion corresponding to a definite range of values of controlled variable, and the direction of motion corresponding to the direction of deviation.

Multivariable Control System. An automatic control system in which there is more than one controlled variable, or more than one manipulated variable.

Neutral Zone. Floating controller adjustment: predetermined range or values of controlled variable in which no corrective action occurs. (Linear controller scale is assumed. Expressed in percentage of controller scale.)

Offset. Sustained deviation obtained with two-position, multiposition, or proportional mode of control.

On-Off Mode. *See* Two-position mode.

Open-and-Shut Mode. *See* Two-position mode.

Oscillation. *See* Cycling.

Positioning Mode. Controller action in which there is a predetermined relation between value of controlled variable and position of final control element.

Power-Operated Controller. Automatic controller with either power-operated controlling means or power-operated measuring means.

Power-Operated Controlling Means. Type of controlling means in which the energy transmitted through the primary element is either supplemented or amplified for operating the final control element by employing energy from another source.

Power-Operated Measuring Means. Type of measuring means in which the energy transmitted through the primary element is either supplemented or amplified for operating the indicating mechanism of an instrument or the controlling means of an automatic controller by employing energy from another source.

Power Unit. Portion of controlling means which applies power for operating final control element.

Primary Measuring Element. Portion of measuring means which first utilizes energy from controlled medium to produce a condition representing the value of controlled variable. Condition produced by primary element is usually pressure, force, or motion.

Process. Operation or series of operations in which the value of a quantity or condition is controlled. It includes all functions which directly or indirectly affect value of controlled variable.

Process Equipment. Physical apparatus, exclusive of automatic control equipment, for carrying out a process.

Process Lag. Retardation or delay in response of controlled variable at point of measurement to a change in value of manipulated variable.

Process Load. Sum, taken at any instant, of the energy or material requirements of the process resulting in a specific value of manipulated variable.

Process Load Change. *See* Load change.

Process Medium. Any energy or material which is supplied to or taken from a process and which directly or indirectly affects the value of the controlled variable.

Process Reaction Rate. Maximum rate of change of controlled variable caused by a specified, sudden change in value of manipulated variable.

Process Self-Regulation. Sustained reaction inherent in the process which assists or opposes the establishment of equilibrium.

Process Variable. *See* Variable.

Program Control System. *See* Time-variable control system.

Proportional Band. Proportional controller adjustment: range of values of controlled variable which corresponds to full operating range of final control element. (Linear controller scale is assumed. Expressed in percentage of controller scale.)

Proportional Mode. Controller action in which there is a continuous linear relation between value of controlled variable and position of final control element. (Linear controller scale is assumed.)

Proportional Plus Floating Mode. Controller action in which proportional and floating actions are combined additively.

Proportional-Reset Mode. Controller action in which proportional and proportional-speed floating actions are combined additively in such a manner that the proportional band adjustment affects both actions simultaneously.

Proportional-Reset-Rate Mode. Controller action in which proportional, proportional-speed floating, and rate response actions are combined additively in such a manner that the proportional band adjustment affects all three actions simultaneously.

Proportional-Speed Floating Mode. Controller action in which there is a continuous linear relation between value of controlled variable and rate of motion of final control element, the direction of motion corresponding to the direction of deviation. (Linear controller scale is assumed.)

Rangeability. Ratio of maximum flow to minimum controllable flow through a final control element.

Rate Response. Controller action used in conjunction with the proportional mode in which there is a continuous linear relation between rate of change of controlled variable and position of final control element. The magnitude of rate response is directly related to rate time and inversely related to proportional band. (Linear controller scale is assumed.)

Rate Time. Proportional-reset-rate controller adjustment: advance of proportional response caused by addition of rate response. (Linear controller scale is assumed. Expressed in minutes.)

Ratio Control System. An automatic control system in which value of the variable is controlled in a predetermined relation to value of another measured variable.

Reaction Curve. Change with time of a measured variable resulting from a sudden change in manipulated variable.

Recovery. Change with time of a controlled variable resulting from a sustained or temporary change in process load.

Regulation. *See* Automatic control.

Regulator. *See* Automatic controller.

Reset Rate. Proportional-reset controller adjustment: number of times per minute that proportional response is duplicated by the proportional-speed floating response. (Linear controller scale is assumed. Expressed in number per minute.)

Reset Response. Controller action used in conjunction with proportional mode in which there is a continuous linear relation between value of controlled variable and rate of motion of final control element. The magnitude of reset response is directly related to reset rate and inversely related to proportional band. (Linear controller scale is assumed.)

Resistance. Potential difference required to produce unit change in flow.

Secondary Controller. An automatic controller in which the control point is automatically and continuously adjusted from an external source.

Self-Operated Controller. Automatic controller with self-operated measuring means and self-operated controlling means.

Self-Operated Controlling Means. Type of controlling means in which all the energy necessary to operate the final control element is derived from the measuring means.

Self-Operated Measuring Means. Type of measuring means in which all the energy necessary to operate the indicating mechanism or controlling means is derived from the controlled medium through the primary element.

Sensitivity. *See* Proportional band. Sensitivity is the inverse of proportional band.

Series Control System. An automatic control system in which the value of the manipulated variable is determined by either one of two controlled variables.

Servo-Operated Controller. *See* Power-operated controller.

Set Point. *See* Control point.

Single-Speed Floating Mode. Controller action in which final control element is moved at a single rate, the direction of motion corresponding to the direction of deviation.

Stability. State of controlled variable in which the variable does not cycle, or cycles with decreasing amplitude.

Static Error. Difference between true value of a quantity or condition not changing with time, and the value indicated by a measuring means.

Supply Change. *See* Load change.

Throttling Mode. *See* Proportional mode.

Throttling Range. *See* Proportional band.

Time-Variable Control System. An automatic control system in which value of the controlled variable is controlled in a predetermined relation to time.

Transfer Lag. Retardation, not delay, in response of controlled variable caused by existence of distributed capacity or two or more separated capacities in a controlled system.

Time constant

Transmission Lag. Retardation or delay caused in transmitting a measurement of variable from primary element to controller.

Transportation Lag. *See* Dead time.

Turndown. Ratio of normal maximum flow to minimum controllable flow through a final control element.

Two-Position Differential-Gap Mode. Controller action in which a final control element is moved from one of two fixed positions to the other at a predetermined value of controlled variable, and subsequently to the other position only after the variable has crossed a range of values to a second predetermined value.

Two-Position Mode. Controller action in which a final control element is moved from one of two fixed positions to the other at predetermined values of the controlled variable.

Upset. *See* Load change.

Variable. Quantity or condition associated with a process, the value of which is subject to change with time.

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