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# Fundamentals of Process Control, Communication, and Instrumentation

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*The ideal engineer is a composite . . . He is not a scientist, he is not a mathematician, he is not a sociologist or a writer; but he may use the knowledge and techniques of any or all of these disciplines in solving engineering problems.*

N. W. Dougherty

*Engineering is the professional art of applying science to the optimum conversion of natural resources to the benefit of man.*

Ralph J. Smith

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## 3.1 Introduction

There are a number of situations in nature where the principles that govern process control are applied. More specifically, in many human actions, such as walking or putting a spoon to one's mouth, we can define our procedure as measurement, comparison, decision, and action. Such is the case of a person who stumbles and loses his balance; certain ear sensors send information to the brain, which compares that information to the baseline information on what it means to be upright and in balance. Using this comparison, the brain makes decisions to correct the imbalance through the coordinated movement of the limbs. The brain continues to receive information about the situation and keeps moving the limbs until it confirms that the person has recovered equilibrium. In process control, this strategy is called feedback control. Independent of the cause of the imbalance, the brain will take the actions necessary to recover equilibrium.

Throughout history and in nature, we see many examples of feedback control, almost instinctively used by various living creatures. One of the first scientific mechanisms of measurement and control was developed for use in the Watt steam engine. Much later, in the 1940s, industrialization forced companies to increase productivity and maintain optimal performance, which ultimately led to the appearance of the first electronic automatic controllers. This was a historic step where the operator was replaced by a machine. Of course, the first thought was that this would create massive unemployment; however, in the 1960s, data showed that many more and skilled jobs had been created. Furthermore, it was possible to significantly reduce the number of accidents, either by reducing human interaction with dangerous equipment or toxic and hazardous materials. In this way, process control began to emerge as one of the most comprehensive disciplines of chemical and bioprocess engineering.

In the field of process control, most of the techniques that are used to describe processes are applied. As mentioned previously, through basic tools, such as material balances, we can determine

the conditions under which a piece of equipment is able to perform a specific role. The designs are made under certain assumptions, for example, steady state. In such cases, the equipment has a feed mass flow rate equal to the output mass flow rate, so there is no accumulation (steady state). However, changes in the feed flow or in its concentration will result in an imbalance in the process. If no control action is taken to prevent the accumulation or deaccumulation of matter, the equipment will eventually be overloaded or emptied.

Control of the process means mastering the process, maintaining it in peak condition, and keeping it safe for people and equipment. How are processes controlled? How does one detect that a process is out of control? What is a smart way to take control of a process? These are some of the questions to be addressed in this section.

## 3.2 Understanding What Process Control Is

Although it may seem strange, there are certain forms of process control that we execute on a daily basis. Suppose you are taking a shower, in which the flow rate of hot water is fixed, and we can adjust the flow rate of cold water to achieve a pleasant water temperature. Most likely, you would proceed as follows:

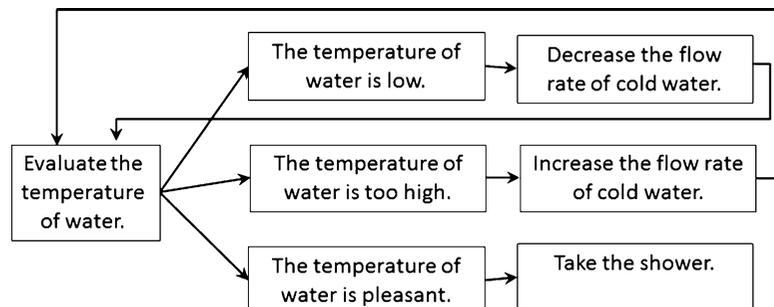
1. Through our skin we are continuously sensing (feeling) the temperature of the water.
2. (a) If the water is warmer than we expect, then we will increase the flow rate of cold water. (b) If the water is colder than we expect, then we will reduce the flow rate of cold water.
3. After changing the flow rate of cold water, given that the skin is constantly sensing water temperature (step 1), then depending on the outcome, we will return to step 2(a) or (b) until we feel a pleasant water temperature.

This procedure could be schematized as depicted in Fig. 3.1.

Using this everyday example, we can identify several elements that constitute a controlled process as follows.

### 3.2.1 Objective of Control

*Creating a pleasant shower.* We start with the target because in this case it is easy to define and evaluate, as it is in many cases. But in some situations, defining the goal, or identifying the desired value, can be a very complex problem. To know what is best involves the resolution of an optimization problem. There are other cases where more than one objective could be involved, and some of them could be in conflict. What if we would like to have a pleasant temperature but also a certain flow rate of water, not too low, not too high? Later, we will revisit such problems (multipurpose or multivariable).



**Fig. 3.1** Schematic representation of the temperature control of the shower

### 3.2.2 Meter

*Skin as temperature meter.* What we did in the shower example was to use our skin directly to see if the water temperature was above or below our feeling of pleasure. The meter is very important: it provides the necessary information for us to take action. Meters are part of what is, by convention, called the instrumentation. Some instruments are capable of measuring a wide variety of magnitudes, such as, for example, temperature, pressure, humidity, and weight. Considering several measurements at different times, the instrument will also provide information on how the system evolves. Later, we will further analyze instrumentation. For now, it should be noted that we are measuring temperature, and the meter is digital (e.g., single digit, 0 or 1, on or off). Since through our skin we cannot know the exact temperature of the water, we just perceive whether the water temperature is higher or lower than the desired pleasant level.

### 3.2.3 The Process to Be Controlled

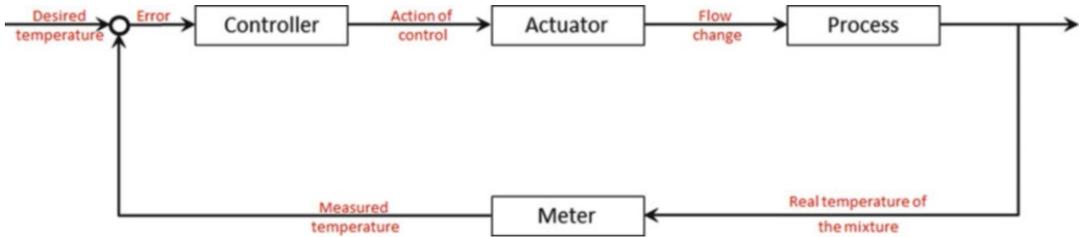
The shower example, although illustrative, is very simple. Real control problems in chemical and bioprocess engineering could range from simple mixers to a large set of reactors/bioreactors, columns, tanks, or other process equipment. In general, transforming a raw material into a finished product often involves several stages of physical, chemical, and biological changes. Also, keep in mind that no matter how complex a process is, it can be addressed using the same fundamental tools, i.e., material balance, energy balance, and the like. With strict effort, discipline, and patience, we will be able to model complex systems.

### 3.2.4 Manipulated Resource

*Flow rate of cold water.* While this flow rate allows us to change the temperature of the water, by convention, it is common to refer to the actuator (valve) rather than the resource (water flow) as part of the control system. This is justified because in practice, we adjust the cold water valve, which, as a result, will change the flow rate of the cold water. We must be clear that while the resource is the flow rate of cold water, it was the water that which was manipulated, by convention called an actuator. Speaking of actuators, we are not only talking about valves: it suffices to mention the case of a fan, which varies the air flow rate to obtain a pleasant temperature.

### 3.2.5 Action of Control

*Increase or decrease the flow rate of cold water.* In this case, the action of control is based on a comparison of the desired pleasant temperature and the temperature of the shower as "measured" by the skin. The element responsible for deciding how much and in what direction the resource will change is called the controller. The controller is the "brain" of any control structure, and in this case our real brain calculates the magnitude of the change, i.e., the flow rate of cold water. The brain processes the information provided by the meter and responds according to its internal configuration. At this stage, we would like to highlight that we have implemented a control strategy called feedback based on the result of a trial-and-error procedure.



**Fig. 3.2** Control loop of the temperature control of the shower

### 3.2.6 Control Loop

The four elements described previously are the main components of what by convention is called a control loop, depicted in Fig. 3.2, as follows:

Observing Fig. 3.2, we see that each component (box) receives information of one nature and delivers information of a different nature, so that it is useful for the next component (box). Walking through the loop, starting from the meter, we note that it is exposed to the process temperature, registers it, then compares it to the desired temperature (or set point). The difference between the two is what we call the error. Then the controller acts on the error, setting the control action. The action could be to open, close, or leave as is the cold water valve. The actuator, in this case the cold water valve, will change according to the action dictated by the controller; this will result in a change in the flow rate of cold water. The process, i.e., the mixture of hot and cold water, receives a different amount of cold water, and thus the mixture will have a different temperature. The meter will record the new temperature, restarting the cycle.

In formal terms, what happens to the information within each block of the control loop is a mathematical transformation that we call a transfer function. Suppose that in the example of the shower, it is not the skin that is used for measuring temperature but a thermometer that is able to deliver the exact temperature of the water. With this assumption, it is easy to explain the transfer function of the comparator (represented by a circle in Fig. 3.2), which is given by the following equation:

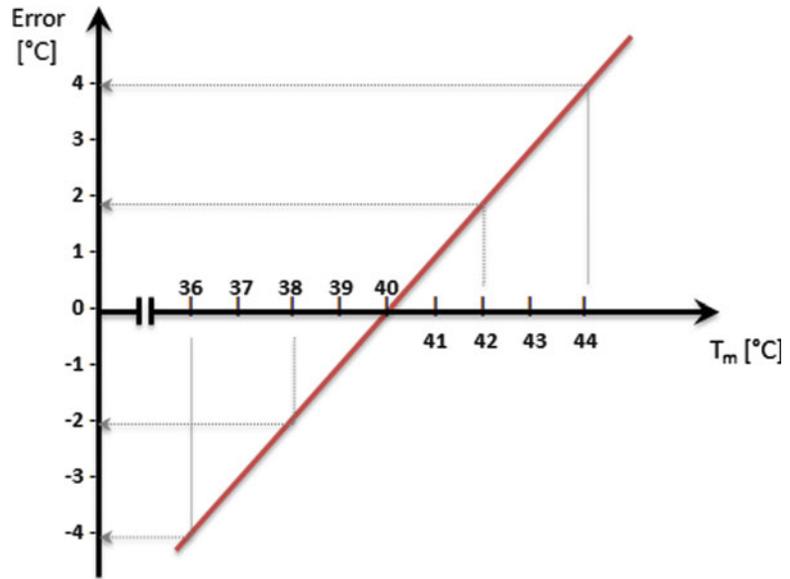
$$e = T_m - T_{SP} \quad (3.1)$$

where  $e$  is the positive feedback temperature error ( $^{\circ}\text{C}$ ),  $T_m$  is the temperature measurement ( $^{\circ}\text{C}$ ), and  $T_{SP}$  is the desired or set point temperature ( $^{\circ}\text{C}$ ).

To understand this more clearly, consider that the desired temperature, the set point, is  $40^{\circ}\text{C}$ . If the measured temperature is  $44^{\circ}\text{C}$ , then the error will be  $44 - 40 = +4^{\circ}\text{C}$ , i.e.,  $4^{\circ}\text{C}$  above the desired temperature (Fig. 3.3). Now, if the measured temperature was  $38^{\circ}\text{C}$ , then the error would be  $38 - 40 = -2^{\circ}\text{C}$ , or  $2^{\circ}\text{C}$  below the desired temperature (Fig. 3.3). In this simple case, it turns out that the transfer function is a straight line, as shown in Fig. 3.3, where the x-axis is the measured temperature and the y-axis is the error. Transfer functions of the other elements of the control loop are a bit more complex; therefore they will be addressed in Chap. 9. As in this example, it is easier to use positive feedback error. However, in practice, it is more common to use negative feedback error, i.e., the set point ( $T_{SP}$ ) minus the measured value ( $T_m$ ).

The strategy of formulating a control problem through a loop has tremendous potential because it is a highly standardized, orderly, and robust procedure to address control problems. It divides a process into elements with clear boundaries and makes it easy to recognize what should work and how to assemble the parts.

**Fig. 3.3** Graphic representation of the temperature error



### 3.3 Instrumentation

Instrumentation refers to all electronic, electrical, mechanical, or any kind of equipment used in a process for control purposes. That is, meters record the state of a process, actuators modify the control resources, and controllers command the action of the actuators.

Consider the case shown in Fig. 3.4, a tank of 10 m height (E-101), which is fed by a flow of water from several production plants. To prevent the tank from overflowing or emptying, we have arranged a control system composed of a level controller (LC-101), a level meter (LT-101), and a valve (LICv-101) that regulates the output flow of water. The chosen notations are not coincidental; the international community has agreed to use a standard symbology for instrumentation to facilitate the transfer of knowledge among different research groups. The international instrumentation notation will be examined in the appropriate section.

The shaded portion of Fig. 3.4 is usually written in summary as indicated on the right-hand side of the figure.

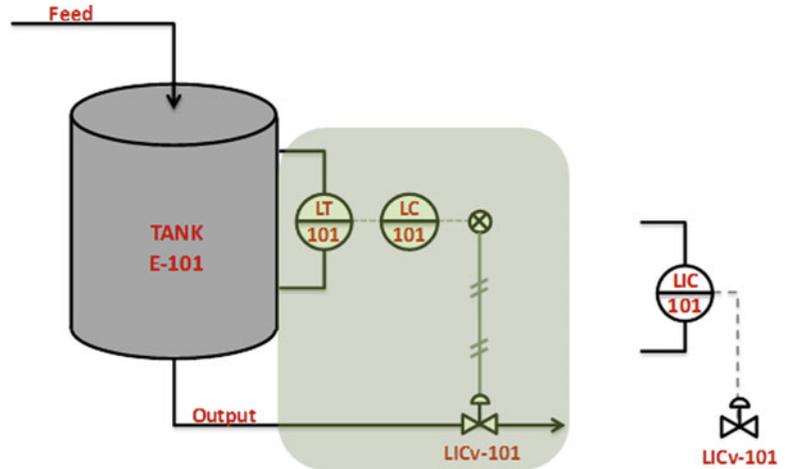
#### 3.3.1 Sensors

The function of meters is to collect information on the current status and progress of a process. In the case of Fig. 3.4, this is the liquid level in the tank. This information (level of the tank) will be used by the controller, the alarm system, or the supervisor to make decisions about the process.

One of the requirements of the meter is to measure the required amounts, which in the case of a level meter for the tank in Fig. 3.4 is to be capable of indicating measurements from 0 to 10 m. The difference between the maximum and the minimum range of work or operation is called the span.

Keep in mind that in this case, the measurement is in the range of 0 to 10 m. In other situations, it may be necessary to measure between 20 and 50 m, in others between 1 and 20 mm. So the question is whether it is necessary to manufacture devices that measure different magnitudes. Sometime a

**Fig. 3.4** Instrumentation of a tank



device can measure in a wide range, for example from 0 to 50 m, but be configured to measure in a desired range.

This is accomplished by setting the zero and the span at the minimum and the maximum values that we are measuring. A critical point is the resolution of the instrument, that is, its ability to identify two measurements as being distinct. For example, let us construct a level meter that delivers its format measurement as 0.0 m, to one decimal place. In addition, it is desired to measure two levels of liquid: the first one 151 cm and the second one 154 cm. If in the first case the meter indicates 1.5 m and in the second measurement 1.5 m, in other words the same measurement, then the meter does not have the resolution to distinguish these two measurements. That is why when selecting a meter, you must consider its working range and its resolution. Finally, it is important to mention that most modern electronic instruments allow you to configure the zero, the span, and the resolution, giving them much greater versatility.

### 3.3.1.1 Accuracy and Precision

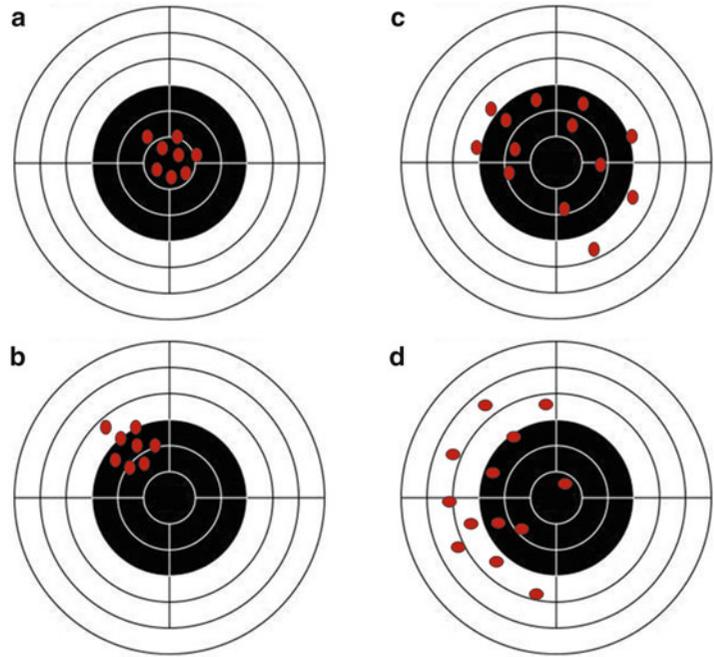
When a physical entity is repeatedly measured, we rarely get the same value for each test. This difference is determined by several factors, some inherent in what is being measured, including by the fact that the measured quantity changes over time. In addition, fluctuations can result from the properties of the meter, such as its precision and accuracy. Precision refers to the dispersion of the values obtained, whereas accuracy means how close the measured value is to the actual value. Examples of groups of accurate or precise measurements are shown in Fig. 3.5.

The most common meters are used to measure temperature, pressure, flow, and level. However, various physical principles allow us to measure, directly or indirectly, the density of a liquid, the concentration of a pollutant in a gas, or the volatility of certain compounds, for example. Tables 3.1, 3.2, 3.3 and 3.4 present descriptions of some devices.

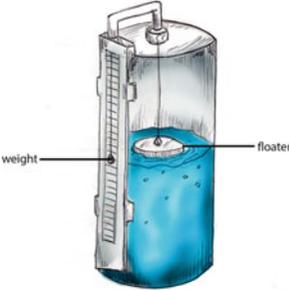
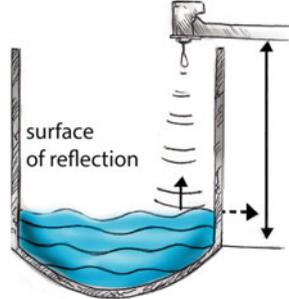
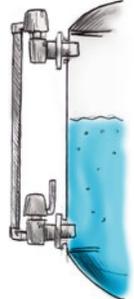
### 3.3.1.2 Biosensors

Recently, the field of bioprocessing has seen the development of a new range of meters called biosensors. These are instruments used to record the presence of biological or chemical agents. They are based on an immobilized enzyme that catalyzes a highly specific reaction and detects what is sought, the catalyzed reaction product. For example, using the urease enzyme, we can detect the presence of urea, and with glucose oxidase/catalase, we can detect glucose. These sensors represent a breakthrough in allowing online measurements and indicate, in real time, the status of a biochemical

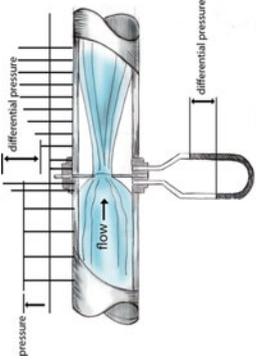
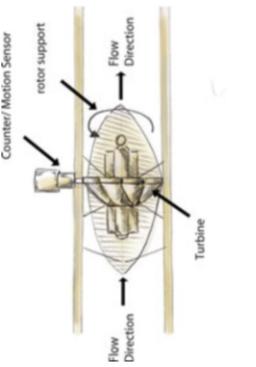
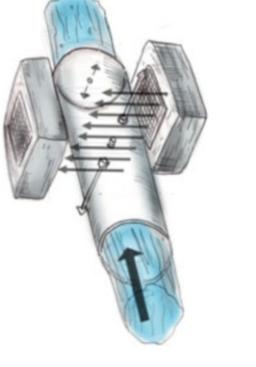
**Fig. 3.5** Examples of types of measurements.  
 (a) Accurate and precise.  
 (b) Inaccurate and precise.  
 (c) Accurate but imprecise.  
 (d) Inaccurate and imprecise



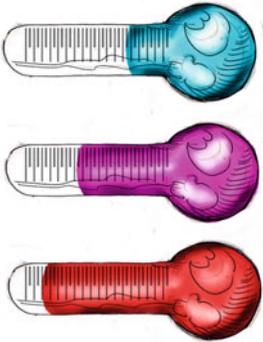
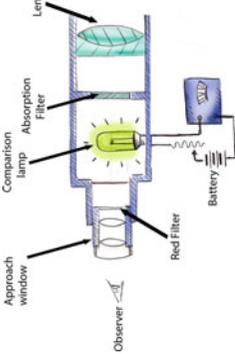
**Table 3.1** Level sensors

Floater	Ultrasonic	DpCell
		
<p>Principle: the floater remains at the liquid surface. It has a rope tied to it and, depending on how full the tank is, will indicate the level on a scale.</p>	<p>Principle: the meter emits an ultrasonic wave that strikes the surface of the liquid and returns to the meter. The level is a function of the time it takes the signal to return to the instrument.</p>	<p>Principle: from fluid mechanics it is known that a column of fluid exerts a pressure equivalent to its height. Measuring the pressure, the level is calculated indirectly.</p>
<p>Comment: there are various ranges of measurements. As shown in the figure, the floater delivers no signal but can be attached to the end of a device that allows the rope to transmit the measurement.</p>	<p>Comment: such meters are expensive, but they deliver a signal and require external power. They can be installed in various ways, including being submerged in liquid</p>	<p>Comment: widely used in the industry. Level is not measured directly, but is very reliable. They can deliver bad measurements if the fluid has a varying density over time.</p>

**Table 3.2** Flow meters

Orifice plate	Turbine	Magnetic
		
<p>Principle: a plate with a hole in the middle is inserted in the pipe through which the fluid passes. The friction on the plate generates a pressure drop in the fluid, making it possible to estimate the average flow.</p> <p>Comment: some orifice plate deliver signals, others not. Generates permanent pressure drops. They are widely used due to their low cost but require intervention on pipes for installation.</p>	<p>Principle: a turbine is inserted in the same direction as the fluid. As the fluid picks up speed, the turbine blades will rotate faster. The flow rate will be a function of the rotational speed of the blades.</p> <p>Comment: turbines are modern and are being increasingly used; they deliver a signal. Pipes should be modified for installation. Different price ranges exist.</p>	<p>Principle: magnetic flow meters are based on Faraday's law, which says that the speed of a conductor is proportional to the voltage induced in a magnetic field. The fluid should be conductive.</p> <p>Comment: they are very expensive but versatile. They deliver a signal and require no intervention on pipes. They have a wide measurement range. Used especially with corrosive fluids.</p>

**Table 3.3** Temperature meters

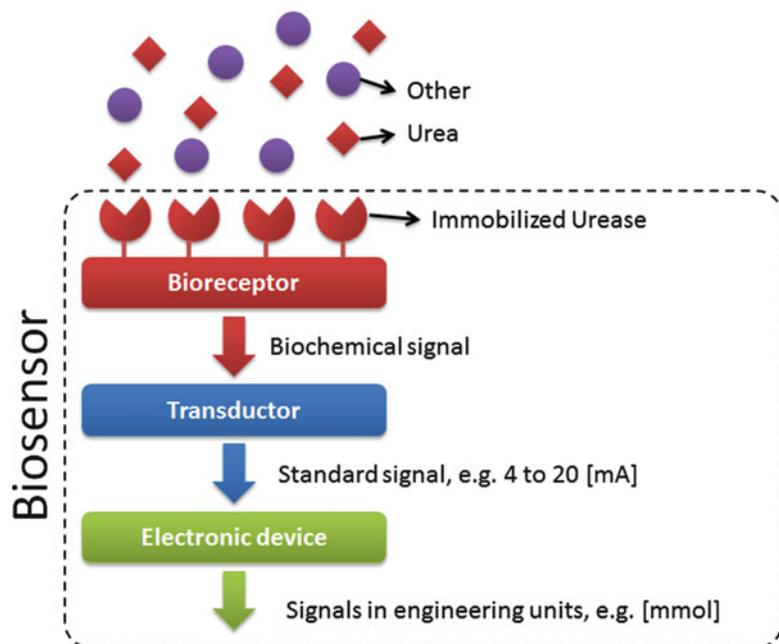
Bulb	Variable resistance	Radiation pyrometer
		
<p>Principle: a sealed tube containing a liquid that significantly changes its volume depending on temperature. The volume is directly related to temperature.</p> <p>Comment: this is a typical home thermometer. It is very cheap but does not deliver a signal. Not used for control purposes.</p>	<p>Principle: this is an electric circuit that has a component with an electrical resistance that varies depending on the temperature. Measuring the electric current it can estimate the temperature.</p> <p>Comment: this is the most commonly used temperature meter in the industry (Pt-100). It has a platinum resistance of 100 ohm at 0 °C. Moderately priced and delivers a signal.</p>	<p>Principle: They are based on the Stefan-Boltzmann law, which relates the radiation from a body with the temperature. By measuring the radiation emitted it can estimate the temperature of the emitting body.</p> <p>Comment: these meters are required not to contact with the medium being measured, are used to measure high temperatures, above 500 °C. The measurement can contain large errors caused by gases or anything between the meter and the element that can shield the radiation.</p>

**Table 3.4** Pressure meters

Bourdon	Piezoelectric	Pressure transmitter
<p>Principle: a Bourdon meter has a tube with a sealed open end, and the other end is open and fixed. The latter end is brought into contact with the fluid, causing a distortion in the free end that is proportional to the pressure.</p> <p>Comment: the Bourdon meter is probably the most widely used meter; it delivers no signal but exists in different ranges and sizes. It is inserted into a line where it will measure pressure. It can be used for gas and liquid pressure.</p>	<p>Principle: a piezoelectric meter has a piece of quartz that changes its electrical resistance when it changes shape. When the quartz is exposed to pressure on one side, it is deformed in proportion to the pressure.</p> <p>Comment: piezoelectric meters deliver signals and have a medium price range. They are capable of measuring from 0.1 to nearly 1,000 bar. Therefore, one of its applications is to detect landslides in mine tunnels.</p>	<p>Principle: pressure transmitters function based on fluid mechanics. It is the same principle as described in differential pressure cells.</p> <p>Comment: pressure transmitters deliver signals but require power. You can set the zero, span, measurement scale and range, and more. They are pricey but very versatile</p>

**Table 3.5** Substances detected by biosensors

Detected substance	Immobilized enzyme	Range mmol/L
Ascorbic acid	Oxidase of Asc. a.	0.05–0.6
ATP	Hexokinase	1–8
Cholesterol	Cholesterol oxidase	0.03–0.15
Ethanol	Alcohol oxidase	0.01–1
Glucose	Glucose oxidase	0.002–0.8
Insecticide (pharation)	Acetylcholinesterase	0.005
Insulin	Antigen immob.	0.1–1 unity/L
Triglyceride	Lipase	0.1–5
Urea	Urease	0.01–500
Uric acid	Uricase	0.5–4

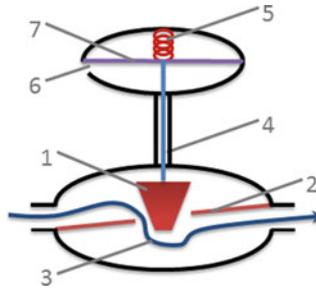
**Fig. 3.6** Schematic representation of the operation of a biosensor

process, measuring and registering properties that previously had to be analyzed in the laboratory, thereby saving much time and money. Table 3.5 presents some substances detected by biosensors.

A biosensor is composed mainly of three parts. A sensitive bed is the tissue culture, enzyme, etc. where the substance detection occurs. A transducer converts the signal produced by the detection in an understandable signal that is quantifiable and measurable by electronic or computer equipment. Finally, the electronic device understands the transducer signal and is able to translate it into engineering units. A scheme of the preceding explanation is shown in Fig. 3.6.

In addition, there are also biothermistors that are used to detect the energy released by a reaction catalyzed by an enzyme. In biotransistors, the product of a catalyzed reaction changes the properties of the electronic device, making it possible to detect the presence of those products.

We must differentiate between two groups of meters, transmitters and nontransmitters. This is one of the most important features of a meter because the value should be reported in a way that is understandable to the controller that will be using the measurement. By convention, the most common way for an instrument to communicate is through a linear electrical signal, which delivers



**Fig. 3.7** Control valve with pneumatic positioner: (1) plug, (2) seat, (3) flow-through, (4) stem, (5) spring, (6) air intake, and (7) diaphragm

4 mA when the instrument is measuring the minimum value and 20 mA when it is measuring the maximum of its span. The choice of the sensor signal when the instrument is measuring the minimum value is not fortuitous: it shows whether the instrument is properly connected since, even if you are measuring the minimum value, it will receive 4 mA. Another standard is 0–5 V, this standard has the disadvantage of not delivering a signal when it is measuring zero and does not have the problem of a current falling through the circuit when they are connected to the instruments and signal contaminations. Instruments that do not deliver a signal are used not to implement automatic control loops but as indicators of not so relevant amounts since they are usually less expensive.

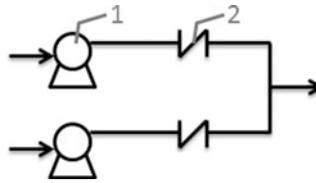
### 3.3.2 Actuators

In processes, by control actuators we mean any mechanism that transforms an electrical signal into a hydraulic or pneumatic change over the process variables, typically material flow. The most common actuators are control valves and servomotors, which execute commands like open, close, or similar operations as indicated by the controller.

Control valves consist essentially of three parts. The valve body is used to obstruct the flow to a desired degree to obtain a specified fluid passage. Figure 3.7 shows a balloon-type valve, where the amount of flow that passes the valve is determined by how far inside the seat the cap is, indicated by numbers 1 and 2.

The valve type is defined by the role it must play within the process. For example, a globe-type valve, as depicted in Fig. 3.7, is commonly used to deliver flows in a continuous range. That is, if the process requires a water flow between 0 and 10 L/s, then the valve must be able to deliver 0, 2, 5, 7 L/s or any number between 0 and 10 L/s. Other valves, such as emergency valves, have only two positions, open and closed, as they seek relief in case of an alarm in the process, removing material from the equipment or adding a fire retardant. Another type of valve with a very specific function is a check valve. In the circulatory system of the human body, there are multiple check valves that prevent blood from flowing through the arteries and veins by gravity in the opposite direction to that desired. Process and bioprocess industries also require check valves. Figure 3.8 shows two pumps operating in parallel. It should be noted that if one pump stops its operation, the fluid may be returned through it. A check valve avoids this undesirable situation.

The position of the plug relative to the valve seat, and therefore the magnitude of the flow, is defined by the rod that is attached to the plug. At the other end of the stem is the valve positioner. Figure 3.7 shows how the rod is connected on one side to the plug and on other side to the positioner, which in this case is pneumatic. Within the positioner there is a flexible diaphragm that divides the



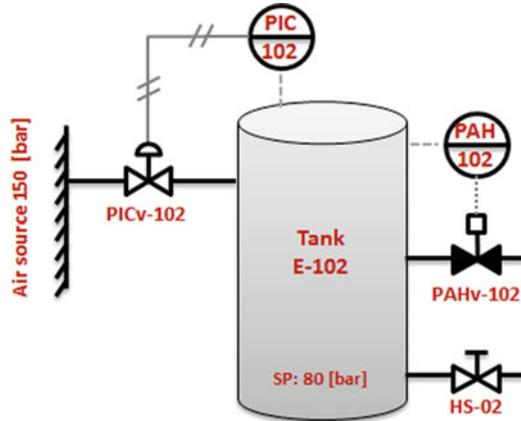
**Fig. 3.8** Arrangement of parallel pumps. 1: Pump. 2: Check valve

positioner into a lower and an upper part. In this case, the lower part has an air inlet, and when the air is injected at a pressure that overcomes the force of the compressed spring across the diaphragm, the spring rises, bringing the stem and, therefore, the plug with it. If because of some defect the air supply to the positioner fails, the spring will not expand, and then the plug will fall completely, thus closing the valve. That is, the valve "closes to failure," but if the air intake was above and the string below the valve, it would "open to failure." This is an important feature within the specifications of the actuator because, depending on the process, under certain failures, some valves should close and others open. International standards indicate that the positioner should be calibrated to be fully open at an air pressure of 3 psig and fully closed at a pressure of 15 psig. Although pneumatic positioners are widely used, when the valves reach large dimensions, for example 2 or 3 m in diameter, it is necessary to use motorized positioners, which differ from pneumatic positioners in that an electric motor moves the stem instead of the assembly, air, diaphragm, and spring.

We can see that the plug transforms the position in a certain flow and the positioner transforms the pneumatic pressure to a certain plug position. But the nucleus of the actuation, i.e., the element that converts the electrical signal of the controller into a physical motion, is the transducer, in this case an I/P transducer. Once the controller has calculated a position for the actuator, it sends an electric current to the transducer, typically from 4 to 20 mA, which transforms it into a pressure between 3 and 15 psig. Commonly, the transducer is part of the valve and therefore is omitted in diagrams, which explains why normal and summary forms (Fig. 3.4) are equivalent. There are cases where the resource to be used is not linked to a valve, as in the case of a fan in a gas pipeline or a pump that delivers a certain flow. In these cases, it is common to use an engine with variable revolutions per minute (rpm), also known as a servomotor. These types of actuators can receive a standard signal from a controller or other similar source.

### 3.3.3 Controllers

Physically, controllers are usually represented by a programmable logic controller (PLC), which is a computer dedicated solely to control tasks. Although sometimes there are special rooms for PLCs, they are usually installed in the field, near the equipment to be controlled, making it essential that they be resistant to shock, dust, electrical noise, and other harsh environments they may be exposed to. Recall that the task of a controller is to use information from sensors to determine the action of the actuators. It does this through logical or mathematical relationships called control algorithms. To understand this logic, we will use Fig. 3.9, which shows an E-102 accumulator tank whose mission is to ensure the availability of compressed air to a process laboratory. Whenever users require compressed air, they connect a hose to the manual valve HS-02 and open it. Because users utilize variable quantities of air, a PIC-102 controller is installed, which reads the pressure inside the tank and commands the PICV-102 valve to fill it. To provide additional security, an alarm is installed (PAH-102) that is scheduled to open the PAHv-102 valve fully if the tank pressure exceeds 100 bar.



**Fig. 3.9** Gas storage tank under automatic control

Starting from a steady state, each time there is a deviation from the desired pressure value inside the tank, the controller will react, calculating a compensating action for that deviation. That is, it will make a change to the current position of the valve based on the error calculated. For this case, we can define the following mathematical expression:

$$c(t) = c_e + \Delta c(t) \quad (3.2)$$

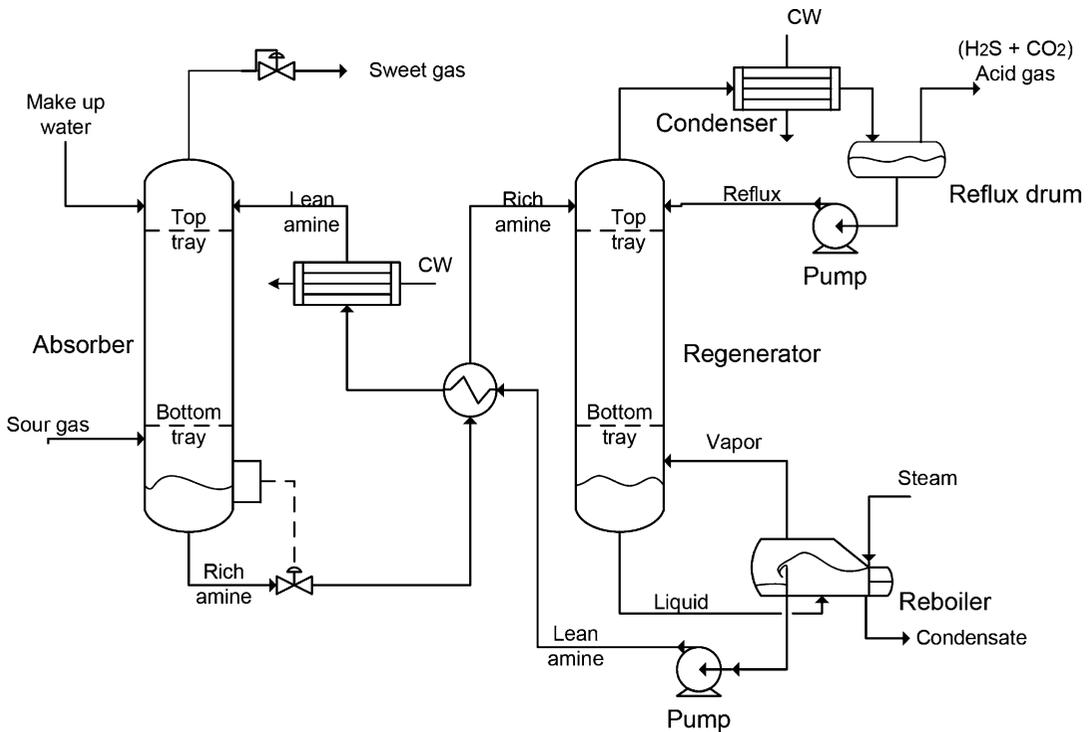
where  $c(t)$  is the actuator position over time (%),  $c_e$  is the position of the actuator at steady state (%), and  $\Delta c(t)$  is the calculated compensatory action taken by the controller (%).

### 3.4 Process Diagrams, PFDs, and P&ID

Chemical and bioprocessing plants may involve tens, even hundreds, of different pieces of equipment. Among these, the most common are tanks, reactors, bioreactors, distillation columns, furnaces, and so forth, as well as minor equipment such as pumps, compressors, and elevators. Even a simple process can involve recirculation, bypass, and derivations of process fluids, aside from electrical power lines and similar electronic signals. Given this complexity, it is not feasible to include all the information of a plant in the same diagram. It is more convenient to generate various functional diagrams, grouping the details of a specific project. It is reasonable to assume that if an electrical failure is detected, the team in charge of repair will want to be clear about the details of all power lines in the plant and may want access to a diagram that does not include all the details of pipelines for liquids and gases and other streams that bear no relationship to electricity.

#### 3.4.1 PFD

The process flow diagram is known by its English acronym, PFD, but it is also known as a flowsheet. It is used by process engineers to indicate the relevant flows and equipment in a processing plant. Minor details are omitted, such as, for example, pipe diameters and heights from the floor. Generally, PFDs contain everything necessary to understand a process and are often accompanied by additional



Typical operating ranges

Absorber: 30 to 50 °C and 5 to 205 atm of absolute pressure

Regenerator: 115 to 126 °C and 1.4 to 1.7 atm of absolute pressure at tower bottom

**Fig. 3.10** A PFD diagram

documents. If necessary, they will include certain relevant elements of the implementation, such as control valves and pumps. An example of a PFD is shown in Fig. 3.10.

It is important that the information contained in a PFD be clear and understandable to all who will need it, so the PFD should be drawn up in conformance with international standards. The most widely used standard is *ISO 10628: Flow diagrams for process plants - General rules*. Some of the most commonly used symbols are depicted in Fig. 3.11.

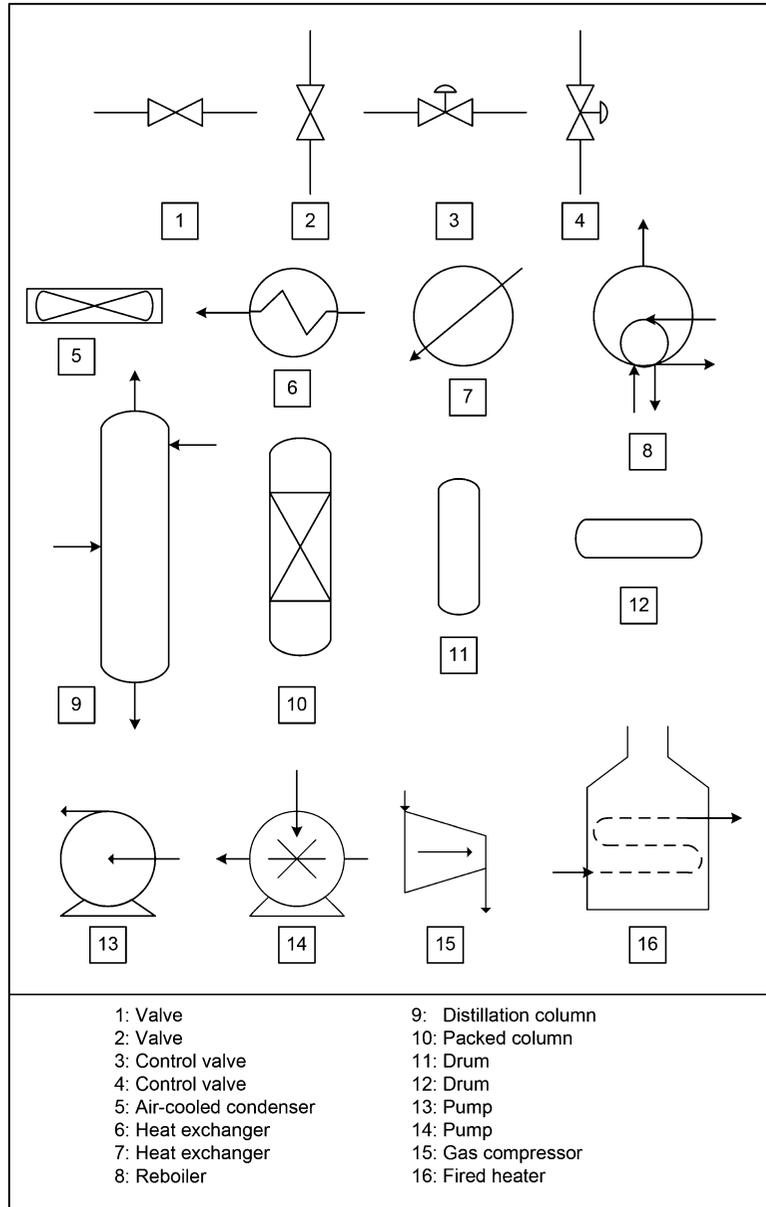
Large databases of PFDs that can be consulted to learn about specific processes. In addition, some commercial versions of computer-aided design (CAD) have ready-to-use embedded symbol libraries.

### 3.4.2 P&ID

This is a diagram that summarizes the instrumentation dedicated to process control, along with its most critical parts. It takes its name from the English term: piping and instrumentation diagram/drawing. It is a bit more complex than a PFD since it includes controllers, actuators, and sensors. An example of a P&ID is shown in Fig. 3.12.

The P&ID plays a vital role in maintaining processes as described. All instrumentation should be reviewed periodically to ensure the functionality of the control and the safety of the systems. Therefore, drawings must be clear and understandable. In such drawings like the PFD, it is preferable to follow the relevant international standards. The most widely used standard is the ANSI/ISA of the

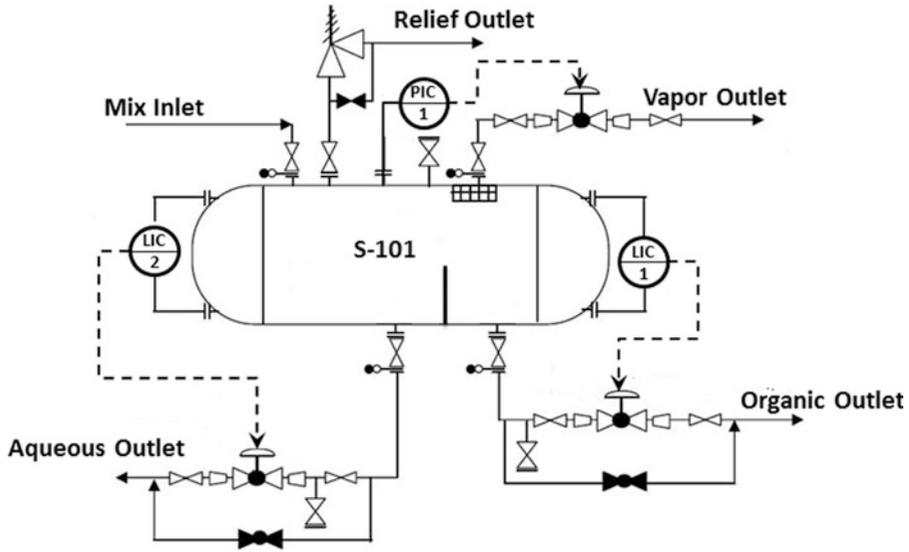
**Fig. 3.11** Most commonly used ISO symbols in PFDs



International Society of Automation, which describes in detail how various types of valves, controllers of all types, gauges, etc., should be represented in diagrams. Figures 3.13, 3.14, 3.15 and 3.16 show some of the symbols used in ANSI/ISA.

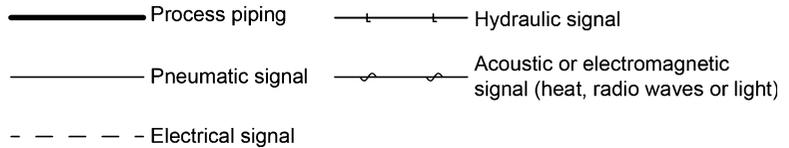
The framework outlined in Fig. 3.12 can contain two, three, or four letters. Most commonly, there are three letters, where the first letter indicates the variable, the second a secondary function, and the third the main function. A description of the most commonly used letters is given in Table 3.6.

Thus, as can be seen in Fig. 3.8, PIC-102 represents the pressure indicator controller number 102, and PAH is a high-pressure alarm number 102. PAHv valve-102 is a normally closed valve, activated by a solenoid that receives an electrical signal, while PICV-102 is a pneumatic valve normally opened with an actuator.

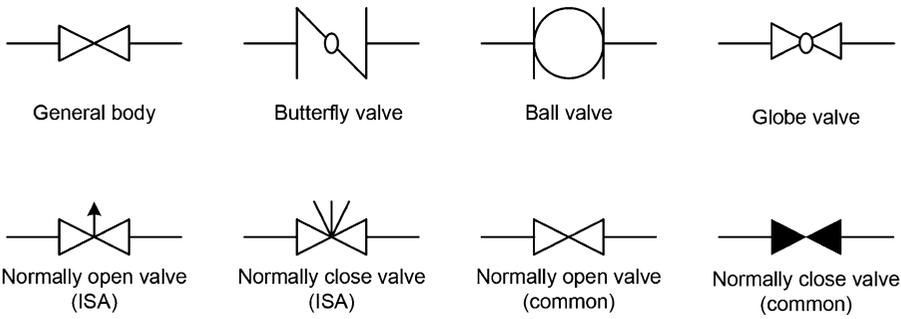


**Fig. 3.12** A P&ID

**Fig. 3.13** Different line representations

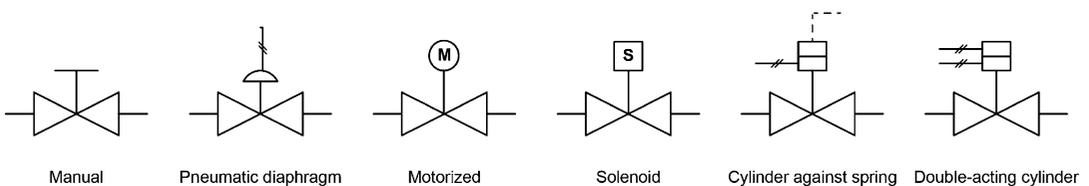


Valve body



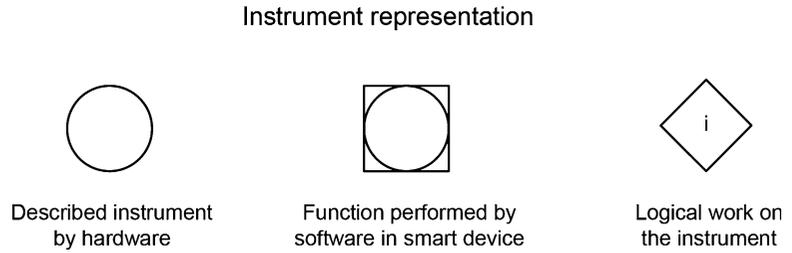
**Fig. 3.14** Different types of valves

Actuators



**Fig. 3.15** Different types of valve actuators

**Fig. 3.16** Representation of sensors and controllers

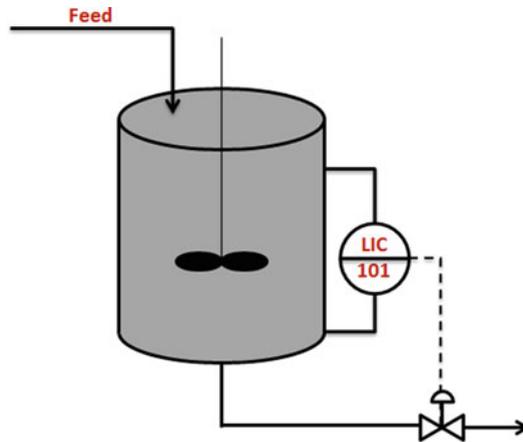


**Table 3.6** Most commonly used letters to describe sensors and controllers

Letter	Position		
	1°	2°	3°
A	Analyzer		Alarm
C	Conductivity		Controller
D	Density	Difference	
F	Flow		
H	Manual		High
I	Current	Indicator	
L	Level		Low
P	Pressure		
S	Speed	Safety	Switch
T	Temperature		Transmitter

### 3.5 Proposed Questions

1. What is the set point of a controller and what should be considered in defining it?  
**A:** The set point is the value you want as a process variable. It must be selected properly to ensure an efficient operating point.
2. What is the most important information in a P&ID and what type of user does it address?  
**A:** A P&ID should contain all elements that explain how a given process is controlled and will depend on the instrument that is being made. It is particularly useful for maintenance engineers, development engineers, and process engineers seeking to diagnose the causes of a process failure or determine why a process is out of control or just looking to improve a process.
3. Suppose that the tank in Fig. 3.17 has a level controller. Then, suddenly the input flow increases twice, and after a while, the tank reaches a new steady-state condition. What will the level be at the new steady state?  
**A:** Because the controller regulates the level and the set point has not been changed, the level will return to the set point, stabilizing the process at the same level prior to the disturbance. In addition, to satisfy the material balance, the input flow must equalize the output flow; therefore, the relief valve will open more as the output flow should be double that of the input flow to maintain the system under steady state.
4. Regarding sensors, what are the precision and accuracy of measurements and why are they important for control?  
**A:** Precision is a measure of the dispersion of values obtained from making the same measurement repeatedly. Accuracy indicates how close those values are, on average, to the actual value they are meant to reflect. Both concepts are important because the control will act based on the state of the process. That information is provided by the sensors. If the sensors are not able to convey accurate information about the process, the control will act incorrectly.



**Fig. 3.17** Control system of a tank

5. Why is it important to use a standard as a guide for identifying the elements of a PFD and P&ID? According to the ANSI/ISA and what is an element identified as TAHL-102?

**A:** It is essential to use standards because, in the face of possible contingencies, process diagrams should be easily understood by anyone consulting them. If standards are not followed, someone might misread the diagrams and not understand in time the steps that need to be taken or the logic behind the process, making decisions difficult. Regarding the identification of the component, the ANSI/ISA norm indicates that the first letter (T) specifies the nature of the measurement, in this case temperature. The second letter indicates that the instrument is an alarm (A) that is activated whenever the temperature exceeds an upper limit (H) or a lower limit (L). The number is the unique identifier of the element.

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- Ullmann, F. *Ullmann's Encyclopedia of Industrial Chemistry*, 7<sup>th</sup> edn. Wiley, New York, 2007. (Only process control chapter)

## Additional Web References

- Principles of Instrumentation and Process Control <http://www.youtube.com/watch?v=vCCc2-qYS2A>
- Basics of BFDs, PFDs, & PIDs [http://www.youtube.com/watch?v=G1\\_iQtvepIg](http://www.youtube.com/watch?v=G1_iQtvepIg)
- How Capacitive Liquid Level Sensors Work <http://www.youtube.com/watch?v=0du-QU1Q0T4>
- Ultrasonic Level Sensor Beam Width Explained <http://www.youtube.com/watch?v=Ie3C9-VmR2g>

Differential pressure level transmitter [http://www.youtube.com/watch?v=Eym\\_D3tGw1E](http://www.youtube.com/watch?v=Eym_D3tGw1E)

The Vortex Flow Measuring Principle <http://www.youtube.com/watch?v=GmTmDM7jHzA>

The Differential Pressure Flow Measuring Principle <http://www.youtube.com/watch?v=oUd4WxjoHKY>

Temperature Measurement Methods. Pyrometers <http://www.youtube.com/watch?v=QgHTeqF-jik>

## **Norms**

ANSI, "Graphical Symbols for Process Flow Diagrams ", ANSI Y32.11, 2003.

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