Open-Ended Problems: A Future Chemical Engineering Education Approach. J. Patrick Abulencia and Louis Theodore.
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9

Process Control and Instrumentation

This chapter is concerned with process control and instrumentation (PCI). As with all the chapters in Part II, there are several sections: overview, several technical topics, illustrative open-ended problems, and open-ended problems. The purpose of the first section is to introduce the reader to the subject of PCI. As one might suppose, a comprehensive treatment is not provided although several technical topics are included. The next section contains three open-ended problems; the authors' solution (there may be other solutions) is also provided. The final section contains 40 problems; *no* solutions are provided here.

9.1 Overview

This overview section is concerned—as can be noted from its title—with process control and instrumentation (PCI). As one might suppose, it was not possible to address all topics directly or indirectly related to PCI. However, additional details may be obtained from either the references provided at the end of this Overview section and/or at the end of the chapter.

Note: Those readers already familiar with the details associated with this subject may choose to bypass this Overview.

Chemical processes can be controlled to yield not only more products but also more uniform and higher quality products, usually resulting in a profit increase. In addition, there are processes which respond so rapidly to change(s) in the system that they cannot be properly controlled by a plant operator; these systems are eligible candidates for some form of automatic control. However, the decision to apply automatic control(s) should be based on an applicable and appropriate cost-effective economic analysis that includes process objectives.

In most modern chemical and petrochemical plants, computers are used for many data acquisition and control operations. Computers can collect data from instruments throughout a plant. The data can be used as input to plant or equipment models in order to provide information to control elements. The data can also be recorded for future analysis. Operators typically watch video display screens which contain information about the plant rather than watch panel boards of actual instruments.

Computer control has led to more optimum control of plants, to better integration of various process units, to make data storage easier, and to provide more up-to-date data for the operators. Complete computer control was slow to be adopted in the 1960's, 1970's and 1980's due to reliability problems, both real and perceived, of the computer systems. Any individual who works extensively with computers knows that interconnected networks often "crash." Highly reliable computer systems with back-up power supplies and data links have been developed for the process industries. In many cases, two fully-redundant systems are installed so that one can be used anytime the other requires service.

In plants using modern computer control, many computers are linked in a hierarchical fashion; single mainframe systems are rarely used. At the lowest level, small *control* computers, with roughly the capability of PCs, are used to record data from and provide control information to individual pieces ot process equipment or small groups of related equipment. These computers are linked to *process unit* computers which contain models of the overall process. Process unit computers periodically send updated instructions to the lower level machines and receive updated process information. The process unit computers throughout a plant are linked to a *supervisory* computer. It periodically provides updated information on such things as feed and product values, inventories, utility system conditions, etc. The *process unit* computers, in turn, provide the supervisory computer with operating information about each unit in the plant.

Full redundancy, either with a second computer system or with conventional control system backup, is needed at the control computer level. The plants can operate for hours at a time, however, if the process unit computers are down, and, perhaps, for days at a time if the supervisory computer is down. Nevertheless, full redundancy is often used since it is relatively inexpensive. Software and training costs are usually greater than hardware costs.

Much of the material to flow has been drawn from the work of Vasudevan [1]; numerous excellent illustrative examples are available in this reference. A number of topics (e.g., Routh criteria for stability, root locus analysis, Bode plots, etc.) are not treated in this chapter. In addition, a decision was made by the authors not to provide any detailed mathematics and complex describing equations. Topics addressed in the remainder of this chapter include the following:

1. Process Control Fundamentals
2. Feedback Control
3. Feedforward Control
4. Cascade Control
5. Alarms and Trips.

As noted above, the reader should note that nearly all of the material in this chapter has been drawn from P. Vasudevan, "Process Control," A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1996 [1]. Also note that Vasudevan's notation has been retained in the presentation.

9.2 Process Control Fundamentals

Automatic control can perhaps be best described via a continuous stirred tank reactor [2] (CSTR) example, as pictured in Figure 9.1. The contents in the reactor are heated to a design temperature by the steam flowing through a heat exchanger, e.g., heating coils [3]. The temperature of the product flow (the variable controlled) and the CSTR mixture are affected by the flow rate and inlet temperature of the reactant(s), the temperature, pressure and flow ratio of the steam, the degree of mixing, and (any) heat losses to the surrounding environment.

Certain process control terms may now be introduced and defined. Figure 9.1 represents an *open-loop* system since the output temperature is not employed to adjust/change any of the reactors variables, i.e., the system cannot compensate/change any of the reactor valuables. A *closed-loop* system is one where the measured value of the temperature (the system variable to be controlled) is used to compensate/change one or more reactor variables, e.g., the system temperature.

In *feedback control* (see Figure 9.2), the temperature is compared to a particular value – often referred to as a *set point* or *design value*. The degree of displacement of the temperature from the set point provides a correction to one of the reactor variables in a manner to reduce the displacement (often referred to as the *error*).

Feedforward control (see Figure 9.3) allows a compensation for any reactor disturbance prior to a change to the controlled variable, i.e., the product temperature. This type of control has an obvious advantage if the controlled variable cannot be measured.

Feedforward and feedback control are often combined (see Figure 9.4) in certain systems.

The employment of *block diagrams* (see Figure 9.5) is the standard method of pictorially representing the controlled system with its variables. The block diagram is obtained from the physical system by dividing it into

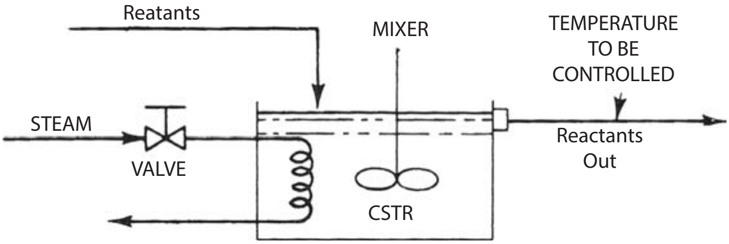

Figure 9.1 Continuous stirred tank reactor.

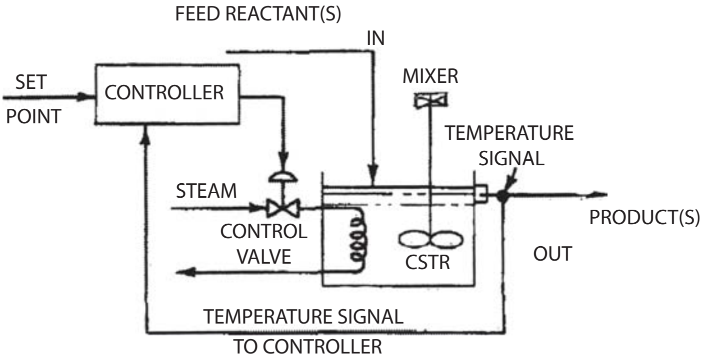

Figure 9.2 Feedback control of a CSTR process.

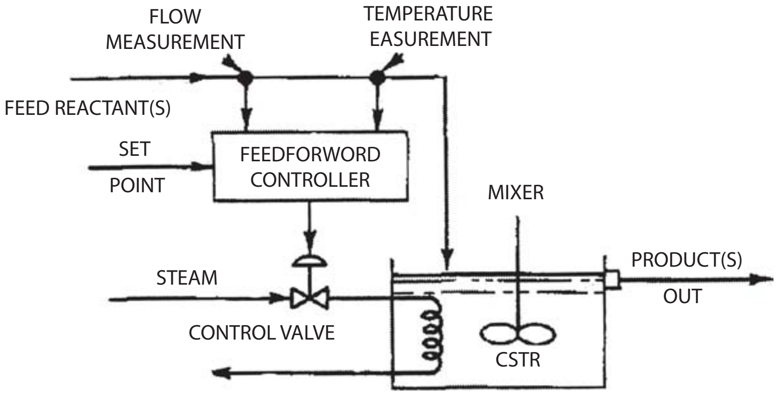

Figure 9.3 Feedforward control of a CSTR process.

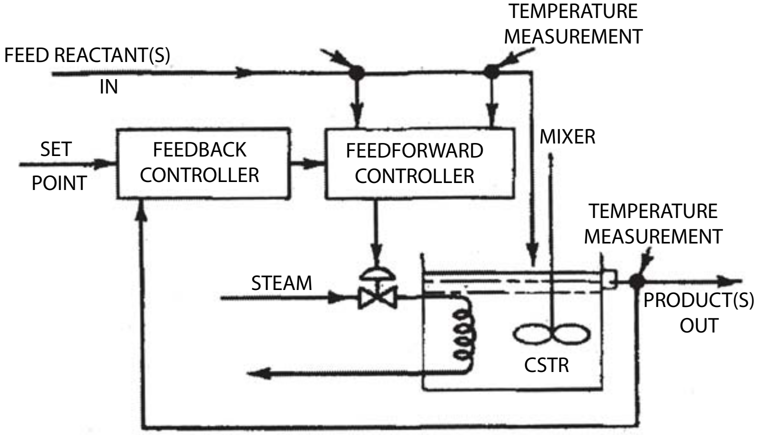

Figure 9.4 Feedforward and feedback control of a CSTR exchanger.

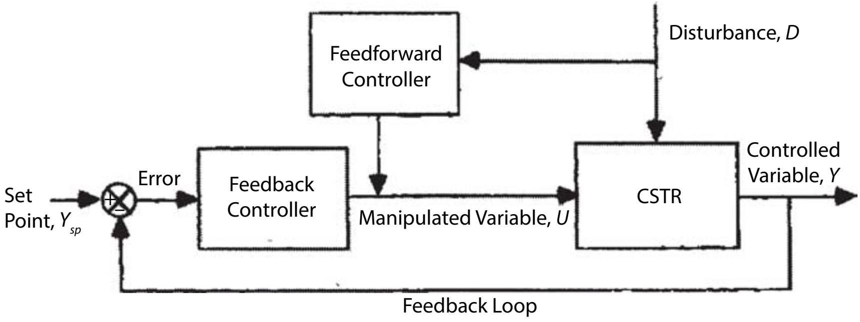

Figure 9.5 Block line diagram for feedforward and feedback control.

functional, non-interacting sections whose inputs and outputs are readily identifiable.

Four parameters that are employed in process control are

1. *Transfer function*
2. *Steady-state gain*
3. *Time constant*
4. *Dead-time or lag.*

These four terms are briefly discussed below:

1. The transfer function relates two variables in a process; one of these is the forcing function or input variable, and the other is the response of the output variable. The input and output variables are usually expressed in the Laplace [4] domain, and are in derivative form.
2. The steady-state gain gives an indication of how much the output variable changes (in the time-domain) for a given change in the input variable (also in the time-domain). The gain is also dependent on the physical properties and operating parameter of the process. The term steady state is applied since a step-change in the input variable results in a change in the output variable which reaches a new steady-state that can be predicted by application of the final-value theorem [1]. Gain may or may not be dimensionless.
3. The process time-constant provides an indication of the speed of the response of the process, i.e., the speed of the output variable to a forcing function or change in the input variable. The slower the response, the larger the time-constant is, and vice versa. The time-constant; with units of time, is usually related to the different physical properties and operating parameters of the process.
4. Process dead-time refers to the delay in time before the process starts responding to a disturbance in an input variable. It is sometimes referred to as *transportation lag* or *time delay*. Dead-time or delays can also be encountered in measurement sensors such as thermocouples, pressure transducers, and in transmission of information from one point to another. In these cases, it is referred to as measurement *lag*.

9.3 Feedback Control

Feedback control is a very important aspect of process control. Its role is best described in terms of an example (see also Figure 9.2). Assume that one desires to maintain the temperature of a polymer reactor at 70°C. Temperature is thus the controlled variable, and the desired temperature level 70°C, is called the aforementioned set-point. In feedback control, the temperature is measured using a sensor (such as a thermocouple device). This information is then continuously relayed to a controller, and a device known as a *comparator*, compares the set-point with the measured signal (or variable). The difference between the set-point and the measured variable is the previously defined error. Based on the magnitude of the error, the controller element in the feedback loop takes corrective action by adjusting the value of a process parameter, known as the *manipulated* variable.

The controller logic (the manner in which it handles the error) is an important process control criterion. Generally, feedback controllers are either *proportional*, P (sends signals to the final control element proportional to the error), *proportional-integral*, PI (sends a signal to the final control element that is both proportional to the magnitude of the error at any instant and the sum of the error), and *proportional-integral-derivative*, PID (sends a signal that is also based on the slope of the error).

In the above example, the manipulated variable may be cooling water flow through the reactor jacket. This adjustment or manipulation of the flow rate is achieved by a *final-control-element.* In most chemical processes, the final-control-element is usually a pneumatic control valve. However, depending upon the process parameter being controlled, the final control element could very well be a motor whose speed is regulated. Thus, the signal from the controller is sent to a final control element which manipulates the manipulated variable in the process.

In addition to the controlled variable, there may be other variables that disturb or affect the process. In the reactor example above, a change in the inlet temperature of the feed or inlet flow rate are considered to be *load* disturbances. A *servo* problem is one in which the response of the system to a change in set-point is *recorded*, whereas a load or regulator problem is one in which the response of a system to a disturbance or load variable is *measured.*

Before selecting a controller, it is very important to determine its action. Consider another example—the heat exchanger shown in Figure 9.6. Steam is used to heat the process fluid. If the inlet temperature of the process fluid increases, an increase in the outlet temperature will result. Since the outlet temperature moves above the set-point (or desired temperature), the

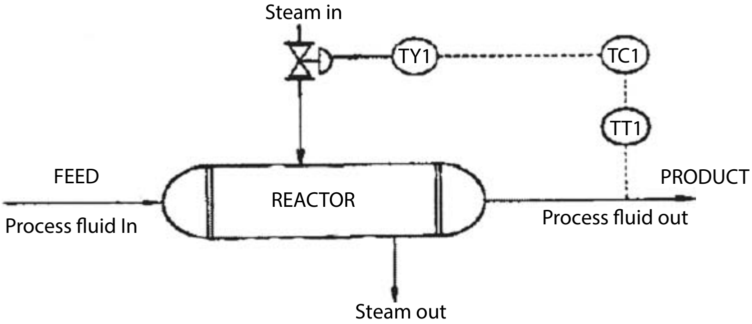

Figure 9.6 Controller actions.

controller must close the steam valve. This is achieved by the controller sending a lower output (pneumatic or current) signal to the control valve, i.e., an increase in the input signal from the controller to the valve. The action of the controller is considered to be *reverse*. If the input signal to the controller and the output signal from it act in the same direction, the controller is *direct acting*.

It is important to consider the process requirements for control to determine the action of the controller and the action of the final control element. The controller action is usually set by a switch on electronic and pneumatic controllers. On microprocessor–based controllers, the setting can be made by changing the sign of the scale factor in the software (which then changes the sign of the proportional gain of the controller).

The functions of a feedback controller in a process control loop is two-fold: (1) to compare the process signal from the transmitter (the controlled or measured variable) with the set point, and (2) to send a signal to the final control element with the sole purpose of maintaining the controlled variable at its set point.

As noted above, the most common feedback controllers are proportionally controllers (P control), proportional-integral controllers (PI control), and proportional-integral-derivative (PID) controllers.

9.4 Feedforward Control

Feedforward control has several advantages. Unlike feedback control, a feedforward control measures the disturbance directly, and takes preemptive action before the disturbance can affect the process. Consider the heated tank example discussed earlier. A conventional feedback controller would entail measuring the temperature in the tank, the controlled variable, and maintaining it at the desired set-point by regulating the heat input, the manipulated variable. In feedforward control, the load disturbances would first be identified, i.e., the inlet flow rate, and the temperature of the inlet fluid. Any change in the inlet temperature, for example, would be monitored in a feedforward control system, and corrective action taken by adjusting the heat input (again the manipulated variable), before the process is affected. Thus, unlike feedback control, the error is not allowed to propagate through the system.

It is clear that a feed forward controller is not a PID controller, but a special computing or digital machine. Good feedforward control relies to a large extent on good knowledge of the process, which is often the biggest drawback. Finally, the stability of a feedforward-feedback system is determined by the roots of the characteristic equation of the feedback loop (feedforward control does not affect the stability of the system) [1].

Vasudevan provides additional developmental material and illustrative examples [1].

9.5 Cascade Control

The simple feedback control loop considered earlier is an example of a Single Input Single Output (SISO) system. In some instances, it is possible to have more than one measurement but one manipulated variable, or one measurement and more than one manipulated variable. *Cascade control* is an example where there is one manipulated variable but more than one measurement. Consider a slight modification of the continuous stirred tank reactor (CSTR) shown in Figure 9.7. The control objective is to maintain the reactor temperature at a set value by regulating the cooling water flow to the exchanger. The load disturbances to the reactor include changes in the feed inlet temperature

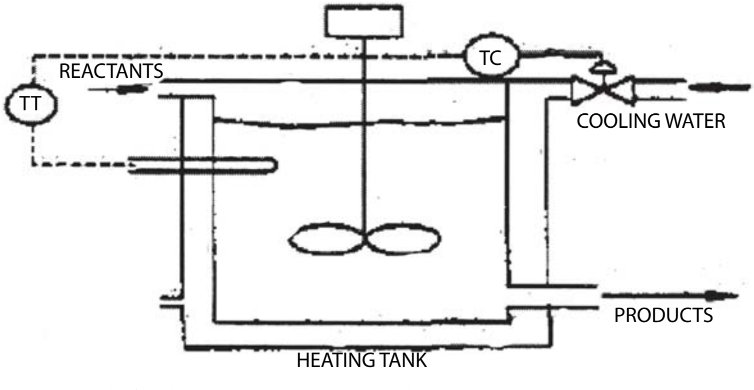

Figure 9.7 Simple feedback temperature control in a CSTR.

or in the cooling water temperature. In simple feedback control, any change in the cooling water temperature will affect the reactor temperature, and the disturbance will propagate through the system before it is corrected. In other words, the control loop will respond faster to changes in the feed inlet temperature compared to changes in the cooling water temperature.

Now consider the following example. In this case, any change in the cooling water temperature is corrected by a new controller added to the process control loop before its effect propagates through the reaction system. These are two different measurements – reaction temperature and cooling water temperature, but only one manipulated variable (cooling water flow rate). The loop that measures the reaction temperature is known as the *primary* control loop, and the loop that measures the cooling water temperature, the *secondary* control loop. The secondary control loop uses the output of the primary controller as its set-point, whereas, the set-point to the primary controller is supplied by the operator. Cascade control has wide applications in chemical processes. Usually, flow rate control loops are cascaded with other control loops.

9.6 Alarms and Trips

Alarms are used in process plants to inform operators that plant conditions are outside of the normal operating range. Trips are devices which sense operation outside of normal range and automatically shut off or turn on some device. Alarms are used when the time constants involved are large enough for an operator to make adjustments to the process and return it to normal conditions. Trips are used when process time constants are very short and immediate action may be needed to prevent a disaster. As might be expected, complex plants may have several different priority levels of alarms and trips.

An everyday example of an alarm would be a high-temperature warning light on the dash board of a car. If it goes on, it indicates that there is a problem and the driver should do something about it. If a trip were installed here, it would shut off the motor when a certain high temperature point was reached. Household gas water heaters have trips on the fuel supply linked to a temperature element which senses whether the flame has gone out.

A detailed and expanded treatment of process control and instrumentation is available in the following two references:

1. P.T. Vasudaven, *Process Dynamics and Control*, A Theodore Tutorial, Theodore Tutorials, East Williston, NY, originally published by the USEPA/APTI, RTP, NC, 1996 [1].

2. L. Theodore, *Chemical Engineering: The Essential Reference*, McGraw-Hill, New York City, NY, 2014 [5].

9.7 Illustrative Open-Ended Problems

This and the last section provide open-ended problems. However, solutions *are* provided for the three problems in this section in order for the reader to hopefully obtain a better understanding of these problems which differ from the traditional problems/illustrative examples. The first problem is relatively straightforward while the third (and last problem) is somewhat more difficult and/or complex. Note that solutions are not provided for the 39 open-ended problems in the next section.

Problem 1: Discuss the solution of linear differential equations using Laplace transforms, particularly as they apply to process control.

Solution: There are three basic steps involved in the solution of ordinary differential equations using Laplace transforms.

1. The first key step is to take the Laplace transform of the differential equation by applying the real differentiation theorem. This transforms the differential equation into an algebraic equation.
2. The algebraic equation is then rearranged in such a way that the output variable, $Y(s)$, is expressed as a function of the input variable, or forcing function, $X(s)$.
3. The resulting equation is inverted in order to obtain the output variable, $Y(t)$, in the real time-domain.

One of the problems associated with Laplace transforms is that they can only be applied to linear systems. The dynamic control responses of most industrial processes is non-linear. However, it is possible to linearize the equations describing a non-linear process.

Refer to Chapter 23, Illustrative Open-ended Problem 3 for additional details.

Problem 2: Process instruments and control devices make up the nerve system, or the "brains" of chemical or petrochemical plant. Control systems consist of sensing devices, models, and control elements. *Sensing devices* measure such things as temperature, flow rate, pressure, composition, level height, etc. *Models* consists of information about how a plant is expected to operate. They may be as simple as individual temperature or flow rate set points, or as complex as dynamic computer models of whole process units. *Control elements* are the actual devices that adjust the conditions of a plant, such as valves or speed controls on rotating machinery.

Standard symbols are used on process flow diagrams and piping instrumentation diagrams to represent various elements of control systems. They consist of small circles, or "bubbles," with key initials inside. List some of the most common initials.

Solution: Most of the initials are concerned with sensing devices and functions. Some of the more common ones are listed below:

Sensing devices:

F	Flow rate
FQ	Integrated flow rate
L	Level
P	Pressure
PD	Pressure difference
pH	pH (-$\log_{10}$ of hydrogen ion concentration)
S	Speed
T	Temperature
W	Weight
X	Chemical composition

Functions:

A	Alarm
AH	Alarm, high reading
AL	Alarm, low reading
C	Controller
I	Indicator
R	Recorder
S	Switch
V	Valve

Problem 3: Describe the role several forcing functions play in process control.

Solution: Commonly encountered forcing functions (or input variables) in process control are step-input (positive or negative), pulse function, impulse function and ramp function. For example, consider a step-input of magnitude 1. The step-function may be represented by $u(t)$, where

$$u(t) = 1 \text{ for } t \geq 0$$

and

$$u(t) = 0 \text{ for } t > 0$$

Substituting the value of this function into the definition of the Laplace transform and solving yields

$$L(u(t)) = 1/s$$

Now consider a rectangular pulse whose magnitude is *H* and duration is *t* units of time. In the time interval $0 \leq t < T$, the function $f(t) = H$. When $t < 0$ or when $t > T$, the function $f(t) = 0$. Substituting the value of the pulse function into the definition of the Laplace transform, and integrating between the limits 0 to *T* yields:

$$L(f(t)) = F(s) = H/s\left(1 - e^{(-T_s)}\right)$$

It is very important for the chemical engineer to understand how a system responds to various forcing-functions. The forcing functions considered above can be used in a number of examples. The effect of a delay in time is also important since processes generally experience a time-lag or 'dead-time.'

9.8 Open-Ended Problems

This last section of the chapter contains open-ended problems as they relate to process control and instrumentation. No detailed and/or specific solution is provided; that task is left to the reader, noting that each problem has either a unique solution or a number of solutions or (in some cases) no solution at all. These are characteristics of open-ended problems described earlier.

There are comments associated with some, but not all, of the problems. The comments are included to assist the reader while attempting to solve the problems. However, it is recommended that the solution to each problem should initially be attempted *without* the assistance of the comments.

There are 40 open-ended problems in this Section. As stated above, if difficulty is encountered in solving any particular problem, the reader should next refer to the comment, if any is provided with the problem.

The reader should also note that the more difficult problems are generally located at or near the end of the section.

1. Describe the early history associated with process control.
2. Discuss the recent advances in process control technology.
3. Select a refereed, published process control article from the literature and provide a review.
4. Provide some normal everyday domestic applications involving the general topic of process control.
5. Develop an original problem that would be suitable as an illustrative example in a book on process control.
6. Prepare a list of the various books which have been written on process control. Select the three best and justify your answer. Also select the three weakest books and, once again, justify your answer.
7. Discuss the advantages and disadvantages of employing process control in the chemical industry.
8. Discuss the advantages and disadvantages of employing instrumentation in the chemical industry.
9. Discuss the role measurement plays in process control.
10. Discuss the advantages and disadvantages of computer process control of plants.
11. Describe and discuss the difference between instrument accuracy and precision.
12. Discuss the general subject of control stability from both a technical perspective and a layman's perspective.
13. Describe the differences between an alarm and a trip. Also provide an everyday example of both.
14. Describe how a pneumatic control element works.
15. Provide a list of the common initials/abbreviations that are employed for a variety of sensing devices and functions.
16. Discuss the role instrumentation flow sheets play in process control.
17. Describe the difference between open and closed loop systems.
18. Provide a technical description of feedforward control.
19. Provide a technical description of feedback control.
20. Provide a layman's definition of feedforward and feedback control.
21. Describe the role block diagrams play in process control.

22. Discuss the difference between process control and instrumentation.
23. Provide definitions for proportional, reset, response lag, and tuning.
24. Discuss the advantages and disadvantages of feedforward control.
25. Discuss the advantages and disadvantages of feedback control.
26. Discuss the role that location plays in process control.
27. List all the process variables that you believe can be controlled.
28. List all the process variable that you believe cannot be controlled… and explain why.
29. Rank (and justify) the order of importance of controlling various process variables.
30. Is it possible to develop a multi-purpose controller? Explain your answer.
31. Discuss the role of (process) control as it applies to heat exchangers.
32. Discuss the role of (process) control as it applies to fluid flow systems.
33. Discuss the role of (process) control as it applies to mass transfer equipment, e.g., distillation columns.
34. Discuss the role of (process) control as it applies to chemical reactors.
35. Discuss the role of (process) control as it applies to drying operations.
36. Which operation in the chemical process industries is most significantly impacted by process control. Justify your answer.
37. Develop an experiment for a Unit Operations Laboratory that would (best) illustrate the role of process control.
38. A controller is *not* operating according to norm. Indicate what steps you would take before purchasing a new unit.
39. As noted in the Overview, trips and alarms are used extensively in chemical and petrochemical processing plants. A "trip" is an automatic control function, typically the opening or closing of a particular valve or the turning on or off a device such as a pump. Trips are used when a very rapid response is needed when a process upset occurs. An alarm is usually an audible and/or visual signal to the operator in

the control room that something is not proper. Alarms are used when a process is drifting away from normal conditions, but there is still adequate time for a human operator to make adjustments and/or shut the process down. Discuss these two factors in layman terms.

40. Logic diagrams, similar to computer program flow charts, are often used to lay out trip and alarm systems. They graphically illustrate what must be built into the control system hardware and software. Lay out a logic diagram for the temperature controller on an exothermic continuous stirred tank reactor. The system should have the following characteristics:
    a If the reactor temperature is below the set-point, T_s, reduce the coolant flow.
    b If the reactor temperature is above the set-point, T_s, increase the coolant flow.
    c If the reactor temperature exceeds the first limit, T_1, sound an alarm in the control room. (ALARM)
    d If the reactor temperature exceeds the second limit, T_2, shut off the feed to the reactor. (TRIP)
    e If the reactor temperature exceeds the third limit, T_3, sound a high priority alarm in the control room. (ALARM)

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