THIRD EDITION

# Instrumentation for Process Measurement and Control

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CHILTON COMPANY RADNOR, PENNSYLVANIA

Third Edition 
Published in Radnor, Pennsylvania 19089, by Chilton Company

Library of Congress Catalog Card No. 78-14643
ISBN 0-8019-6766-x

Designed by Jean Callan King/Visuality
Manufactured in the United States of America

67890 98765

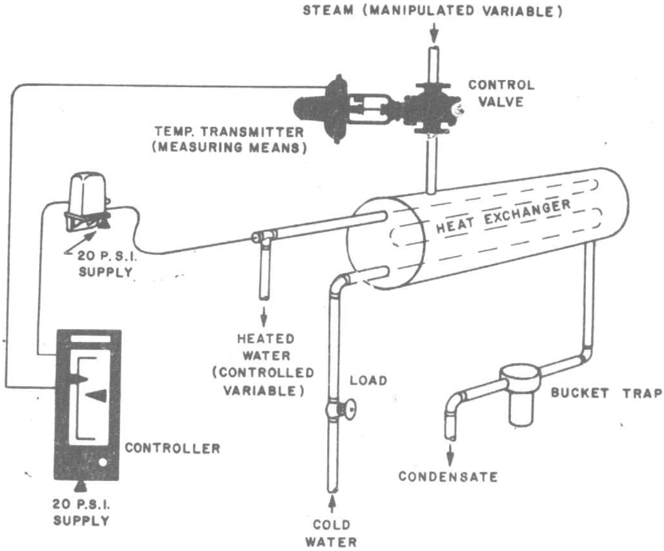
# 1

# Introduction to Process Control

The technology of process instrumentation continues to grow in both application and sophistication. In 1774, James Watt employed the first control system applying feedback techniques in the form of a flyball governor to control the speed of his steam engine. Ten years later, Oliver Evans used control techniques to automate a Philadelphia flour mill.

Process instrumentation developed slowly at first because there were few process industries to be served. Such industries began to develop at the turn of the twentieth century, and the process instrumentation industry grew with them. However, only direct-connected process instruments were available until the late 1930s. In the 1940s, pneumatic transmission systems made complex networks and central control rooms possible. Electronic instrumentation became available in the 1950s, and its popularity has grown rapidly since. The most recent decade has produced digital computer techniques to improve the performance of more complex processes. However, present trends indicate that future process plants will employ combinations of analog and digital systems.

True control balances the supply of energy or material against the demands made by the process. The most basic (feedback) systems



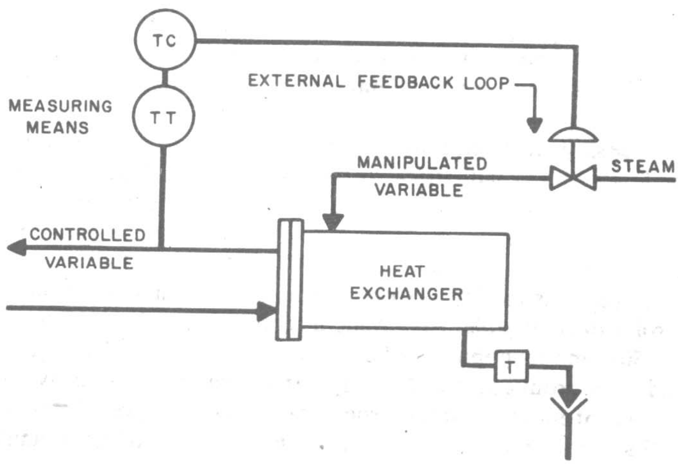




**Fig. 1-1.** (*A*) The process to be controlled occurs in a heat exchanger. All elements of the pneumatic control system are shown—transmitter, controller, valve, input water, output water, and steam. (*B*) Block diagram of the elements listed in *A*.

measure the controlled variable, compare the actual measurement with the desired value, and use the difference between them (error) to govern the required corrective action. More sophisticated (feedforward) systems measure energy and/or material inputs to a process to control the output. These will be discussed in Chapter 16.

The control loop in Figure 1-1 is shown in both actual and schematic form. The process is a shell and tube heat exchanger, and the temperature of the heated water is the controlled variable. This temperature is measured by a pneumatic temperature transmitter, which sends a pneumatic signal proportional to temperature to the pneumatic analog controller. The desired water temperature is set on the controller's set-point dial. The controller changes a pneumatic output signal according to the difference between the existing value (temperature) and the desired value (set point). The output signal is applied to the valve operator, which positions the valve according to the control signal. The required quantity of heat (steam) is admitted to the heat exchanger, causing a dynamic balance between supply and demand.

The various control equipment components that may be used to

**Table 1-1.** Analogy Between Characteristics of Basic Physical Systems

| *Variable* | *Electrical System* | *Hydraulic System* | *Pneumatic System* | *Thermal System* |
|---|---|---|---|---|
| Quantity | Coulomb | $ft^3$ or $m^3$ | Std. $ft^3$ or $m^3$ | Btu or joule |
| Potential or effort variable | emf<br>E<br>(volt) | Pressure<br>P<br>(psi or kPa)<br>(ft or m of head) | Pressure<br>P<br>(psi or kPa)<br>(m or mm of head) | Temperature<br>T<br>(degrees Fahrenheit or Celsius) |
| Flow variable | Coulomb/s<br>Current<br>I<br>(amperes) | Flow<br>Q<br>($ft^3$/s or L/s)<br>(gal/min) | Flow<br>Q<br>($ft^3$/s or $m^3$/s)<br>(lb/min) | Heat flow<br>dQ/dt<br>(Btu/s or watts) |
| Resistance | R<br>(ohm)<br>$= \frac{\text{volt}}{\text{amp}}$ | psi/($ft^3$/s)<br>ft head/$ft^3$/s)<br>sec/$ft^2$ | psi/($ft^3$/s) | deg/(Btu/s)<br>deg/watt |
| Capacitance | q(farad)<br>$\frac{\text{Coulombs}}{\text{volts}}$ | $ft^3/ft = ft^2$ | $ft^2$ | Btu/deg |
| Time | Seconds | Seconds | Seconds | Seconds |

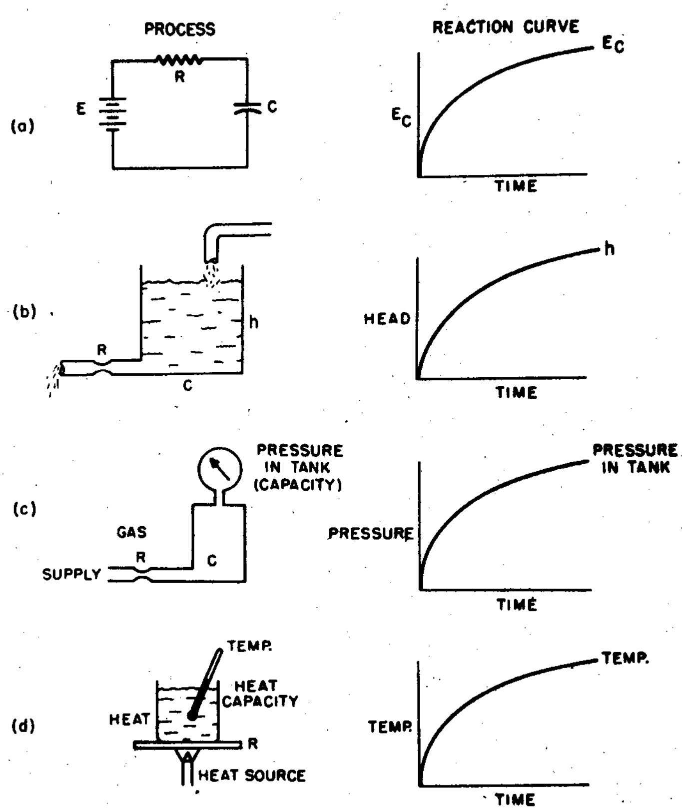



**Fig. 1-2. Four types of systems: (a) electric, (b) hydraulic, (c) pneumatic, and (d) thermal. Each has a single capacity and a single resistance and all have identical response characteristics.**

regulate a process and certain aspects of process behavior will be discussed in this text. Examples of some completely instrumented process systems will be given to demonstrate the practical application of the instrument components.

The physical system to be controlled may be electrical, thermal, hydraulic, pneumatic, gaseous, mechanical, or any other physical type. Figure 1-2 and Table 1-1 compare several common systems. All follow the same basic laws of physics and dynamics.

The behavior of a process with respect to time defines its *dynamic characteristics*. Behavior not involving time defines its *static characteristics*. Both static (steady) and dynamic (changing with time) responses must be considered in the operation and understanding of a process control system.

## Types of Processes

The simplest process contains a single capacity and a single resistance. Figure 1-2 illustrates a single-capacity, single-resistance process in (a) electrical, (b) hydraulic, (c) pneumatic, and (d) thermal forms. To show how these behave with respect to time, we can impose a step upset (sudden change) in the input to the process and examine the output. The resulting change in process variable with respect to time is plotted in Figure 1-3. The reaction curve of all four types of systems will be identical.

This type of curve (exponential) is basic to automatic control. It can be obtained easily with an electrical capacitor and resistor arranged as in Figure 1-2a.

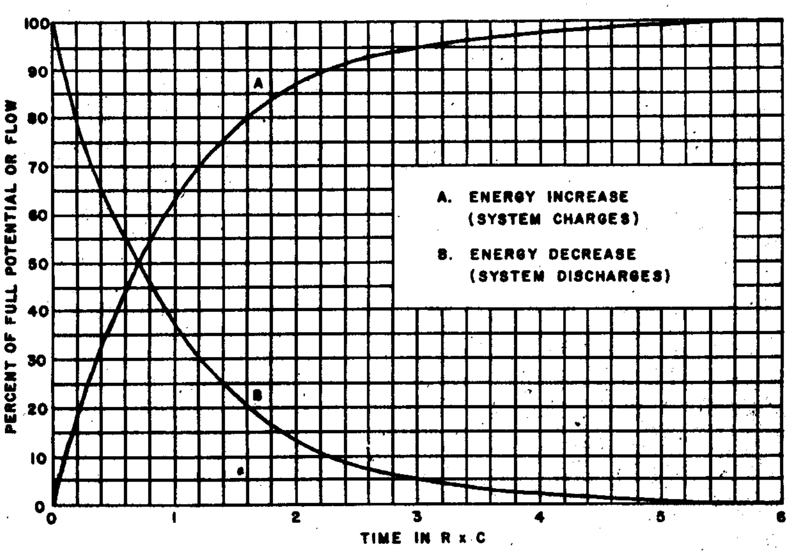



**Fig. 1-3. Universal time-constant chart, showing exponential rise and decay.**

Figure 1-2a shows a simple *RC* circuit—a resistor, capacitor, and battery source in series. The instant the circuit is closed, the capacitor starts to charge to the voltage of the battery. The rate at which the capacitor charges gradually decreases as the capacitor voltage approaches the battery voltage (voltage curve A in Figure 1-3). Although the rate varies, the time it takes the capacitor to charge to 63 percent of the battery voltage is a constant for any one value of *R* and *C*. Thus, no matter what the voltage of the battery, the capacitor charges to 63 percent of the battery voltage in a time interval called the time constant, or characteristic time (*T*) of the circuit. The value of *T* in seconds is the product of the resistance (in ohms) and the capacitance (in farads).

Note that the charging time increases with an increase in either *R* or *C*.

This simple *RC* circuit is often used to produce the transient waveform shown, which is called an *exponential-rise transient*.

On discharge, the circuit reacts similarly. For example, if the battery in Figure 1-2a is replaced by a solid conductor, the charged capacitor discharges 63 percent of its charge in *RC* seconds.

The simple *RC* circuit shown in Figure 1-2a symbolizes many real physical situations. It is important to examine the circuit in detail.

In *RC* seconds, the capacitor charges to 63.2 percent of the applied voltage. In the next *RC* seconds, the capacitor charges to 63.2 percent of the remaining voltage, or to 87 percent of the applied voltage. In the third interval of *RC* seconds, the capacitor charges to 95 percent of the applied voltage. Although the capacitor never charges to exactly 100 percent of the applied voltage, it does charge to 99 percent in 4.6 *RC* seconds as shown in Figure 1-3, which is a curve of capacitor voltage (or current) versus time. Note that time is plotted in *RC* (time-constant) units.

## Processes with More Than One Capacity and Resistance

In practice, a process will contain many capacitance and resistance elements. Figure 1-4 illustrates a process containing two resistance elements and two capacitance elements. Figure 1-5 shows the resulting process reaction curve. Note that the additional capacitance and resistance essentially affect the initial curve shape, adding a delay to the process.

## Dead Time

Dead time is a delay between two related actions. For example, assume that the temperature sensor shown in Figure 1-1 was located 10 feet

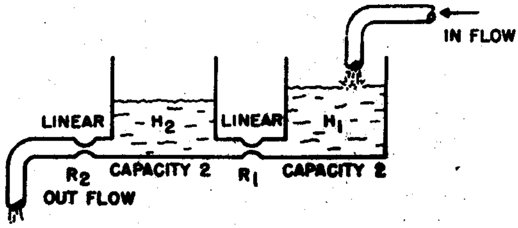



Fig. 1-4. Multicapacity system.

(3.048 m) away from the heat-exchanger. If the liquid travels at a velocity of 10 feet (3.048 m) per second, a dead time of one second will occur. In some process control situations, dead time becomes the most difficult factor in the equation. Dead time may also be called pure delay, transport lag, or distance/velocity lag. Dead time is rarely found in its pure form, but occurs frequently in combination with resistance-capacitance and other types of lags. Dead time is a difficult factor to equate when applying control to the process.

## Measurement

To employ feedback control, we must first measure the condition we wish to maintain at the desired standard. The condition (variable) may be temperature, pressure, flow, level, conductivity, pH, moisture content, or the like.

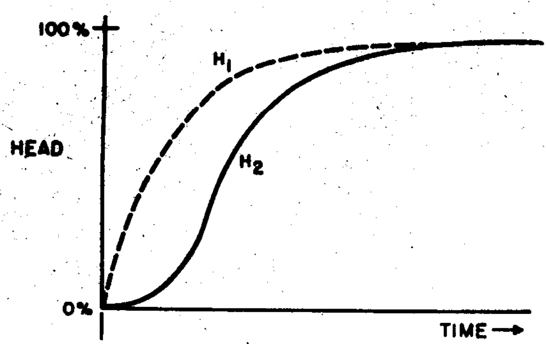



Fig. 1-5. Characteristic curve of multicapacity system.

The measuring element is connected to the control element. In many installations, the measurement is located far from the controller. This problem is solved by using a measuring transmitter (Figure 1-6). The measuring transmitter usually develops an electrical signal for an electronic controller or a pneumatic signal for a pneumatic controller.

Measuring transmitters have attained great popularity in the process industries. They perform the measurement and develop a pneumatic or electric signal proportional to the variable in one unit. This signal can be transmitted long distances. Pneumatic transmitters generally produce an air pressure change of 3 to 15 psi or 20 to 100 kPa (see p. 36 for definition of pascal unit) for measurement change of 0 to 100 per-

Fig. 1-6. Measuring transmitters convert the variable to be measured into a proportional pneumatic or electrical signal.

**Table 1-2. Standard ISA and SAMA Functional Diagram Elements**

| | | | | | |
|---|---|---|---|---|---|
| FT | FLOW TRANSMITTER | $\sqrt{\ }$ | SQUARE ROOT EXTRACTOR | K | PROPORTIONAL CONTROL ACTION |
| LT | LEVEL TRANSMITTER | X | MULTIPLIER | $\int$ | INTEGRAL (RESET) CONTROL ACTION |
| PT | PRESSURE TRANSMITTER | $\div$ | DIVIDER | $d/dt$ | DERIVATIVE CONTROL ACTION |
| TT | TEMPERATURE TRANSMITTER | $\pm$ | BIAS, ADDITION OR SUBTRACTION | f(t) | TIME FUNCTION CHARACTERIZER |
| ZT | POSITION TRANSMITTER | $\Delta$ | COMPARATOR, DIFFERENCE | f(x) | UNSPECIFIED OR NONLINEAR FUNCTION CHARACTERIZER |
| | PANEL LIGHT | $\Sigma$ | ADDER, SUMMER | X.XX | QUOTATION ITEM NUMBER |
| I | INDICATOR | $\Sigma/n$ | AVERAGER | $\ast$ | MOUNTED ON THE FRONT OF PANEL |
| R | RECORDER | $\Sigma/t$ | INTEGRATOR | | REGULATED PROCESS AIR |
| T | RELAY COIL | | NORMALLY OPEN RELAY CONTACT | | NORMALLY CLOSED RELAY CONTACT |
| T | AUTO/MANUAL TRANSFER SWITCH | | MANUAL SIGNAL GENERATOR | A | ANALOG SIGNAL GENERATOR |
| T | TRANSFER OR TRIP RELAY | S | SOLENOID ACTUATOR | M | ELECTRIC MOTOR |
| $>$ | HIGH SIGNAL SELECTOR | | HIGH SIGNAL LIMITER | H/ | HIGH SIGNAL MONITOR |
| $<$ | LOW SIGNAL SELECTOR | | LOW SIGNAL LIMITER | L/ | LOW SIGNAL MONITOR |
| V | VELOCITY OR RATE LIMITER | | HIGH AND LOW LIMITER | H/L | HIGH AND LOW SIGNAL MONITOR |
| A/D | ANALOG TO DIGITAL CONV. | R/I | RESISTANCE TO CURRENT CONV. | R/V | RESISTANCE TO VOLTAGE CONV. |
| mV/V | THERMOCOUPLE TO VOLTAGE CONV. | V/I | VOLTAGE TO CURRENT CONV. | I/V | CURRENT TO VOLTAGE CONV. |
| V/V | VOLTAGE TO VOLTAGE CONV. | P/I | PNEUMATIC TO CURRENT CONV. | P/V | PNEUMATIC TO VOLTAGE CONV. |
| MO | MOTORIZED OPERATOR | I/P | CURRENT TO PNEUMATIC CONV. | V/P | VOLTAGE TO PNEUMATIC CONV. |
| HO | HYDRAULIC OPERATOR | | PNEUMATIC OPERATOR | | STEM ACTION (GLOBE) VALVE |
| f(x) | UNSPECIFIED OPERATOR | | THREE-WAY SELECTOR VALVE | | ROTARY ACTION (BALL) VALVE |

cent; that is, 0 percent of measurement yields an output pressure of 3 psi or 20 kPa, 50 percent of measurement yields 9 psi or 60 kPa and 100 percent yields 15 psi or 100 kPa output. Electronic transmitters produce either voltage or current signal outputs. For instance, the output of analog transmitters is commonly 4 to 20 mA dc.

## Symbols

A set of symbols has been adopted to show instrumentation layouts and to make these layouts more uniform. Once you become familiar with these symbols, it will become easy to visualize the system.

At present, two sets of symbols are in use. One set is provided by the Scientific Apparatus Makers Association (SAMA) and the other by Instrument Society of America (ISA). In this book the ISA symbols will be used where applicable. Figure 1-7 and Tables 1-2 and 1-3 describe the symbols and identification letters often used. If you are involved in the preparation or use of instrument loop diagrams, it is suggested that you obtain the publication that defines the standards employed. A loop diagram must contain the information needed for both engineering and construction. This includes identification, description, connections and location, as well as energy sources.

## The Feedback Loop

The objective of a control system is to maintain a balance between supply and demand over a period of time. As noted previously, supply and demand are defined in terms of energy or material into (the manipu-

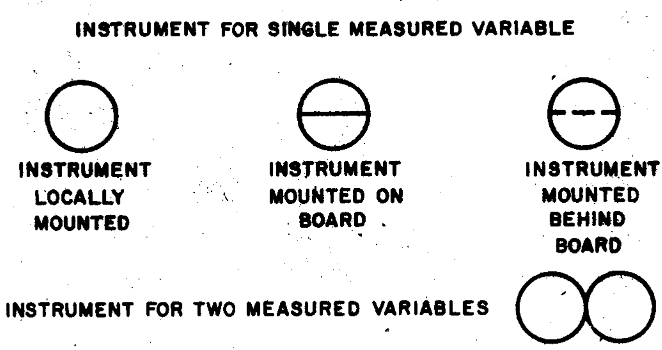



**Fig. 1-7. Instrument for measured variables.**

## Table 1-3. Meanings of Identification Letters

| | *FIRST LETTER* | | *SUCCEEDING LETTERS* | | |
|---|---|---|---|---|---|
| | *Measured or Initiating Variable* | *Modifier* | *Readout or Passive Function* | *Output Function* | *Modifier* |
| *A* | Analysis | | Alarm | | |
| *B* | Burner flame | | User's choice | User's choice | User's choice |
| *C* | Conductivity (electrical) | | | Control | |
| *D* | Density (mass) or specific gravity | Differential | | | |
| *E* | Voltage (EMF) | | Primary element | | |
| *F* | Flow rate | Ratio (fraction) | | | |
| *G* | Gaging (dimensional) | | Glass | | |
| *H* | Hand (manually initiated) | | | | High |
| *I* | Current (electrical) | | Indicate | | |
| *J* | Power | Scan | | | |
| *K* | Time or time schedule | | | Control station | |
| *L* | Level | | Light (pilot) | | Low |
| *M* | Moisture or humidity | | | | Middle or intermediate |
| *N* | User's choice | | User's choice | User's choice | User's choice |
| *O* | User's choice | | Orifice (restriction) | | |
| *P* | Pressure or vacuum | | Point (test connection) | | |
| *Q* | Quantity or event | Integrate or totalize | | | |
| *R* | Radioactivity | | Record or print | | |
| *S* | Speed or frequency | Safety | | Switch | |
| *T* | Temperature | | | Transmit | |
| *U* | Multivariable | | Multifunction | Multifunction | Multifunction |
| *V* | Viscosity | | | Valve, damper, or louver | |
| *W* | Weight or force | | Well | | |
| *X* | Unclassified | | Unclassified | Unclassified | Unclassified |
| *Y* | User's choice | | | Relay or compute | |
| *Z* | Position | | | Drive, actuate or unclassified final control element | |

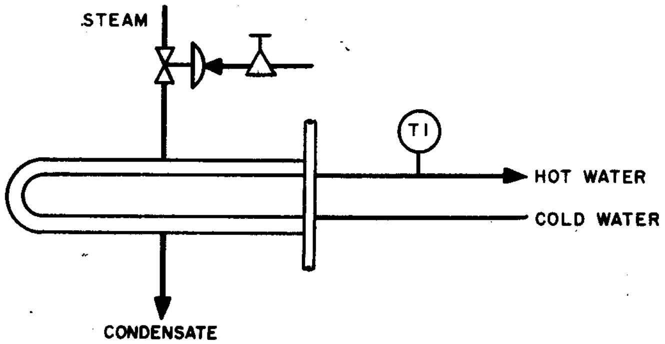



Fig. 1-8. Heat exchanger.

lated variable) and out of (the controlled variable) the process. The closed-loop control system achieves this balance by measuring the demand and regulating the supply to maintain the desired balance over time.

The basic idea of a feedback control loop is most easily understood by imagining what an operator would have to do if automatic control did not exist. Figure 1-8 shows a common application of automatic control found in many industrial plants: a heat exchanger that uses steam to heat cold water. In manual operation, the amount of steam entering the heat exchanger depends on the air pressure to the valve, which is set on the manual regulator. To control the temperature manually, the operator would watch the indicated temperature, and by comparing it with the desired temperature, would open or close the valve to admit more or less steam. When the temperature had reached the desired value, the operator would simply hold that output to the valve to keep the temperature constant. Under automatic control, the temperature controller performs the same function. The measurement signal to the controller from the temperature transmitter is continuously compared to the set-point signal entered into the controller. Based on a comparison of the signals, the automatic controller can tell whether the measurement signal is above or below the set point and move the valve accordingly until the measurement (temperature) comes to its final value.

The simple feedback control loop shown in Figure 1-9 illustrates the four major elements of any feedback control loop.

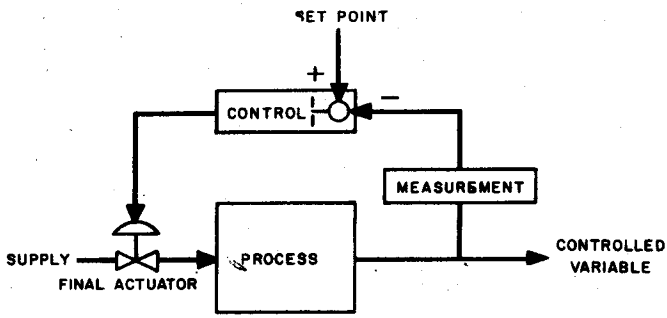



Fig. 1-9. Feedback control loop.

1. *Measurement* must be made to indicate the current value of the variable controlled by the loop. Common measurements used in industry include flow rate, pressure, level, temperature, analytical measurements such as pH, ORP and conductivity; and many others particular to specific industries.
2. For every process there must be a *final actuator* that regulates the supply of energy or material to the process and changes the measurement signal. Most often this is some kind of valve, but it might also be a belt or motor speed, louver position, and so on.
3. The kinds of *processes* found in industrial plants are as varied as the materials they produce. They range from the commonplace, such as loops to control flow rate, to the large and complex, such as distillation columns in the petrochemical industry. Whether simple or complex, they all consist of some combination of capacity resistance and dead time.
4. The last element of the loop is the *automatic controller*. Its job is to control the measurement. To "control" means to keep the measurement at a constant, acceptable value. In this chapter, the mechanisms inside the automatic controller will not be considered. Therefore, the principles to be discussed may be applied equally well to both pneumatic and electronic controllers and to the controllers from any manufacturer. All automatic controllers use the same general responses, although the internal mechanisms and the definitions given for these responses may differ slightly from one another.

One basic concept is that for automatic feedback control to exist, the automatic control loop must be closed. This means that information must be continuously passed around the loop. The controller must be able to move the valve, the valve must be able to affect the measurement, and the measurement signal must be reported to the controller. If this path is broken at any point, the loop is said to be open. As soon as the loop is opened—for example, when the automatic controller is placed on manual—the automatic unit in the controller is no longer able to move the valve. Thus, signals from the controller in response to changing measurement conditions do not affect the valve and automatic control does not exist.

### Feedback Control

Several principles associated with feedback control can be observed by considering a familiar control situation—adjusting the temperature of water in a bathtub. This is obviously a manually controlled system. One hand feels the water in the tub while the other manipulates the inflow to reach the desired temperature. If a thermometer were used to measure the temperature, greater accuracy would result. Improved measurement generally results in improved control.

The bathtub also illustrates the important effect of process capacity. Capacity (Figure 1-2) is a measure of the amount of energy it takes to change a system a unit amount; thermal capacity is Btu/°F, or the amount of heat required to increase the temperature 1°F. Since the bathtub has a large capacity, it can be controlled in any of several ways—by partially filling the tub with cold water, for example, and then adding enough hot water to reach the desired temperature; or by mixing the hot and cold to get the same result.

## Controlling the Process

In performing the control function, the automatic controller uses the difference between the set-point and the measurement signals to develop the output signal to the valve. The accuracy and responsiveness of these signals is a basic limitation on the ability of the controller to control the measurement correctly. If the transmitter does not send an accurate signal, or if there is a lag in the measurement signal, the ability of the controller to manipulate the process will be degraded. At the same time, the controller must receive an accurate set-point signal. In