PROCESS CONTROL SYSTEMS

10

LEARNING ACTIVITY PACKET

CONTROL LOOP PERFORMANCE

AMATROL

INTEGRATED SYSTEMS TECHNOLOGY

B270-XD

CONTROL LOOP PERFORMANCE

INTRODUCTION

Performance is a primary concern in any industrial process. The performance of a process is defined by the response of the system to disturbances (e.g. does the PV return quickly to the SP after a disturbance). If the response is not what is desired, the performance of the process suffers.

There are many factors that can affect the performance of a process. Most of them fall into two basic categories: physical component characteristics and programming. This LAP covers these factors and what can be done to minimize their effects on the performance of a process.

ITEMS NEEDED

Amatrol Supplied
- 1 T5552 Process Control Learning System

School Supplied
- 1 Water Supply (10 Gallons)
- 1 Compressed Air Supply

FIRST EDITION, LAP 10, REV. A

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SEGMENT 1

RESOLUTION

OBJECTIVE 1 DEFINE CONTROL LOOP OPTIMIZATION AND EXPLAIN ITS IMPORTANCE

Read This

Control loop optimization is the process of ensuring that all loop components are selected and configured to provide the desired system response. In temperature control systems, the desired response involves maintaining the process variable (PV) at or near a particular setpoint (SP).

For example, consider a temperature control system for which the desired response is a quick reaction to disturbances and accurate control of the temperature. After a disturbance, the system should have a short transient state where the PV quickly returns to the SP. In addition, the system should accurately maintain the set point in steady state, as figure 1 shows.

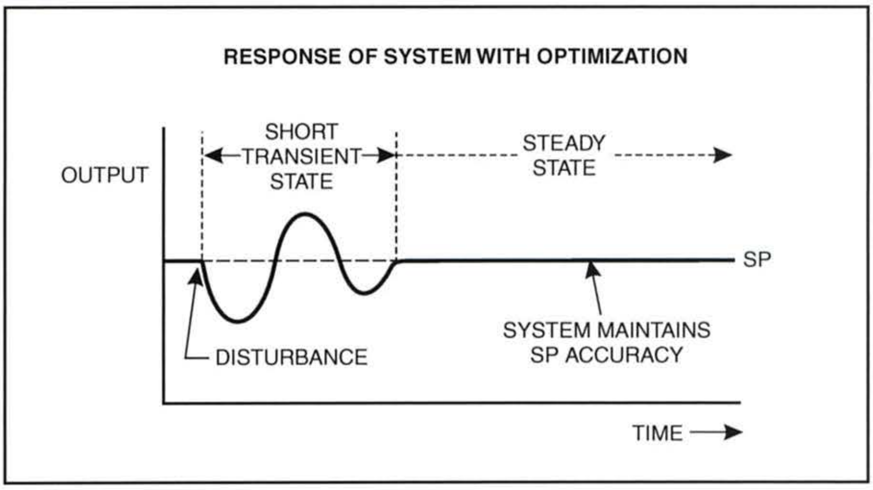

Figure 1. Optimal Desired System Response

If the loop is not properly optimized, the system may not react quickly to disturbances or accurately maintain the process variable at the SP, as figure 2 shows.

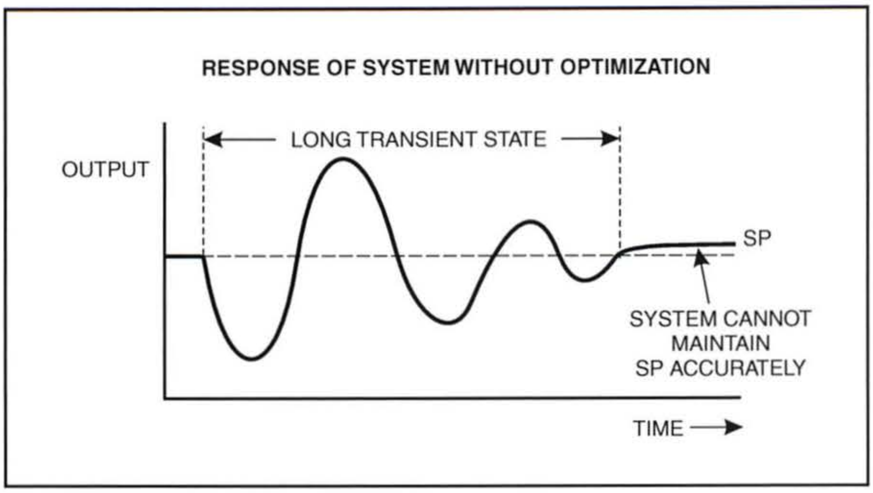

Figure 2. System Response Without Optimization

The process of optimization is composed of two basic parts:

- **Physical -** The physical part of optimization involves making sure that the process instruments have the needed performance characteristics to achieve the desired system response. Two of the most important performance characteristics that are contained in the instrument specifications are resolution and accuracy. More is discussed about these characteristics later.
- **Programming -** The programming part of optimization involves making sure the controller settings are sufficient to control the process as desired. This action is referred to as tuning. More about tuning is discussed later as well.

It is estimated that 70-80% of process control loops are not optimized due to initial cost or time concerns. This is unfortunate because optimizing the control loop reduces operating costs, increases efficiency, and extends the life of the process instruments.

For example, a control valve, like the one shown in figure 3, is the component in most control loops that physically controls the process. Optimization reduces the amount of cycling and therefore wear on the valve, making the process more efficient and extending the life of the valve. This is extremely important since the valve is often one of the most expensive instruments in the loop.

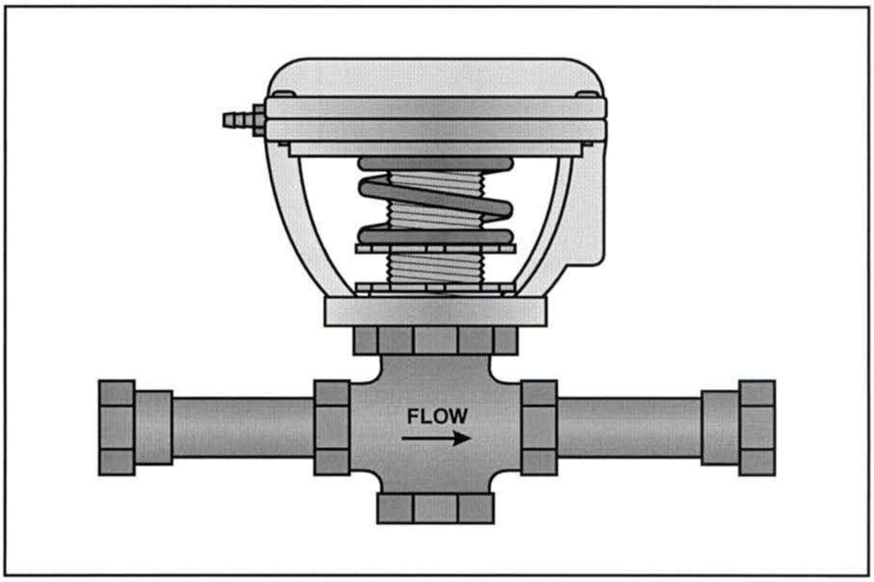

Figure 3. A Control Valve

OBJECTIVE 2 DEFINE INSTRUMENT RESOLUTION AND EXPLAIN ITS IMPORTANCE

Resolution is the smallest distinguishable interval between two measurements or values. When applied to process instruments, resolution describes the smallest interval an instrument can sense or control.

For example, suppose a controller has an input resolution of 1 mV, as figure 4 shows. An input change of 0.5 mV does not cause the controller to change its output because it is not sensitive enough to sense the 0.5 mV change. However, if the input change is 1 mV or more, the controller will change its output.

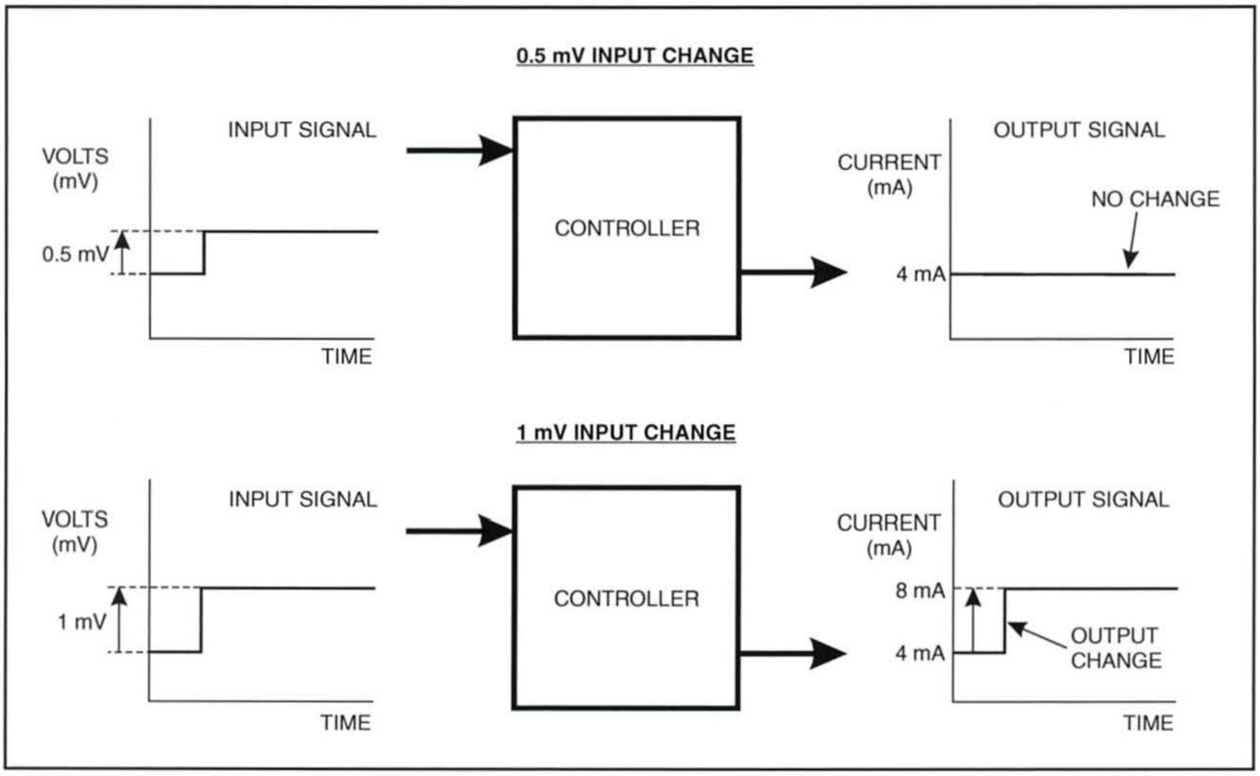

Figure 4. Impact of Resolution

Resolution is important because it identifies how closely a process can hold the process variable to the desired setpoint (the overall accuracy of the process). For example, if the process must maintain the temperature within one-half of a degree, but the resolution of the temperature sensor only allows a sensitivity of one degree, the controller cannot determine if the temperature is truly within one-half of a degree of the setpoint.

OBJECTIVE 3 DESCRIBE HOW TO CALCULATE INSTRUMENT RESOLUTION IN UNITS OF THE MEASURED PARAMETER

Read This

Since the resolution of an instrument is often influenced by the range of measurement, many instrument manufacturers give their span and the points of resolution. With this information, the resolution for the given span is calculated using the following formula:

FORMULA: CALCULATE THE RESOLUTION FOR A GIVEN SPAN

$$R_{mp} = \frac{Sp}{Res}$$

Where:

R_{mp} = *Resolution in Units of Measurement Parameters*
Sp = *Span*
Res = *Instrument Resolution*

It is important to be able to identify and use this information when replacing process instruments so that the replacement meets or exceeds the required resolution.

Example - Determine the resolution of the temperature sensor in figure 5 given the following information:

Span = 5° C

Resolution = 5 points

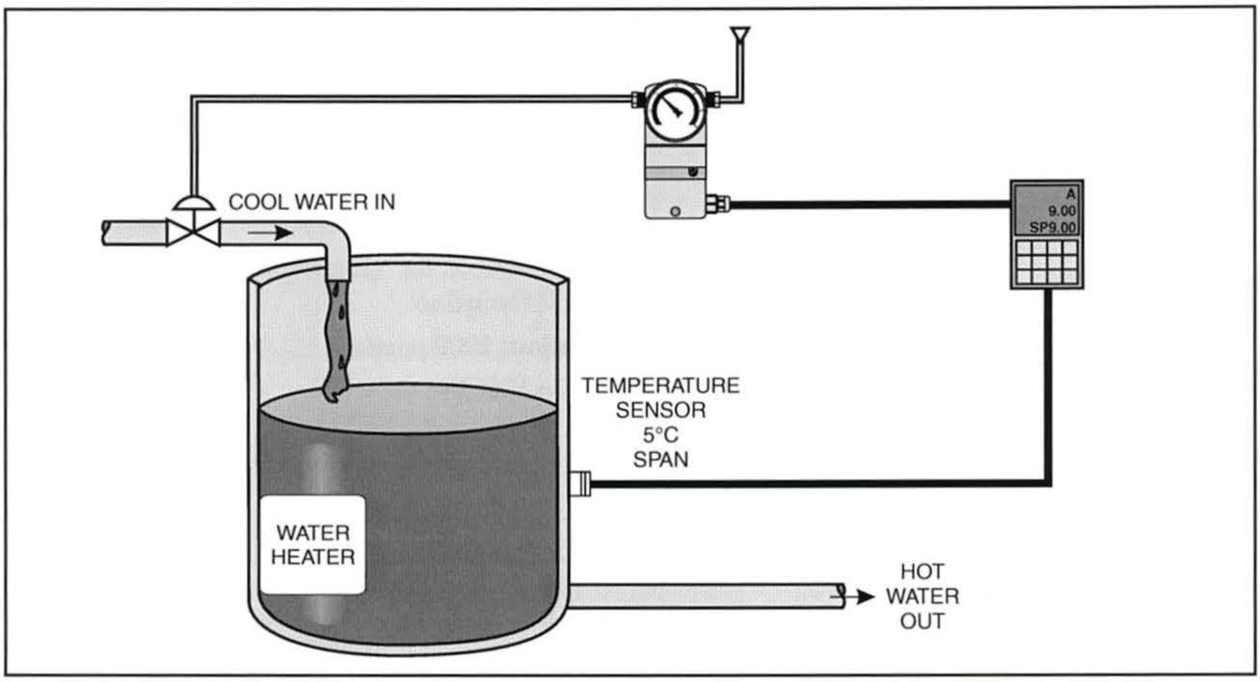

Figure 5. Temperature Sensor with a Span of 5° C and a Resolution of 5 Points

The solution is as follows:

$$R_{mp} = \frac{Sp}{Res}$$

$$R_{mp} = \frac{5^\circ C}{5}$$

$$R_{mp} = 1^\circ C$$

Therefore, the smallest measurable interval for the instrument is 1°C.

SKILL 1 CALCULATE RESOLUTION IN UNITS OF THE MEASURED PARAMETER

Procedure Overview

In this procedure, you will determine the span of a process given its range. You will then use the calculated span and the instrument resolution to determine the resolution in terms of the measured parameter.

❑ 1. Determine the resolution of the temperature sensor in figure 6 given the following information:

Instrument Resolution: 1000 points

Process Range: 0° to 100° F

Span ____________________

Resolution____________________

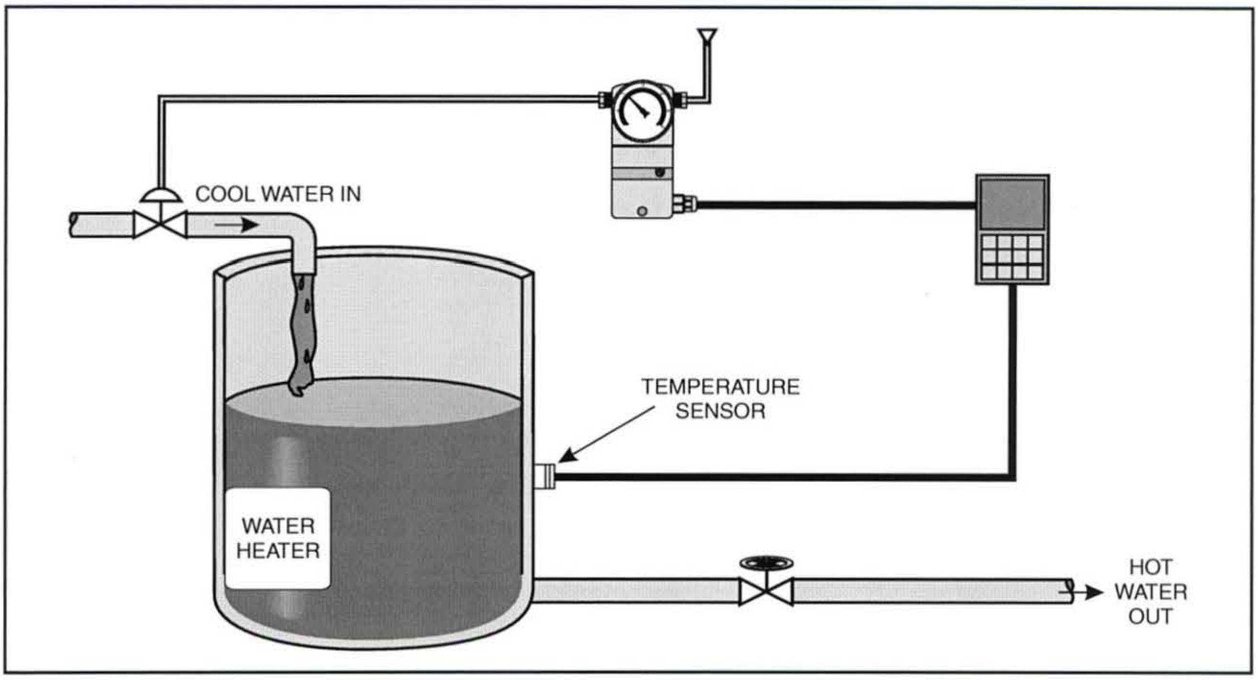

Figure 6. Temperature Sensor with a Range of 0°F to 100°F

You should find that the span is 100°F and resolution is 0.1° F (100/1000 = 0.1).

This means that the smallest change in temperature that this instrument can detect is one tenth of a degree.

❑ 2. Determine the resolution of a pressure sensor given the following information:

Instrument Resolution: 500 points

Process Range: 100 to 350 psi

Span ______________________________

Resolution ______________________________

You should find that the span is 250 psi and the resolution is 0.5 psi.

❑ 3. Determine the resolution of a flow control process, based on the following information:

Instrument Resolution: 500 points

Process Range: 25 to 110 GPM

Span ______________________________

Resolution______________________________

You should find that the span is 85 GPM and the resolution is 0.17 GPM.

❑ 4. Determine the resolution of a level sensor given the following information:

Instrument Resolution: 1000 points

Process Range: -5 ft to 85 ft. of water

Span ______________________________

Resolution ______________________________

You should find that the span is 90 ft and the resolution is 0.09 ft.

❑ 5. Determine the resolution of a temperature sensor given the following information:

Instrument Resolution: 1000 points

Process Range: 89° to 205° C

Span ______________________________

Resolution ______________________________

You should find that the span is 116° and the resolution is 0.116°C.

SEGMENT 1 SELF REVIEW

1. If the loop is not properly _______, the system may not react quickly to disturbances or accurately maintain the PV at SP.

2. Control loop ______________ is the process of ensuring that all loop components are properly sized and configured.

3. _______________ is the smallest distinguishable interval between two measurements or values.

4. When installing or replacing a(n) ____________, make sure it has the needed resolution.

5. Many instrument manufacturers give the instrument's span and the __________ of resolution.

6. The process of optimization is made up of two parts: physical and _______________.

SEGMENT 2

ACCURACY AND REPEATABILITY

OBJECTIVE 4 DEFINE INSTRUMENT ACCURACY AND EXPLAIN ITS IMPORTANCE

Read This

Instrument accuracy is a measure of how closely an instrument's output matches the actual value of the process variable. For example, figure 7 shows the output of a sensor with an accuracy of ± 5%. As you can see, the sensor's output at any point falls within the ± 5% band but does not closely match the actual value of the process variable. This sensor has a high degree of inaccuracy.

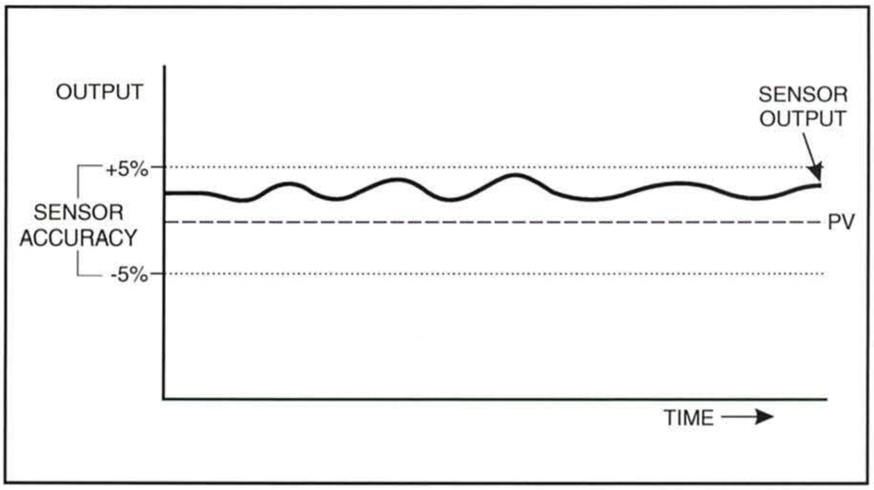

Figure 7. Output of a Sensor with ± 5% Accuracy

The accuracy of each instrument in a process has an effect on the overall accuracy of the process. If an instrument in a process is inaccurate, the overall accuracy of the process is lowered. The goal is to make sure that each instrument in a process is accurate enough to allow the process to control the PV with the desired amount of accuracy.

While all process instruments introduce some inaccuracy to the process, instrument accuracy must be high enough to enable the overall process accuracy to meet the needs of the application.

Common causes of inaccuracy include: mechanical backlash in gears, hysteresis and stiction in valves, and improper calibration of process instruments. Of these, improper calibration is the most common and the easiest to correct.

OBJECTIVE 5 DESCRIBE FIVE METHODS OF EXPRESSING ACCURACY

Instrument manufacturers use different methods of expressing accuracy. Five common methods of expressing accuracy are:

- A factor of the measured variable
- Percentage of the span
- Percentage of the upper range value (URV)
- Percentage of the scale length
- Percentage of the displayed reading

A Factor of the Measured Variable

Accuracy expressed as a factor of the measured variable depends on the actual value of the measured variable. To determine the accuracy, simply adjust the measured variable by the factor provided by the instrument manufacturer (typically located in the specifications). This tells you the maximum variance for any measurement. For example, suppose a pressure sensor is installed in a tank and the instrument specifications list the accuracy as ±1 psi. This means the actual value can be as much as 1 psi different from the measurement. Applying this information to the tank in figure 8, the actual value of the pressure can be anywhere from 99 psi (100 – 1 = 99) to 101 psi (100 + 1 = 101).

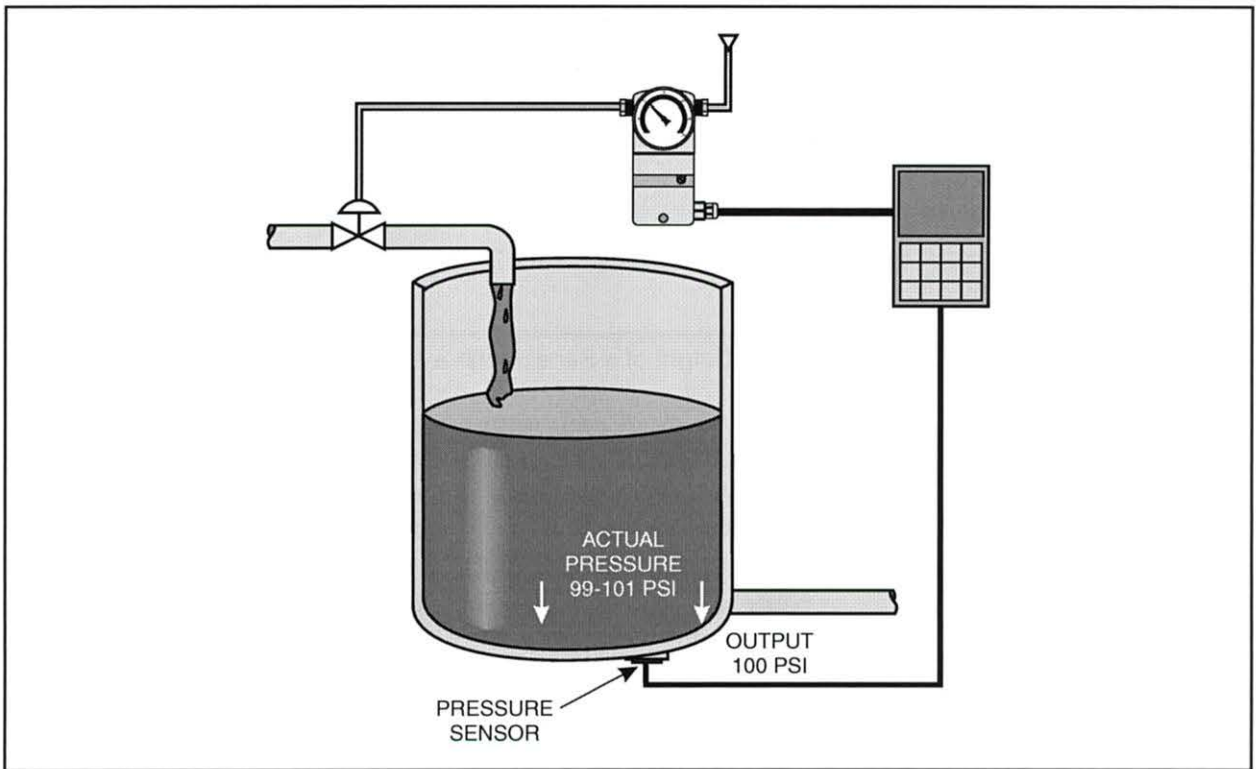

Figure 8. Accuracy as a Factor of the Measured Variable

Percentage of the Span

Accuracy expressed as a percentage of span is based on the calibrated span of the instrument. For example, suppose the calibrated span of a level sensor is 50 inches of water and its accuracy is given as 1%. To determine the accuracy as a percentage of the span, simply multiply the span by the percentage. In this case, the accuracy is ±0.5 inch of water ($50 \times 0.01 = 0.5$).

Applying this information to the tank in figure 9, the actual level could vary from 24.5 inches to 25.5 inches of water due to the ±0.5 inch accuracy.

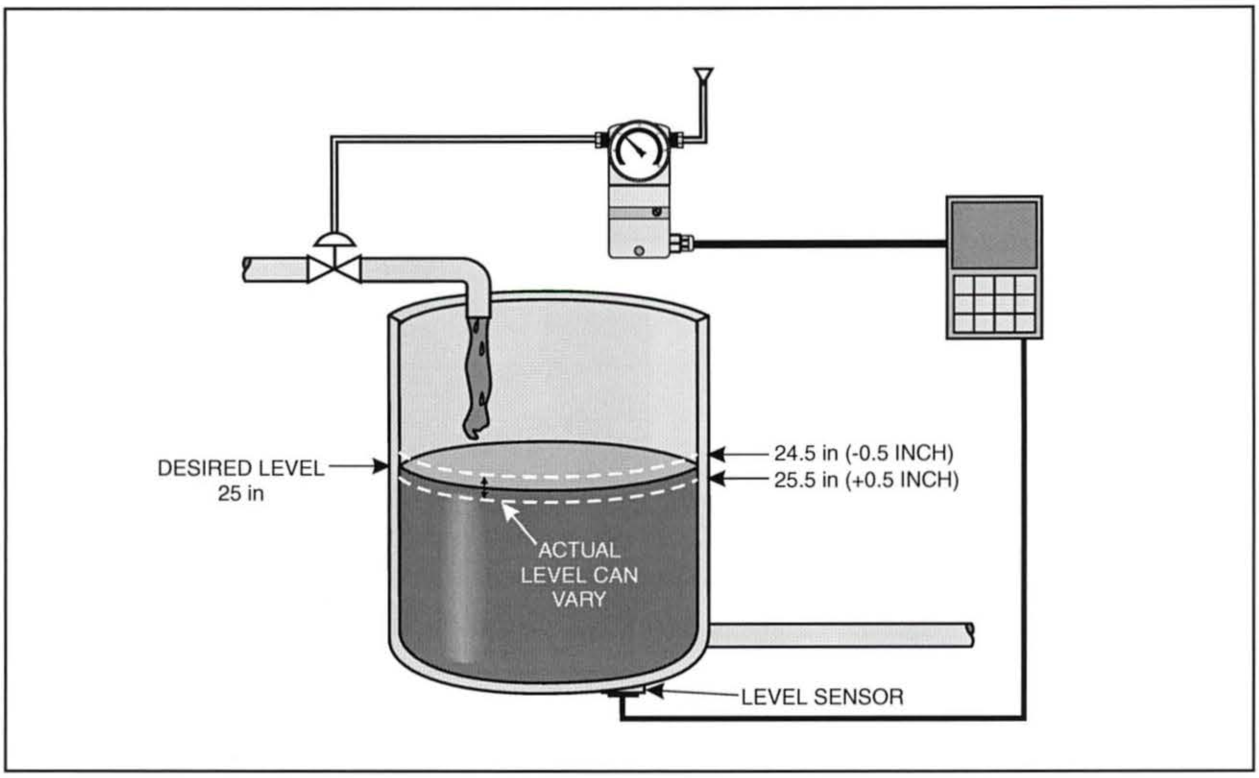

Figure 9. Accuracy as a Percentage of the Span

Percentage of the Upper Range Value (URV)

Accuracy expressed as a percentage of the upper range value (URV) is based on the upper value of the controlled range. For example, suppose a temperature sensor in a control loop measures the temperature in a vat. The temperature range for the process is 100° to 120° C. The accuracy of the sensor is 2.5%. To determine the accuracy as a percentage of the URV, multiply the URV by the percentage. For this application, the accuracy is ±3° C (120 × 0.025 = 3).

For the displayed temperature of 105° C in figure 10, the actual temperature of the material could range from 102° to 108° C.

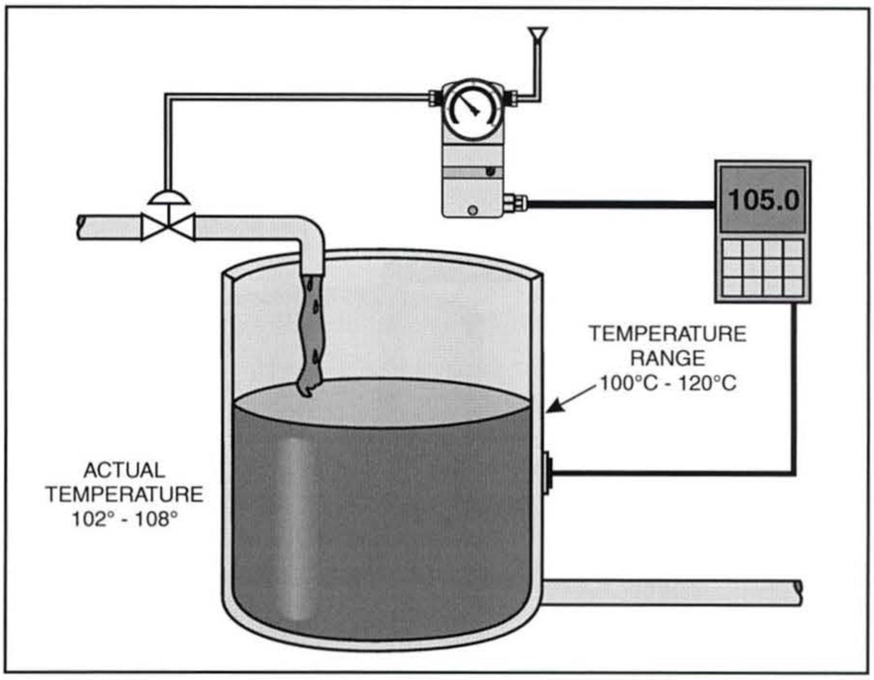

Figure 10. Accuracy as a Percentage of the URV

Percentage of the Scale Length

Accuracy expressed as a percentage of the scale length is based on the physical length of the indicating scale. For example, suppose a process tank has a level scale of 20 inches and the accuracy is 1%. To determine the accuracy as a percentage of the scale length, multiply the scale length by the percentage. For this application, the accuracy is ±0.2 inches ($20 \times 0.01 = 0.2$).

For the application in figure 11, the actual level in the tank could range from 11.8 to 12.2 inches.

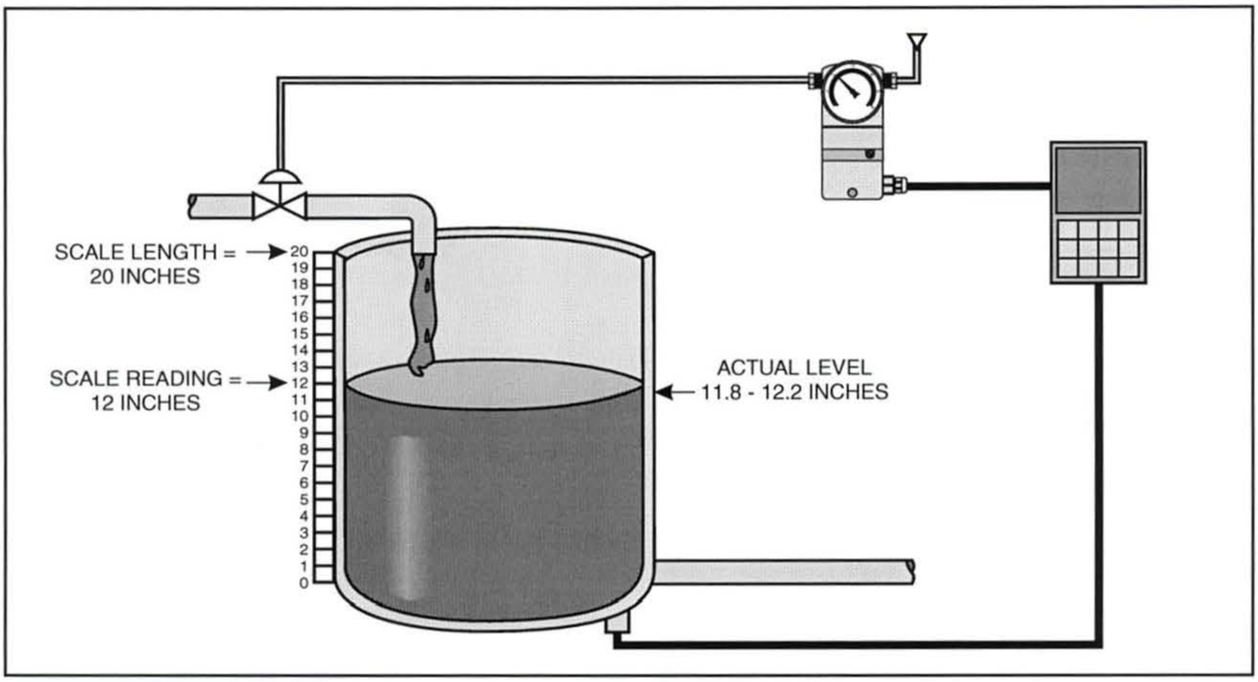

Figure 11. Accuracy as a Percentage of Scale Length

Percentage of the Displayed Reading

Accuracy expressed as a percentage of the displayed reading is based on the displayed value of the PV. For example, suppose a controller is displaying the level as 75 feet. The accuracy is ±2%. To determine the accuracy as a percentage of the displayed reading, multiply the displayed reading by the percentage. For this application, the accuracy is ±1.5 feet ($75 \times 0.02 = 1.5$).

As a result, the actual level could range from 73.5 to 76.5 feet for an indicated level of 75 feet, as figure 12 shows.

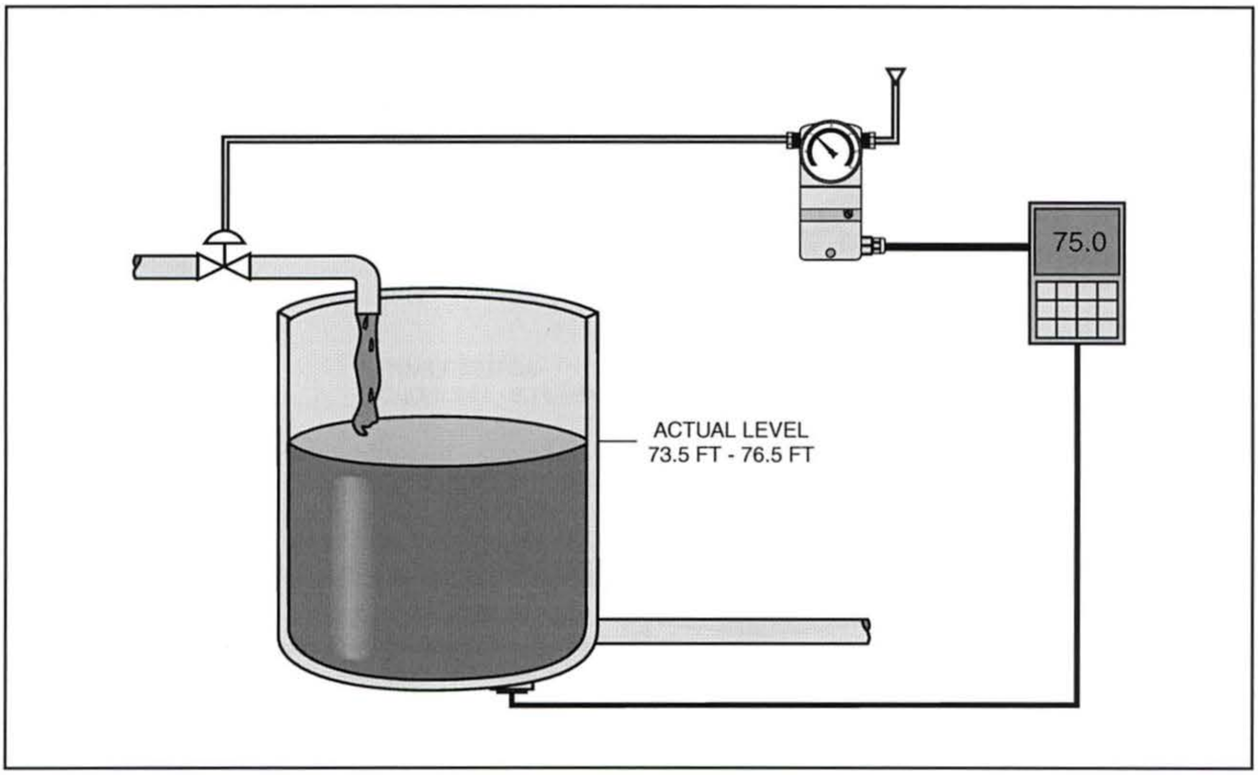

Figure 12. Accuracy as a Percentage of the Displayed Reading

It is important that each instrument in a process be accurate enough to achieve the needed overall accuracy. For example, suppose the goal of the process in figure 13 is to control the temperature of the fluid in the tank with an accuracy of ±0.5° C. However, the accuracy of the temperature sensor is ±1° C. In this case, the sensor is not accurate enough to allow the controller to meet the goal, since the sensor cannot sense a 0.5° C change in temperature.

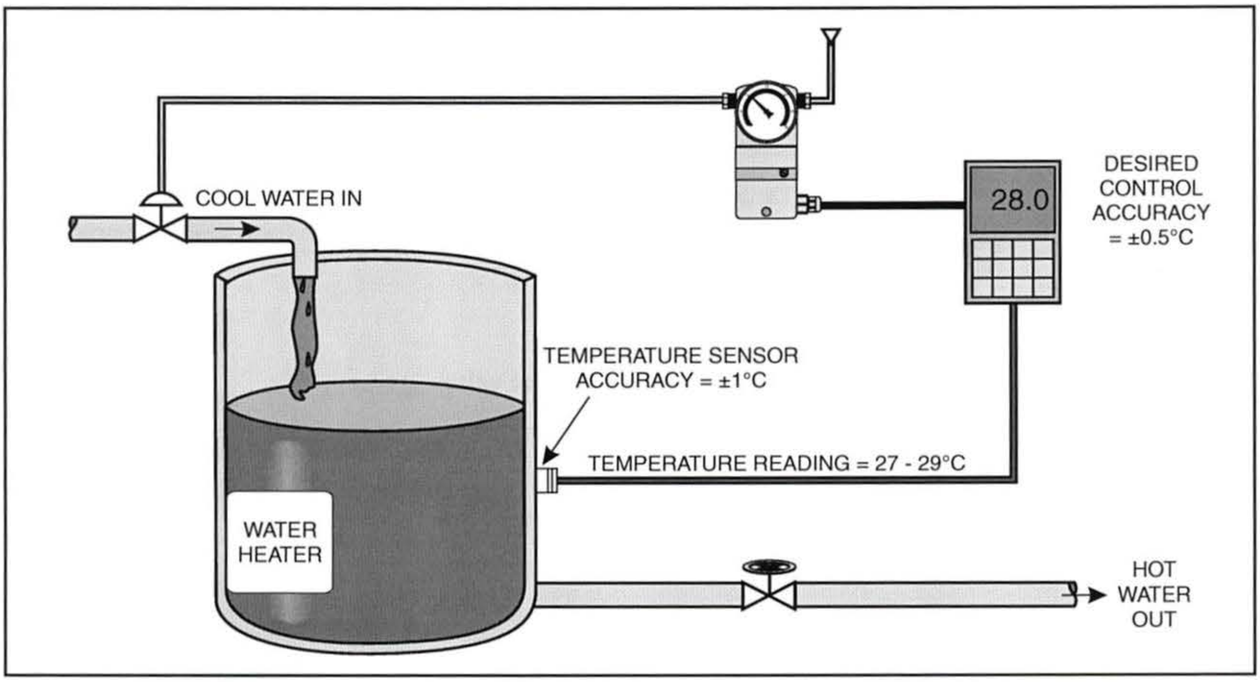

Figure 13. A Temperature Control Process

Procedure Overview

In this procedure, you will be given a method for determining accuracy, the multiplier (i.e. the mathematical correction factor to calculate the accuracy), and the actual process value. You will then calculate the actual value range of the process.

❑ 1. Determine the accuracy of the process shown in figure 14 as a factor of the measured variable, given the following information:

Measured Value: 78° F

Accuracy: ±2° F

Possible range of actual value ________________

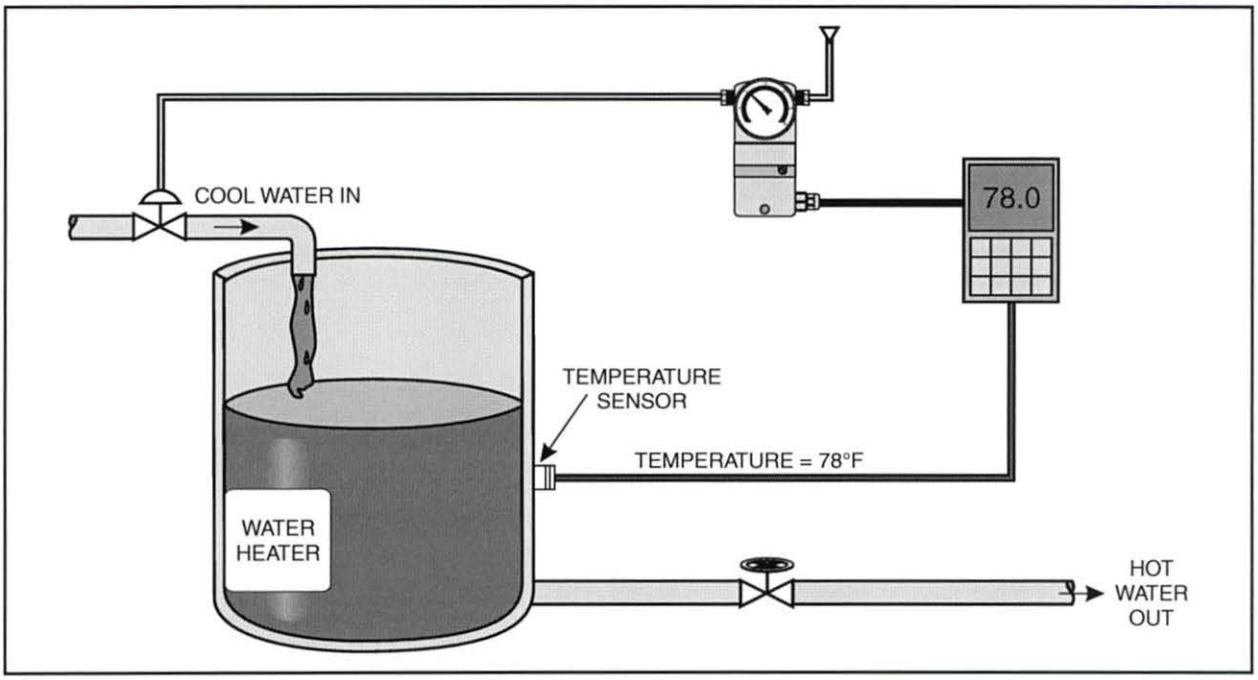

Figure 14. Temperature Control Process with Temperature at 78°F

You should find the range to be 76° F (2° below measured value) to 80° F (2° above measured value).

❑ 2. Determine the accuracy of a process as a factor of the measured variable, given the provided information:

Measured Value: 150 psi

Accuracy: ±5 psi

Possible range of actual value ______________________

You should find the range to be 145 - 155 psi.

❑ 3. Determine the accuracy of a process as a percentage of the span, given the following information:

Span: 30 in. of water

Accuracy: ±1.5%

Displayed Value: 27 in. of water

Accuracy as a percentage of the span ________________

Possible range of actual value ______________________

You should find the accuracy as a percentage of the span to be ±0.45 inch and the range to be from 26.55 to 27.45 inches of water.

❑ 4. Determine the accuracy of a process as a percentage of the span, given the following information:

Range: 10 to 150 gpm

Accuracy: ±2% of span

Displayed Value: 123 gpm

In order to calculate the accuracy as a percentage of the span, you first need to determine the span.

Span ______________________________________

Accuracy as a percentage of the span ________________

Possible range of actual value ______________________

You should find the range to be 120.2 gpm to 125.8 gpm.

❑ 5. Determine the accuracy of a process as a percentage of the upper range value (URV), given the following information:

Range: 25-75 lbs per min.

Accuracy: ±2%

Displayed Value: 68 lbs per min.

Accuracy as a percentage of the URV ________________

Possible range of actual value ______________________

You should find the accuracy as a percentage of the URV is ±1.5 lbs per min and the range of the actual value to be 66.5 to 69.5 lbs per min.

❑ 6. Determine the accuracy of the temperature control process shown in figure 15 as a percentage of the upper range value, given the following information:

Range: 30° C to 75° C

Accuracy: ±1.5%

Displayed Value: 50° C

Accuracy as a percentage of the URV ________________ (° C)

Possible range of actual value ________________________

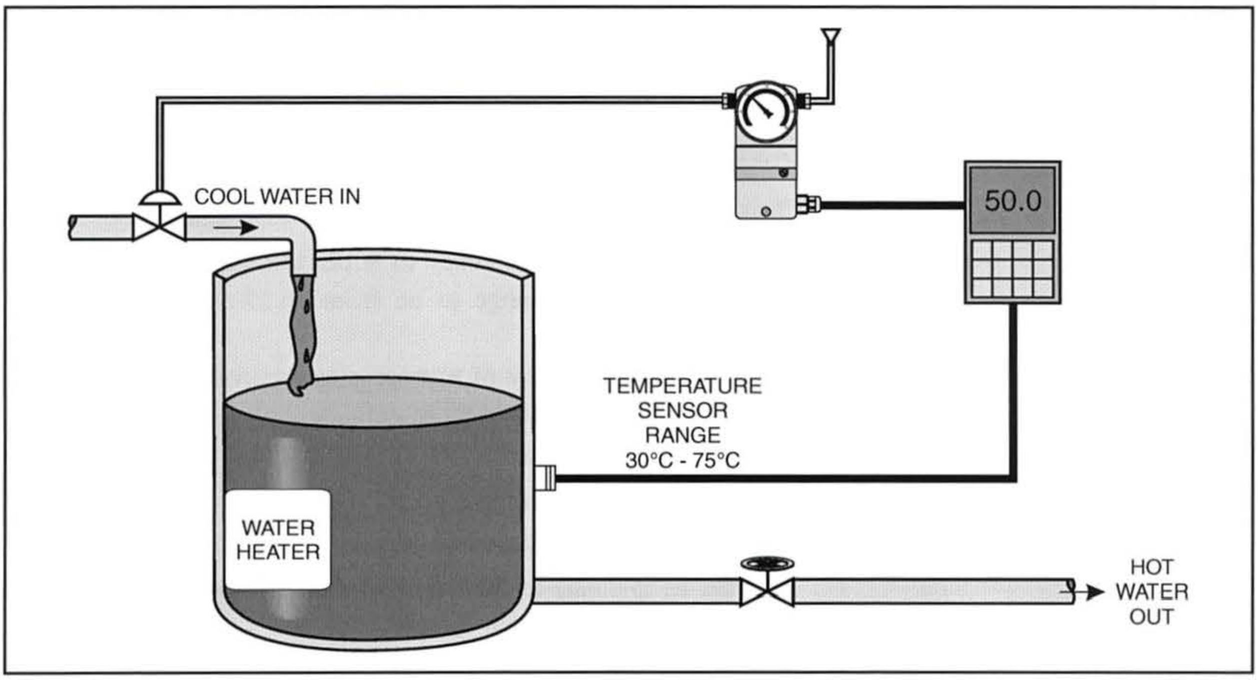

Figure 15. Temperature Control Process with a Range of 30°C to 75°C

You should find the accuracy is ±1.125° C and the range to be 48.845 °C to 51.125 °C

❑ 7. Determine the accuracy as a percentage of the scale length, based on the provided information:

Scale Length: 5.5 in.

Accuracy: ±2%

Accuracy as a percentage of the scale length __________ (Inches)

You should find the accuracy as a percentage of the scale length is ±0.11 inch.

❑ 8. Determine the accuracy as a percentage of the scale length, given the following information:

Scale Length: 4 in.

Accuracy: ±2%

Accuracy as a percentage of the scale length __________ (Inches)

Possible range of values ________________________________

You should find that the accuracy is ±0.08 and the possible range of values is 3.92 - 4.08 in.

❑ 9. Determine the accuracy as a percentage of the displayed reading, given the following information.

Displayed Value: 13 mA

Accuracy: ±1%

Accuracy as a percentage of the displayed reading ________ (mA)

Possible range of values ________________________________

You should find the accuracy as a percentage of the displayed reading is ±0.13 mA and the range to be 12.87 mA to 13.13 mA.

❑ 10. Determine the accuracy as a percentage of the displayed reading, given on the following information.

Displayed Value: 110° F

Accuracy: ±2%

Accuracy as a percentage of the displayed reading _________ (°F)

Possible range of values ________________________________

You should find the accuracy is ±2.2°F and the possible range of value is to be 107.8°F to 112.2°F.

OBJECTIVE 6 DEFINE REPEATABILITY AND EXPLAIN ITS IMPORTANCE

Read This

Repeatability is the ability of a device to consistently give the same reading or output if the same input is repeated a number of times. As an example, consider the temperature sensor in the process tanks in figure 16. The process holds the liquid in the tanks at a constant temperature of 25° C.

For test 1, as shown on the left, the temperature sensor indicates the temperature is 25.0° C. However, for test 2 (shown on the right), the same temperature sensor indicates the temperature is 20.5° C. In this case, the results of the temperature measurements are not repeatable.

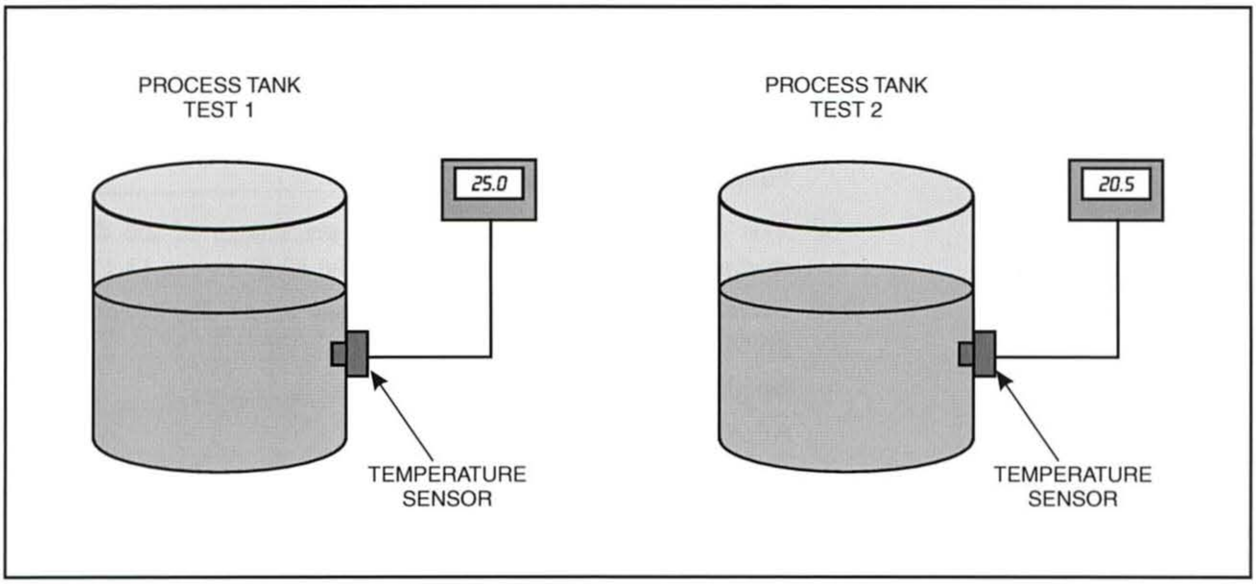

Figure 16. Thermometer Displays Repeatable Measurements

The terms accuracy and repeatability are sometimes used interchangeably. This is unfortunate since the terms do not mean the same thing. Measurements that are repeatable are not necessarily accurate and vice versa.

For example, figures 17 through 20 show temperature measurements taken over time from four different processes. The Xs represent temperature measurements. Looking at the results from process 1, the temperature measurements are not within the desired control range, as shown in figure 17. However, the values are all very close to the same temperature. In this case, the results are not accurate but they are repeatable.

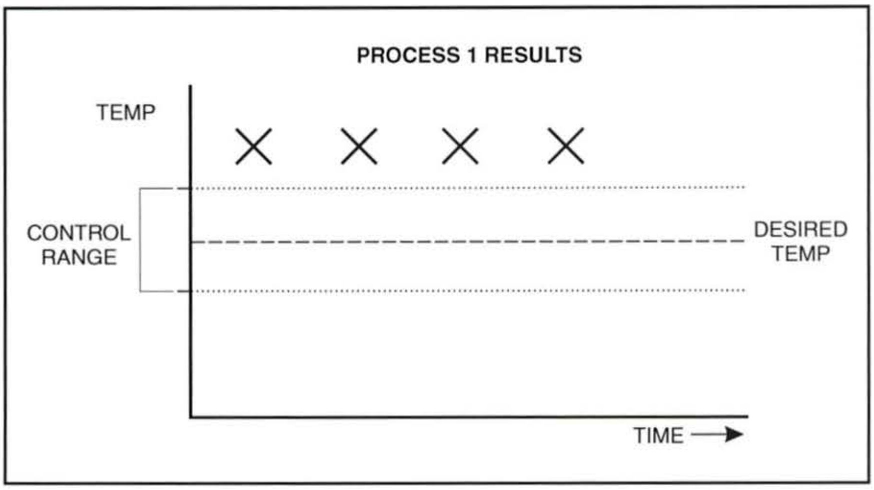

Figure 17. Results Repeatable/Not Accurate

For process 2 in figure 18, the temperature values are not close to each other, although one of the values does fall within the control range. Since a measurement falls within the control range, the results are considered accurate. However, because the values are not close to each other, the results are not repeatable.

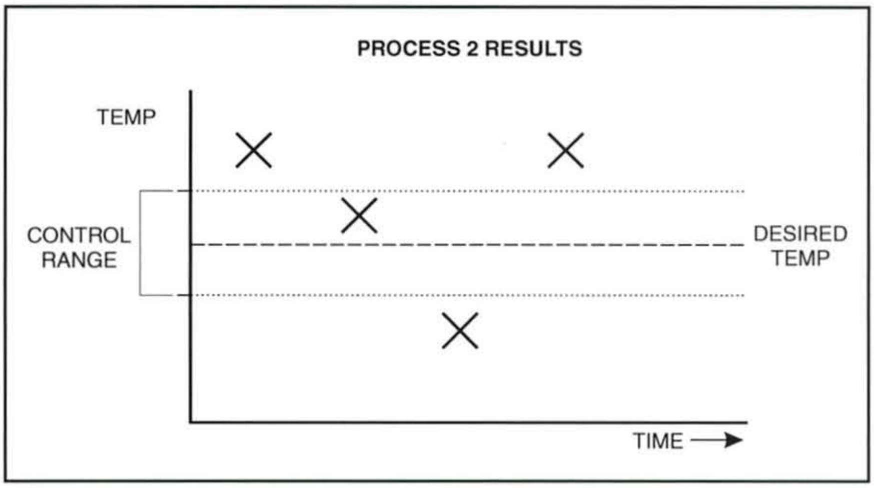

Figure 18. Results Accurate/Not Repeatable

The results for process 3 in figure 19 show that the temperature values are not close to each other, nor do they fall within the control range. In this case, the results are neither accurate nor repeatable.

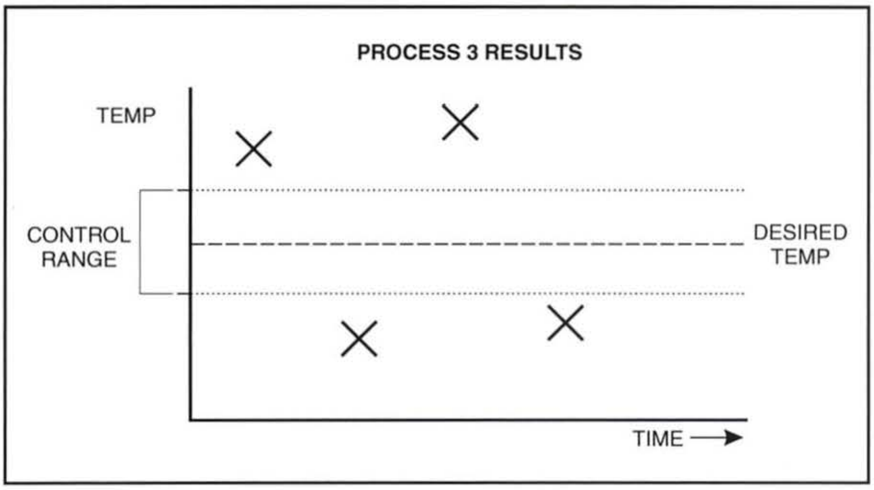

Figure 19. Results Not Accurate/Not Repeatable

Finally, the results for process 4 in figure 20 show that the temperature values all fall within the control range and they are close to each other. In this case, the results are accurate and repeatable, which is the ultimate goal for a process.

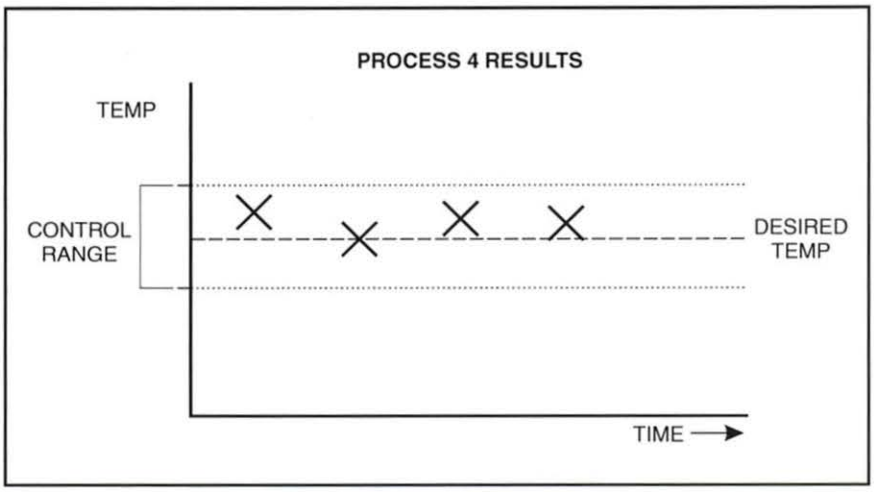

Figure 20. Results Accurate/Repeatable

Results that are both accurate and repeatable are often difficult to achieve. In applications where both cannot be achieved, it is usually better to have repeatable results because it is easier to compensate for inaccuracy than for repeatability.

SEGMENT 2

SELF REVIEW

1. Instrument _______________ is a measure of how closely an instrument's output matches the actual value of the process variable.

2. An example of inaccuracy is _______________ or stiction in a control valve.

3. The accuracy as a percentage of the span of a level sensor with a calibrated span of 60 inches and an accuracy of 2% is _____________.

4. What is the accuracy as a percentage of the displayed reading if the display shows 25° C and the accuracy is ± 2%? _______________

5. _______________ is the ability of a device to consistently give the same reading or output if the same input is repeated a number of times.

6. Just because measurements are repeatable does not mean they are _______________.

SEGMENT 3

OPEN-LOOP TUNING

OBJECTIVE 7 DEFINE LOOP TUNING AND EXPLAIN ITS IMPORTANCE

Read This

Loop tuning is the process of determining the best control settings (e.g. proportional, integral, and derivative) for optimal loop performance and entering them into the controller. Loop tuning is usually the last step in optimizing a control loop. It is performed when a loop is first started and repeated periodically as needed.

One goal of tuning is to control the process variable as accurately as possible. Therefore, when a disturbance occurs (i.e. changing setpoints or load conditions), the response should bring the process variable back to the setpoint as quickly as possible. A system that is able to do this is said to have "tight" control, as figure 21 shows.

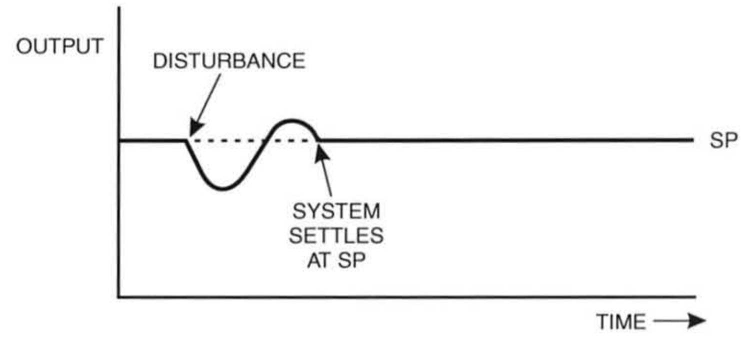

Figure 21. Tight System Response

A number of different standards exist for determining when a loop is tuned. Most of them depend on the desired response of the system. One widely accepted standard is quarter wave decay response, as shown in figure 22.

For this type of response, the amplitude of the first oscillation after a disturbance is large, as figure 22 shows. The amplitude of the second oscillation is one quarter (1/4) the size of the first oscillation, thus the term "quarter wave decay". After the second oscillation, the response usually damps out (settles) quickly at the setpoint.

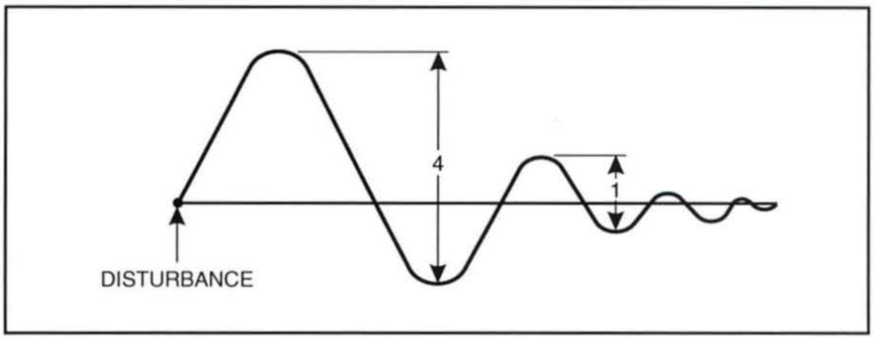

Figure 22. Quarter Wave Decay Response

The difficult part of tuning is determining which of the three modes (proportional, integral and derivative) to use and how much of each to apply. The type of control loop (e.g. level, flow, temperature, pressure or analytical) often determines which control modes to use. The table in figure 23 lists the control modes most commonly used in different types of control loops.

	CONTROLLER MODE		
CONTROL LOOP	**PROPORTIONAL**	**INTEGRAL**	**DERIVATIVE**
Flow	Always	Usually	Never
Level	Always	Usually	Rarely
Temperature	Always	Usually	Usually
Analytical	Always	Usually	Sometimes
Pressure	Always	Usually	Sometimes

Figure 23. Controller Mode Selection Table

Tuning methods are procedures for learning the dynamic characteristics (dynamics) of the process. Tuning methods are typically grouped into three basic categories:

- Open-Loop Methods
- Closed-Loop Methods
- Tuning Software

These methods focus on the two major system dynamics: time and amount. Learning these system dynamics helps to identify the needed controller settings.

Proper tuning helps to ensure the quality of the product that is produced by the process. An added benefit is that tuning extends the life of the process instruments, especially the control valves.

OBJECTIVE 8 DEFINE OPEN-LOOP TUNING AND GIVE AN APPLICATION

Open-loop tuning is a process that determines the PID settings for closed-loop operation by testing the system dynamics with the controller in the manual mode (open loop). There are a number of open-loop tuning methods, including:

- Process Reaction Curve
- Point of Inflection
- Open-Loop Process Gain

Each method looks at a different aspect of the process response to a step change in the input while the controller is in the manual mode. The data collected from the resulting reaction curve, like the one shown in figure 24, can be inserted into standard equations to determine the needed PID settings.

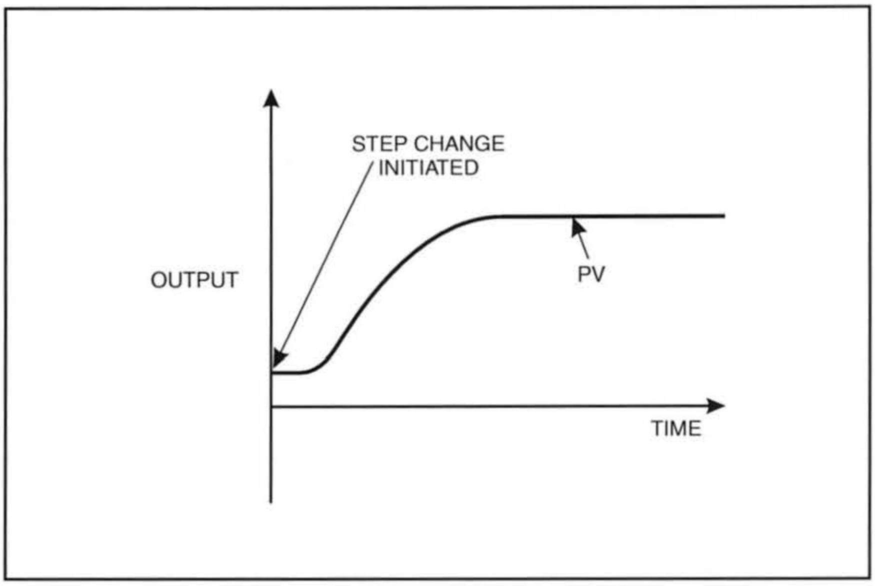

Figure 24. A Process Reaction Curve

The major advantage of open-loop tuning is that it results in a system that responds quickly to disturbances or changes in the setpoint. This makes open-loop tuning a good choice for pH control loops, like the one in figure 25, because the tight response allows the loop to hold the pH of the material near the setpoint, regardless of conditions.

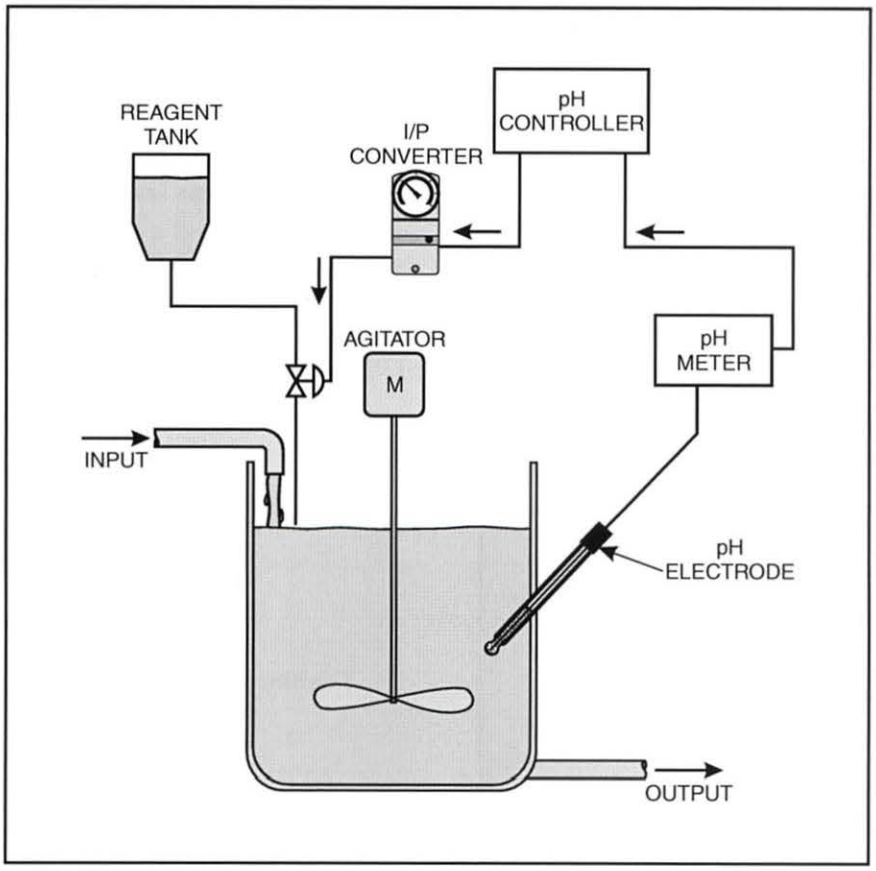

Figure 25. A pH Control Loop

The major disadvantage of open-loop tuning is that it requires the system to be taken out of the automatic mode. This can be disruptive to the process.

OBJECTIVE 9 DESCRIBE HOW TO TUNE A LOOP USING THE PROCESS REACTION CURVE OPEN-LOOP METHOD

Read This

In 1942, J.G. Ziegler and N.B. Nichols of Taylor Instruments set out to develop standard methods of tuning PID control loops. That year, Ziegler and Nichols introduced two methods. One method is an open-loop method called the process reaction curve method. The other method is a closed-loop method that is covered later.

The process reaction curve method uses a reaction curve, like the one in figure 26, which is created using data collected from the response of a control loop with the controller in the manual mode. An analysis of the reaction curve helps to determine the reaction rate and lag time. Inserting the reaction rate and lag time into equations developed by Ziegler and Nichols determines the appropriate proportional, integral, and derivative settings.

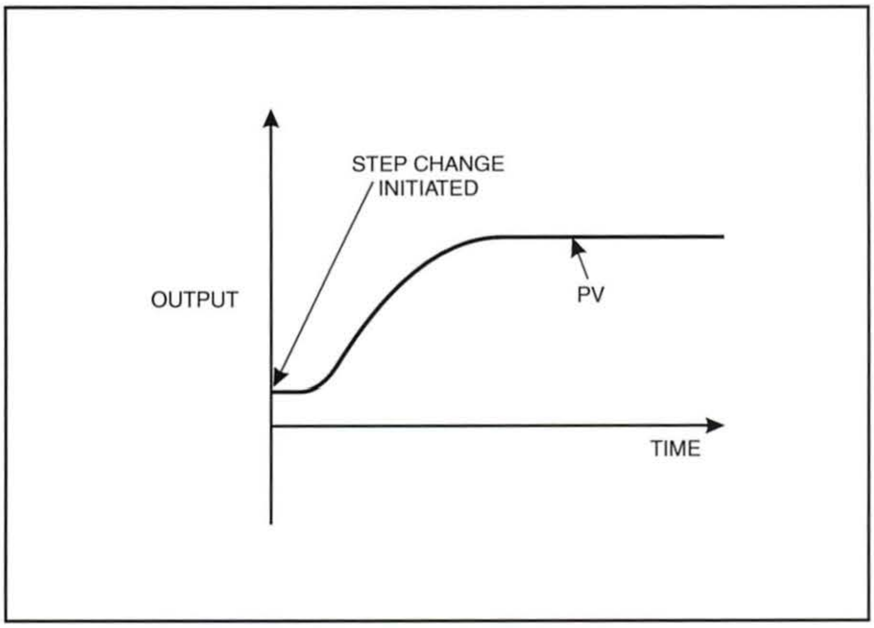

Figure 26. Sample Process Reaction Curve

The following steps describe how to use the process reaction curve tuning method:

Step 1: Create a reaction curve for the process
Step 2: Use the reaction curve to determine the reaction rate and lag time
Step 3: Calculate the values for the PID settings using the reaction rate and lag time
Step 4: Enter the calculated values into the controller
Step 5: Test the process for the desired response

Step 1: Create a Reaction Curve for the Process

Make sure the process is in a steady state and place the controller in the manual mode. Initiate a step change in the controller's output (e.g. 5% change in output) and record the response of the process as it reacts to the change. You can record the response using a chart recorder like the one in figure 27 or by plotting it by hand. Once this is done, return the controller's output to its previous value and return the controller to automatic control.

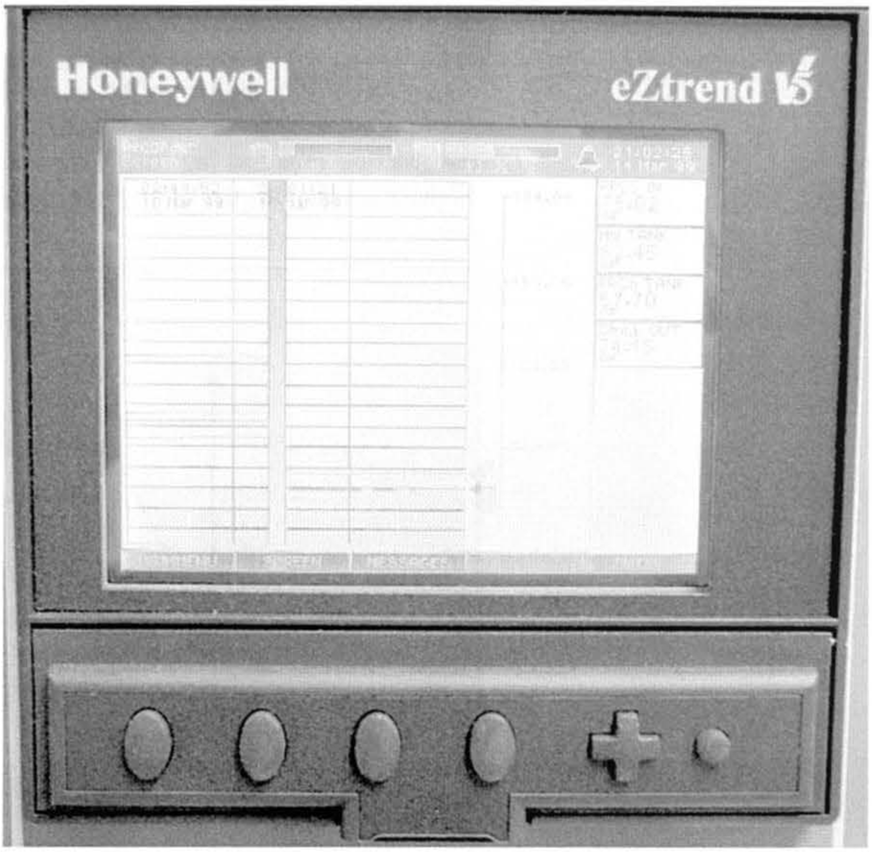

Figure 27. A Chart Recorder

Step 2: Use the Reaction Curve to Determine the Reaction Rate and Lag Time

To determine the reaction rate, identify the maximum slope of the process reaction curve, as figure 28 shows. The maximum slope represents the reaction rate R_r.

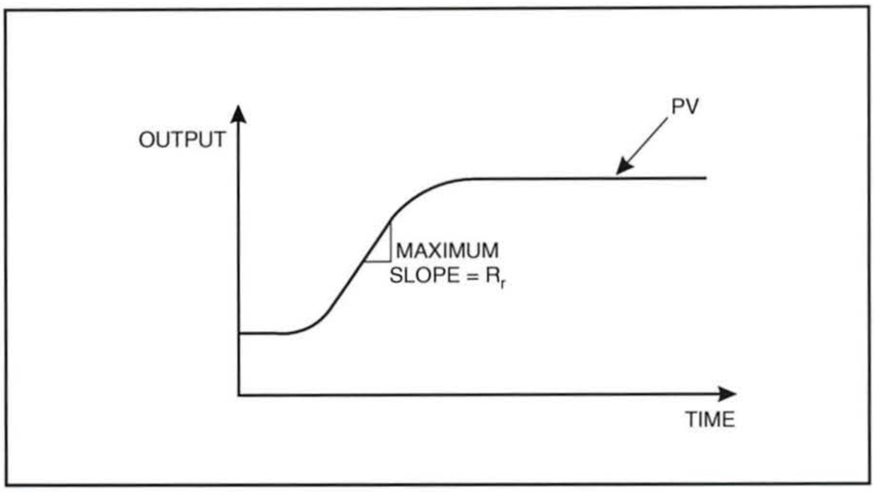

Figure 28. Maximum Slope Represents the Reaction Rate

Next, draw a tangent line through the point of maximum slope. Extend the line so that it crosses the vertical axis, as shown in figure 29.

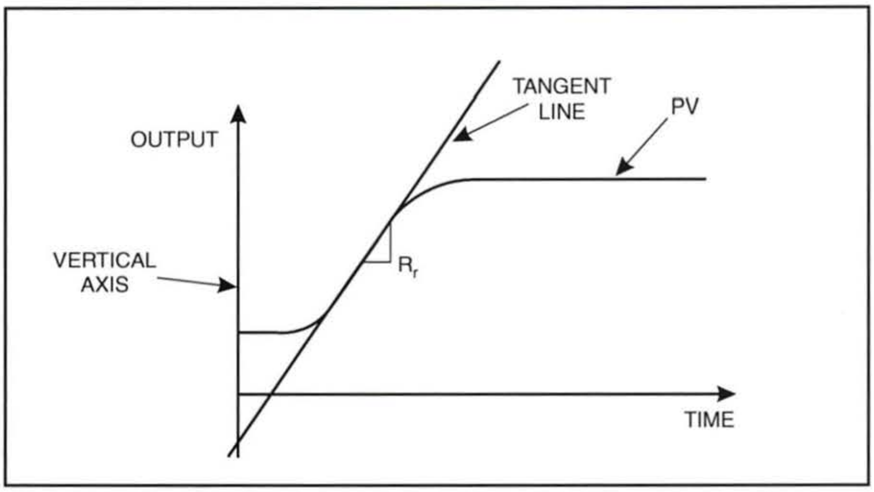

Figure 29. Tangent Line through Maximum Slope on a Process Reaction Curve

Determine the distance between the vertical axis and the point at which the tangent line intersects the horizontal baseline of the process reaction curve, as figure 30 shows. This distance represents the lag time, L_r.

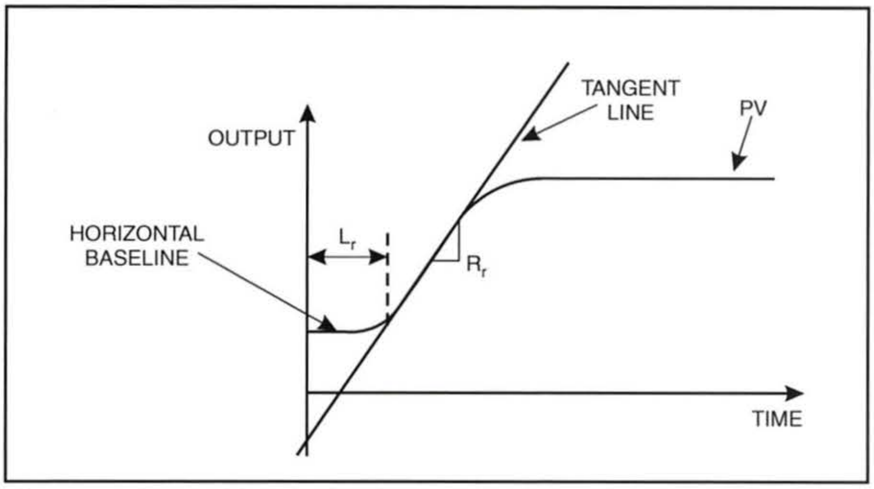

Figure 30. Determining the Lag Time on a Process Reaction Curve

Finally, determine the distance between the point at which the horizontal baseline of the reaction curve intersects the vertical axis and the point at which the tangent line intersects the vertical axis, as figure 31 shows. This distance represents the product of $L_r \times R_r$, which is used in the loop tuning equations.

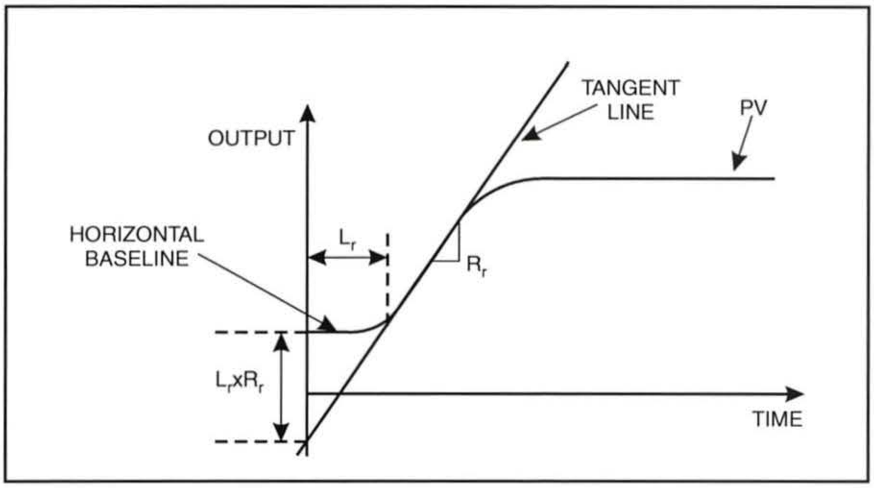

Figure 31. Product $L_r \times R_r$ on a Process Reaction Curve

Step 3: Calculate the Values for the PID Settings using the Reaction Rate and Lag Time

Insert the reaction rate and lag times determined in the previous step into the equations developed by Ziegler and Nichols. There are separate equations for proportional control only, proportional-integral control, and proportional-integral-derivative control, as the table in figure 32 shows. K_p represents the proportional gain, T_i represents the integral or reset time, and T_d represents the derivative rate.

PID EQUATIONS - REACTION CURVE METHOD	
CONTROLLER MODE	**EQUATIONS**
Proportional Only (K_p = Proportional Gain)	$K_p = 1 / (L_r \times R_r)$
Proportional + Integral (T_i = Reset Time)	$K_p = 0.9 / (L_r \times R_r)$ $T_i = 3.33 \times L_r$
Proportional + Integral + Derivative (T_d = Derivative Rate)	$K_p = 1.2 / (L_r \times R_r)$ $T_i = 2.0 \times L_r$ $T_d = 0.5 \times L_r$

Figure 32. PID Equations for Process Reaction Curve Tuning

Step 4: Enter the Calculated Values into the Controller

Tune the controller by entering the controller's setup menu, as figure 33 shows, and inserting the settings calculated in the previous step.

Figure 33. Controller's Setup Menu

Step 5: Test the Process for the Desired Response

Once the controller is tuned, return it to automatic control and test the process for the desired response. Again, you can check the response using a chart recorder or by plotting it by hand. If the settings are correct, the process response should be quarter wave decay, similar to figure 34.

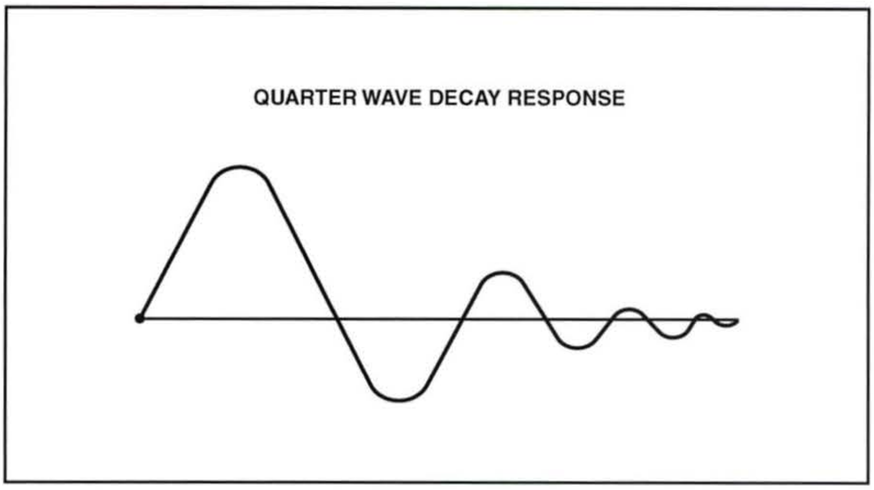

Figure 34. Desired Process Response (Quarter Wave Decay)

SKILL 3 TUNE A CONTROL LOOP USING THE PROCESS REACTION CURVE METHOD

Procedure Overview

In this procedure, you will tune a level control loop on the T5552 using the process reaction curve method. You will be given a pre-determined process reaction curve to use in calculating the controller settings.

- ❑ 1. Perform a lockout/tagout.
- ❑ 2. Perform the following substeps to set up the T5552, as shown in figure 35.

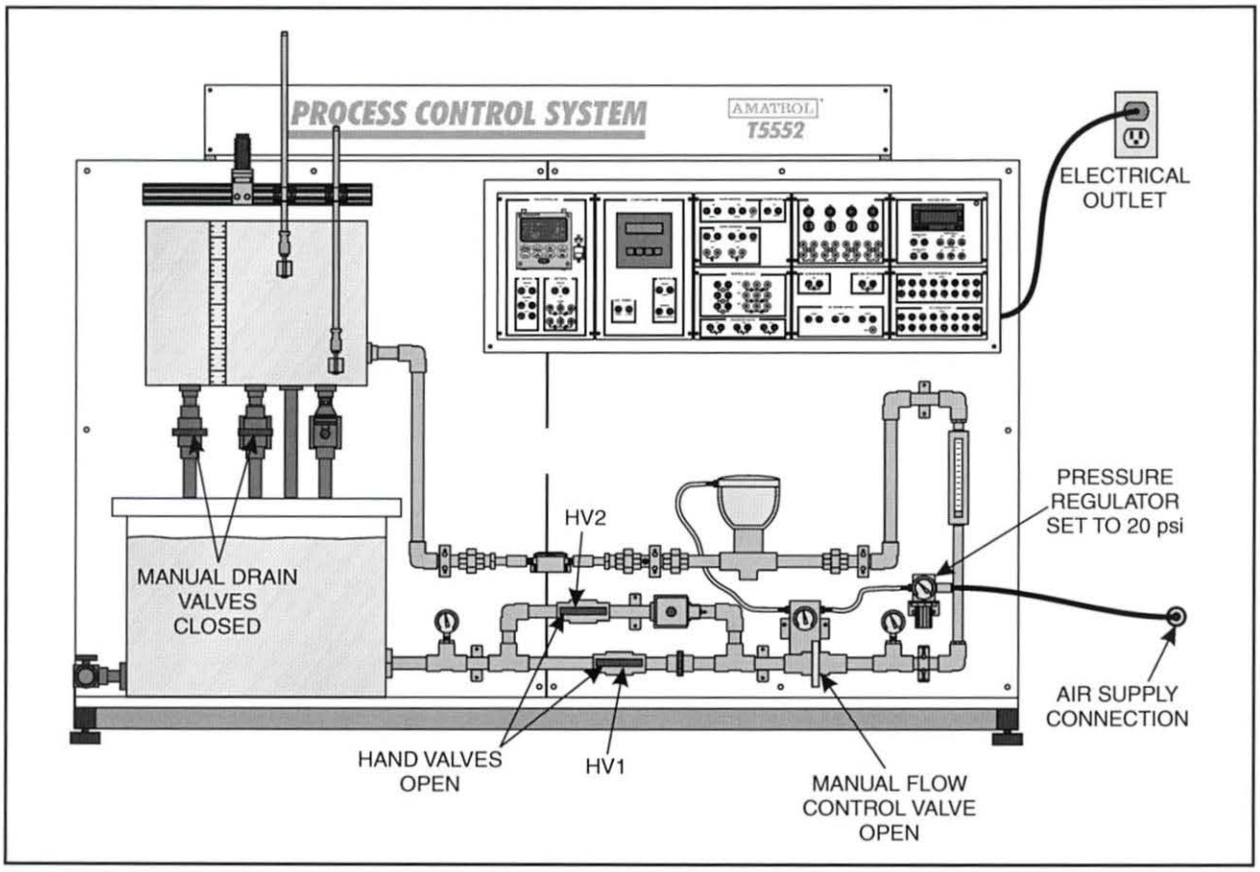

Figure 35. T5552 Setup

A. Connect the power cord to an available outlet.

B. Connect the air supply line to the T5552.

C. Set the pressure regulator to 20 psi.

D. Fill the reservoir tank with water.

E. Connect the circuit shown in figure 36.

This circuit allows you to control the level of water in the tank using the PID controller.

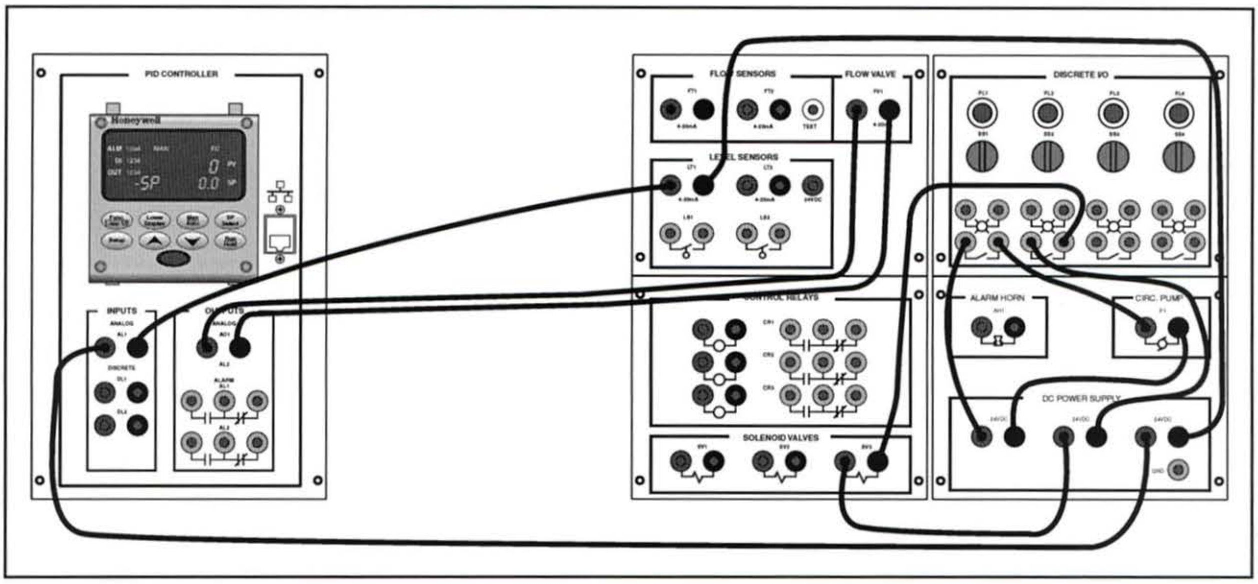

Figure 36. Level Control Circuit

Figure 37 shows the P&ID for the T5552. The active components and wiring are highlighted.

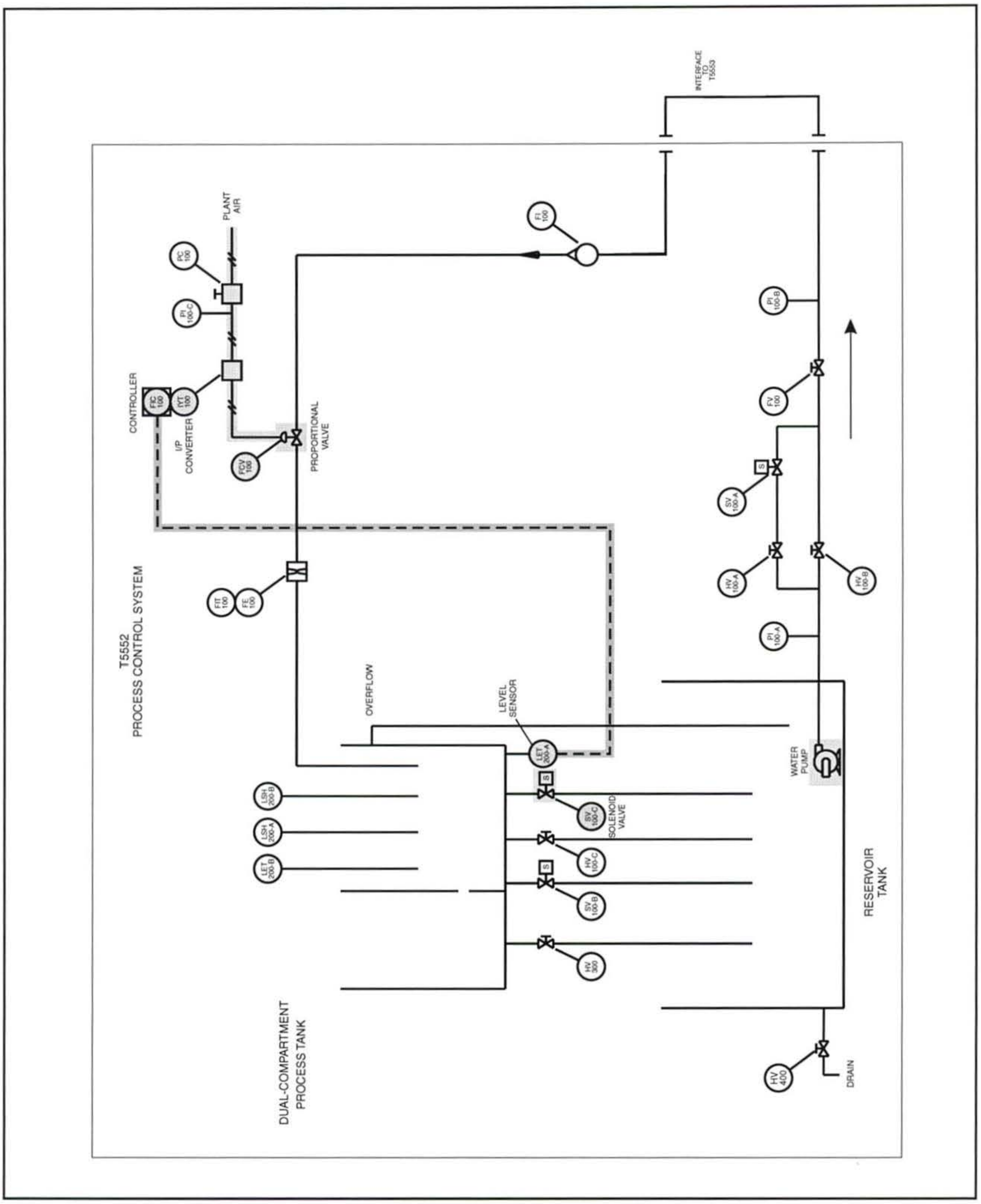

Figure 37. T5552 P&ID

❑ 3. Remove the lockout/tagout.

❑ 4. Turn on the main circuit breaker.

❑ 5. Set the following parameters in the ALGORITHM setup group.

PARAMETER	SETTING
CONT ALG	PID A

❑ 6. Set the following parameters in the INPUT 1 setup group.

PARAMETER	SETTING
IN1 TYPE	1-5V
XMITTER	LINEAR
IN1 HI	27.70
IN1 LO	0
BIAS	-1.6

❑ 7. Set the following parameters in the CONTROL setup group.

PARAMETER	SETTING
PV SOURCE	INPUT 1
PID SETS	1 ONLY
SP HiLIM	10.0
SP LoLIM	0.0
ACTION	DIRECT
OUTHi LIM	100
OUTLo LIM	0
IHi LIM	100
ILo LIM	0

❑ 8. Change the set point of the PID controller to **3.0** inches.

Don't worry about the tuning parameters at this point.

❑ 9. Place the controller in the automatic mode.

❑ 10. Start the circulation pump by turning on **SS1**.

The process tank should begin to fill.

❑ 11. Open the solenoid drain valve (**SS2** on) when the level (PV) reading reaches 3.0 inches.

❑ 12. Allow the process to become stable.

❑ 13. Close the solenoid drain valve (**SS2** off) and shut off the circulation pump (**SS1** off).

❑ 14. Place the controller in the manual mode.

☐ 15. Perform the following substeps to calculate the controller settings to tune the level control loop using the process reaction curve method.

Typically, a high-resolution chart recorder is required to graph the process reaction curve.

Since you may not have a chart recorder, we are supplying the $L_r \times R_r$ process reaction curve values.

$L_r = 4.51$ seconds

$R_r = 0.008$ inch

A. Determine the product $L_r \times R_r$.

$L_r \times R_r =$ ________________________________ (in/sec)

The product should be 0.036 in/sec.

Since this is a level control loop, the preferred controller modes are proportional and integral. Therefore, you should calculate the values for the proportional gain and the integral time.

B. Calculate the value for the proportional gain (K_P), using the appropriate equation from the table in figure 38.

$K_P =$ ________________________________

C. Calculate the value for the integral time (T_i), using the appropriate equation from the table in figure 38.

$T_i =$ ________________________________

PID EQUATIONS - REACTION CURVE METHOD	
CONTROLLER MODE	**EQUATIONS**
Proportional Only (K_p = Proportional Gain)	$K_p = 1 / (L_r \times R_r)$
Proportional + Integral (T_i = Reset Time)	$K_p = 0.9 / (L_r \times R_r)$ $T_i = 3.33 \times L_r$
Proportional + Integral + Derivative (T_d = Derivative Rate)	$K_p = 1.2 / (L_r \times R_r)$ $T_i = 2.0 \times L_r$ $T_d = 0.5 \times L_r$

Figure 38. PID Equations for Process Reaction Curve Tuning

☐ 16. Perform the following substeps to tune controller using the settings you calculated in step 15.

A. Place the PID controller in the setup mode, scroll to the TUNING group, and set the proportional gain (GAIN) to the value you calculated in step 15B.

B. Set the integral setting (RSET MIN) to the value you calculated in step 12C.

C. Set the derivative setting (RATE MIN) to zero to eliminate the derivative action.

D. Press the **Lower Display** key to exit the Setup mode and return to the control display mode.

❑17. Perform the following substeps to place the controller in the automatic mode and record the reaction of the process.

A. Place the controller in the automatic mode.

B. Open the solenoid drain valve (SS2 on).

C. Start the circulation pump (SS1 on).

D. Record the value of the PV every five seconds in a table similar to the one in figure 39 until the system becomes stable.

This data allows you to plot a response curve for the process. If the controller is properly tuned, the response curve should indicate quarter wave decay.

PROPORTIONAL-INTEGRAL CONTROL RESPONSE							
TIME (seconds)	PV READING	TIME (seconds)	PV READING	TIME (seconds)	PV READING	TIME (seconds)	PV READING

Figure 39. Table to Record Response

E. Create a graph of PV vs. time, similar to figure 40, on a piece of graph paper.

You will use this to plot the response of the system.

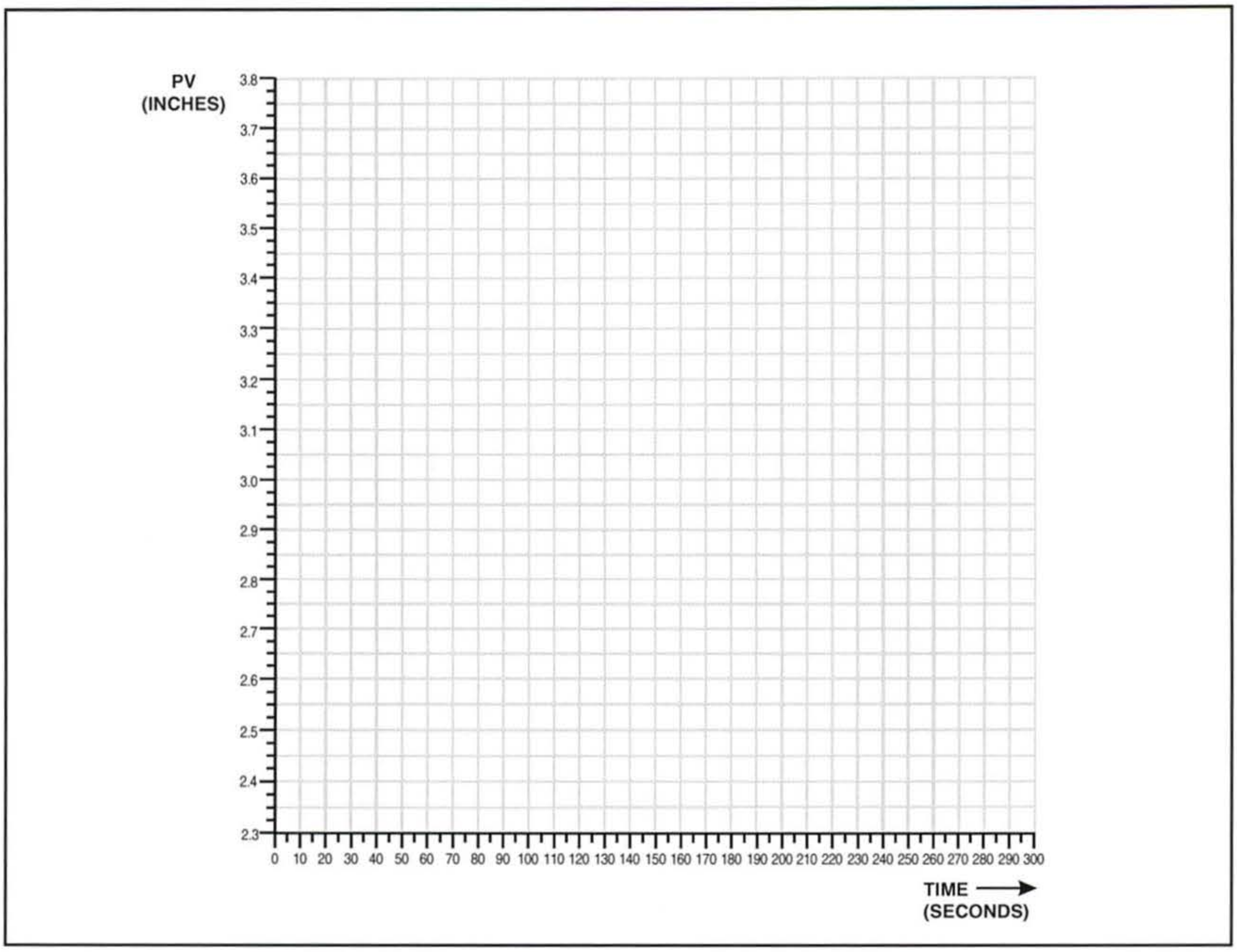

Figure 40. Graph of PV vs. Time

F. Plot the response using the data you collected in substep D. Your response curve should be similar to the one in figure 41.

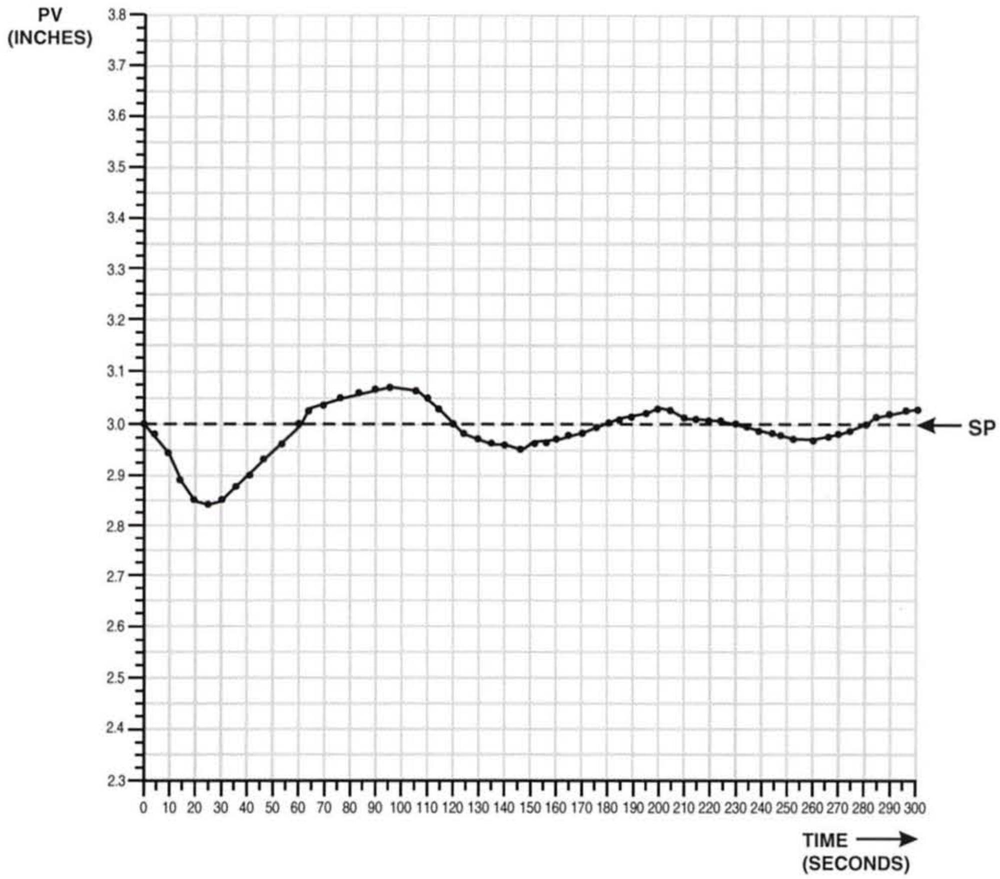

Figure 41. Response of the System (Quarter Wave Decay)

If you do not get the desired response (quarter wave decay), go back, check your calculations and retune the controller. Then, plot a new response curve.

❑ 18. Perform the following substeps to shut down the T5552.

A. Place the selector switch **SS1** in the **OFF** position (up). This stops the circulation pump.

B. Place the selector switch **SS2** in the **OFF** position (up). This closes the drain solenoid valve.

C. Switch the controller to the manual mode.

D. Open both of the manual drain valves on the process tank to completely drain the tank. When the tank is empty, close both valves.

E. Turn off the main circuit breaker.

F. Disconnect the control circuit.

OBJECTIVE 10 DESCRIBE THE FUNCTION OF TUNING SOFTWARE AND GIVE AN APPLICATION

Tuning software is any computer software designed to determine the PID values based on process data entered. Tuning software, like the software shown in figure 42, provides a way to simulate a process and predict the optimal settings. Because the process is simulated on a computer, the actual process is not disturbed while determining the settings. This is a major advantage that tuning software has over open-loop and closed-loop tuning, which disturb the actual process to determine the settings. Once the software determines the settings, the controller settings are updated by going "on-line" with the software and downloading the settings to the controller.

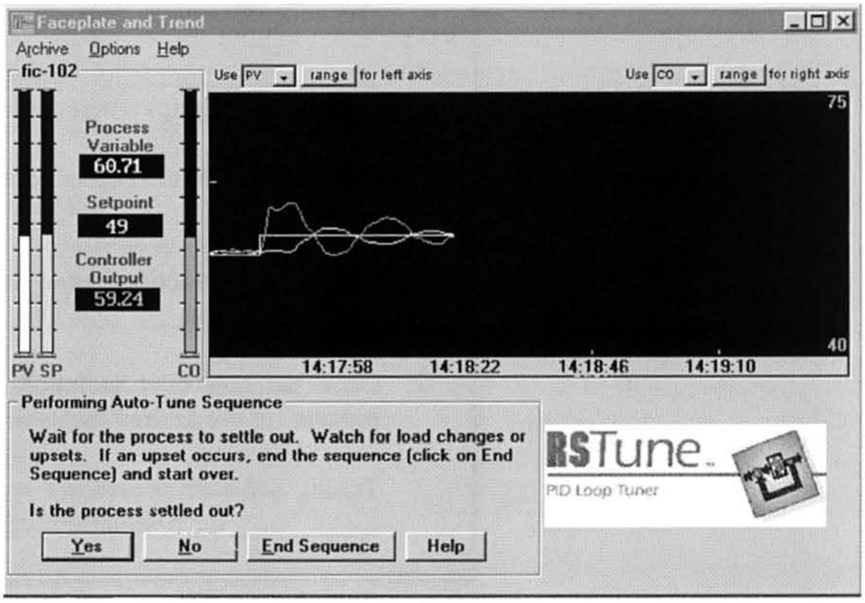

Figure 42. Process Tuning Software (RSTune)

Tuning software is versatile and can be used with any control loop. It is becoming very popular in processes where all of the control loops are networked together.

SEGMENT 3

SELF REVIEW

1. Loop __________ is the process of determining the best control settings for optimal loop performance and entering them into the controller.

2. One widely accepted standard for determining when a loop is tuned is ____________________ response.

3. Tuning methods are typically grouped into three different categories: ____________________ methods, closed-loop methods, and tuning software.

4. ____________________ tuning involves determining the needed PID settings with the controller in the manual mode.

5. The first step of the process reaction curve tuning method is to ____________________.

6. The process reaction curve allows you to determine the reaction rate and ________________ of the process.

7. Once the controller is tuned, you should _________ the process for the desired response.

8. Tuning software provides a way to simulate a process and __________ the optimal settings.

SEGMENT 4

CLOSED-LOOP TUNING

OBJECTIVE 11 DEFINE CLOSED-LOOP TUNING AND GIVE AN APPLICATION

Read This

Closed-loop tuning is a process that determines the PID settings for closed-loop operation by testing the system dynamics with the controller in the automatic mode (closed loop). Since the controller remains in the automatic mode, the controller continues to control the process while the settings are determined and changed. Two common closed-loop tuning methods are:

- Ultimate gain method
- "Short cut" method

Each method produces a different process response, as figure 43 shows. Just like the open-loop methods, the response curves are examined and the needed data is inserted into standard equations to determine the PID settings.

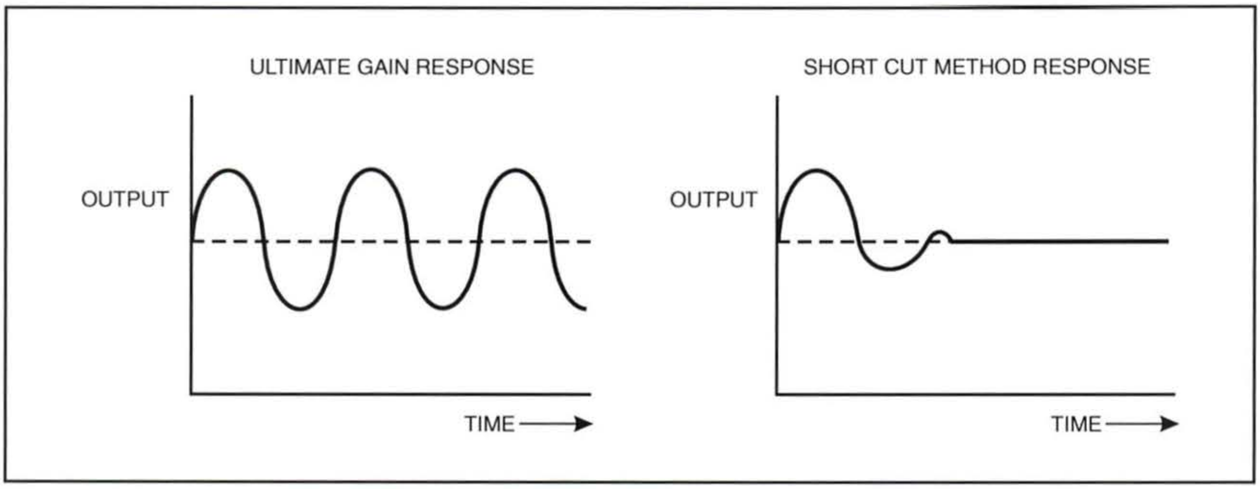

Figure 43. Process Response for the Ultimate Gain and Short Cut Methods

The advantage of closed-loop tuning is that it is more comprehensive than open-loop tuning because it includes the effects of control valve hysteresis and process dead time. By including these effects, closed-loop tuning enables the process to find a good compromise between tight control and fast response.

The disadvantage of closed-loop tuning is that since the controller continues to control the process during tuning, changes to the settings could have adverse effects on the process for a short time. Often, the decision to use closed-loop tuning depends on whether the process can tolerate the effects of the changes or is capable of being taken off-line temporarily.

Closed-loop tuning is used frequently in reactor pressure loops and temperature loops because it allows the controller to react to large errors in a way that does not result in a run-away condition. A run-away condition results when the controller reacts too quickly and drives the process out of control. Run-away conditions are undesirable because the system often cannot recover from them automatically, requiring the process to be brought under control manually.

OBJECTIVE 12 DESCRIBE HOW TO TUNE A LOOP USING THE ULTIMATE GAIN CLOSED-LOOP METHOD

The ultimate gain method is the closed-loop tuning method developed by Ziegler and Nichols in 1942. The goal of this method is to determine the ultimate gain of the system. The ultimate gain is the value of the proportional gain (K_p) that causes a stable sine wave response, as figure 44 shows.

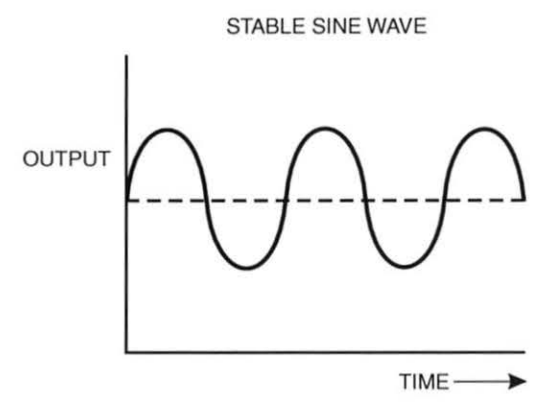

Figure 44. Stable Sine Wave Response to Ultimate Gain

The basic idea of this method is to increase the proportional gain in small increments until the stable sine wave response is achieved. Once this occurs, you can determine the ultimate gain and ultimate period of the sine wave. These values plug into standard equations that determine the needed PID settings.

The following steps describe how to use the ultimate gain tuning method:

Step 1: Set the controller so that only proportional control is active
Step 2: Bump the setpoint and create a response curve
Step 3: Adjust the gain until the response is a stable sine wave
Step 4: Determine the ultimate gain and ultimate period
Step 5: Calculate the PID settings using the ultimate gain and ultimate period
Step 6: Enter the calculated values into the controller
Step 7: Test the process for the desired response

Step 1: Set the Controller so that only Proportional Control is Active

Set the integral and derivative settings to a value that causes them to have no effect on the process. This usually involves changing the integral setting (reset time) to a high value and the derivative setting to zero. Next, change the proportional gain setting to a low value (e.g. 1.0).

Step 2: Bump the Setpoint and Create a Response Curve

Create a disturbance in the process. You do this by changing (bumping) the value of the setpoint for a few seconds and then returning the setpoint to its previous value, as figure 45 shows.

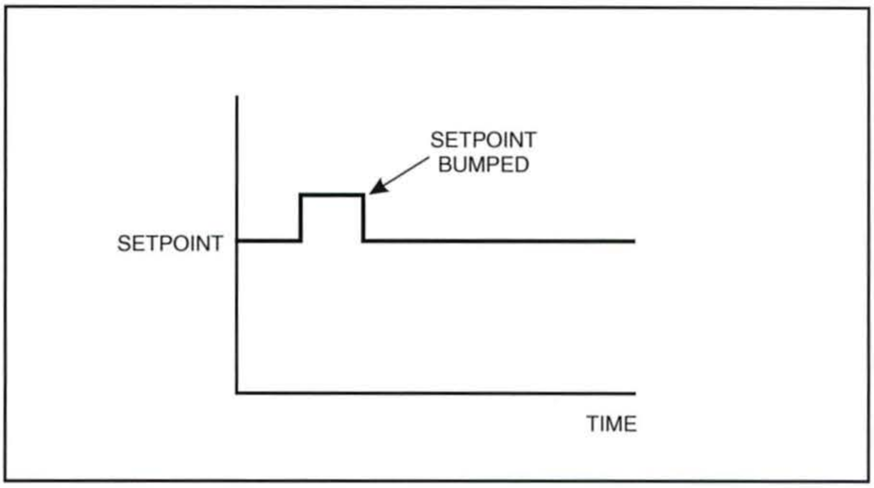

Figure 45. Bumping the Setpoint

Record the response of the process to the setpoint bump using a chart recorder or by hand. Use the data collected to create a reaction curve. The reaction curve indicates when the ultimate gain has been reached.

Step 3: Adjust the Gain until the Response is a Stable Sine Wave

Examine the reaction curve to determine if the ultimate gain has been reached. A stable sine wave, as shown in figure 46, indicates the ultimate gain. If the response shows a stable sine wave, proceed to the next step.

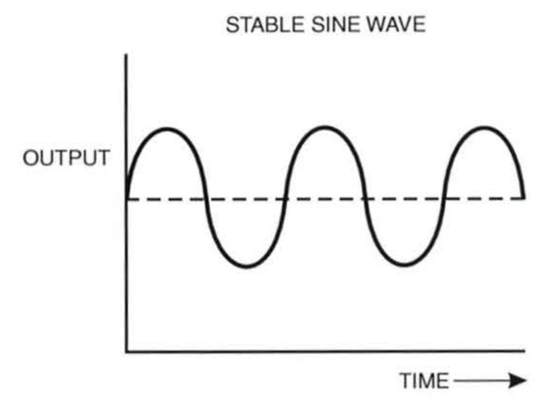

Figure 46. A Stable Sine Wave Response

If the reaction curve indicates an unstable system (continuously growing oscillations), as figure 47 shows, the gain is too high. Reduce the gain in small increments and repeat step 2 until the system displays a stable sine wave response.

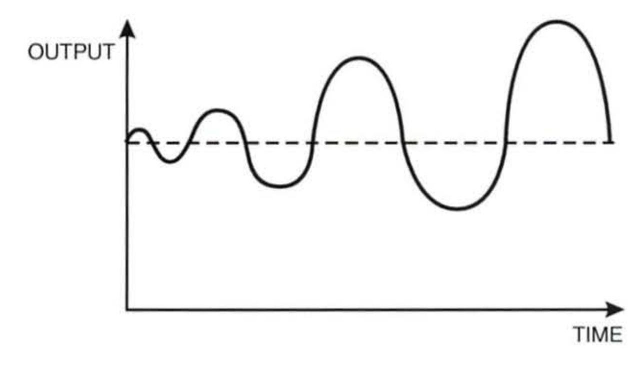

Figure 47. Unstable System Response

If the reaction curve damps out (oscillations decrease and stop), as figure 48 shows, the gain is too low. Increase the gain in small increments and repeat step 2 until the system displays a stable sine wave response.

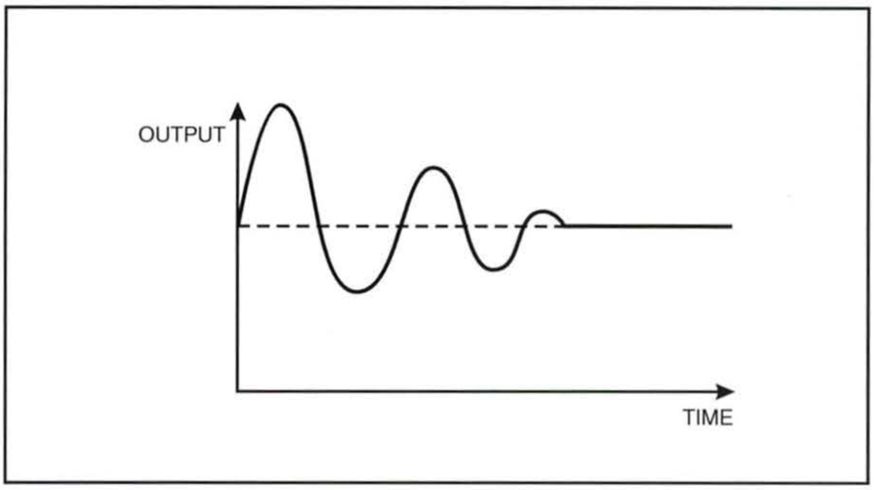

Figure 48. Response Damps Out

Step 4: Determine the Ultimate Gain and Ultimate Period

Once the system displays a stable sine wave response, the ultimate gain (K_u) is determined by simply reading the gain from the display of the controller. The ultimate period (P_u), sometimes also called the natural period, is determined by measuring the time it takes to complete one cycle, as figure 49 shows.

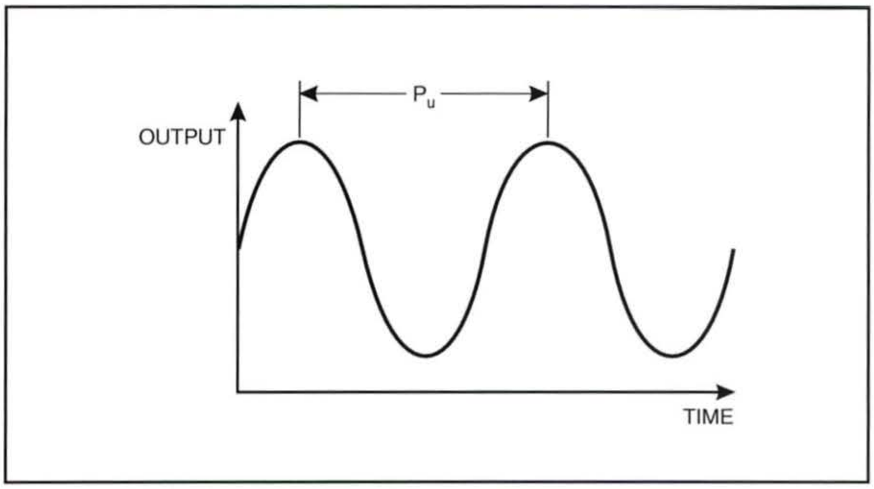

Figure 49. Ultimate Period Measurement

Step 5: Calculate the PID Settings using the Ultimate Gain and Ultimate Period

Insert the ultimate gain and ultimate period values determined in the previous step into the equations. Just like for the process reaction curve method, there are separate equations for each of the control modes (e.g. P only, PI, PD, and PID), as the table in figure 50 shows.

PID EQUATIONS - ULTIMATE GAIN METHOD	
CONTROLLER MODE	**EQUATIONS**
Proportional Only (K_p = Proportional Gain)	$K_p = 0.5 \times K_u$
Proportional + Integral (T_i = Reset Time)	$K_p = 0.45 \times K_u$ $T_i = P_u / 1.2$
Proportional + Derivative (T_d = Derivative Rate)	$K_p = 0.6 \times K_u$ $T_d = P_u / 8$
Proportional + Integral + Derivative	$K_p = 0.6 \times K_u$ $T_i = 0.5 \times P_u$ $T_d = P_u / 8$

Figure 50. PID Equations for Ultimate Gain Tuning

Step 6: Enter the Calculated Values into the Controller

After calculating the needed settings, tune the controller by entering the controller's setup menu and input the settings. Since the controller is still in the automatic mode, the system should respond immediately to the new settings.

Step 7: Test the Process for the Desired Response

Check the response of the system with the new settings using a chart recorder or by plotting the response by hand. If the settings are correct, the process response should indicate quarter wave decay. If not, retuning may be necessary.

SKILL 4 TUNE A CONTROL LOOP USING THE ULTIMATE GAIN CLOSED-LOOP METHOD

Procedure Overview

In this procedure, you will tune a level control loop on the T5552 using the ultimate gain tuning method.

❑ 1. Perform a lockout/tagout.

❑ 2. Perform the following substeps to set up the T5552, as shown in figure 51.

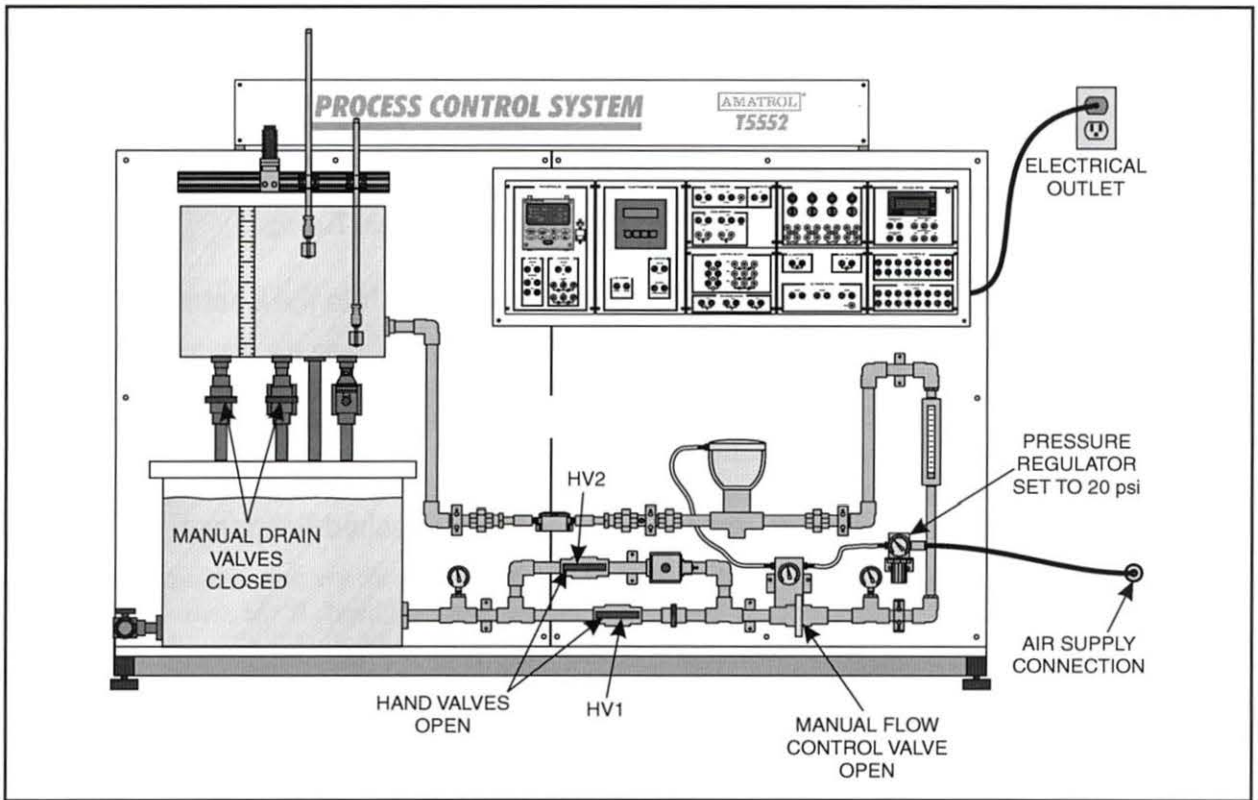

Figure 51. T5552 Setup

A. Connect the power cord to an available outlet.

B. Connect the air supply line to the T5552.

C. Set the pressure regulator to 20 psi.

D. Fill the reservoir tank with water.

E. Close the manual drain valves.

F. Connect the circuit shown in figure 52.

This circuit allows you to control the level of water in the tank using the PID controller.

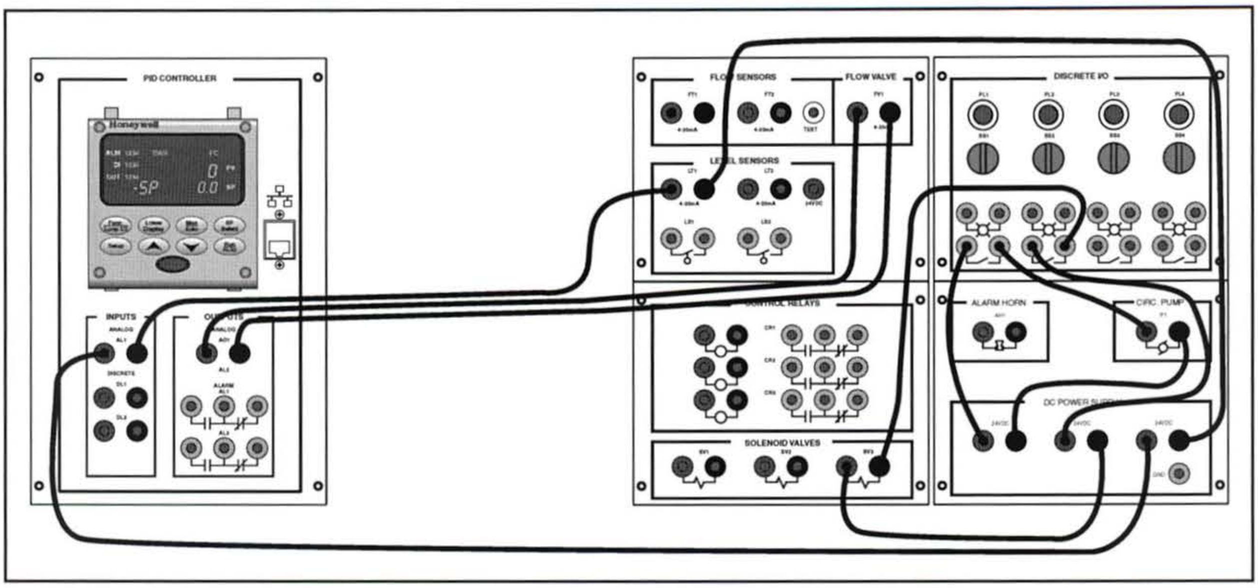

Figure 52. T5552 Setup

Figure 53 shows the P&ID for the T5552. The active components and wiring are highlighted.

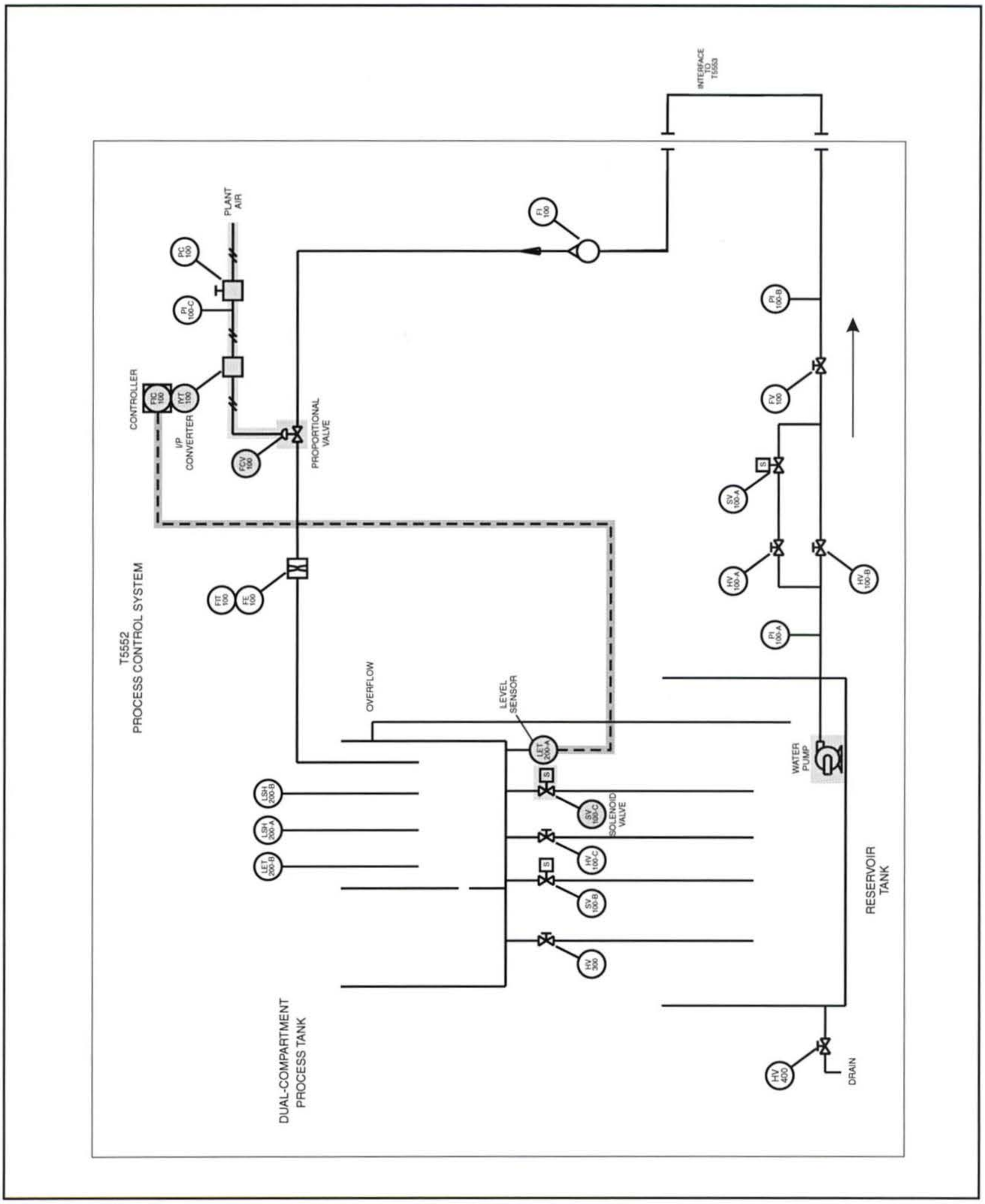

Figure 53. T5552 P&ID

❑ 3. Remove the lockout/tagout.

❑ 4. Change the set point of the PID controller to **3.0** inches.

Don't worry about the tuning parameters at this point.

❑ 5. Place the controller in the automatic mode.

❑ 6. Start the circulation pump by turning on **SS1**.

The process tank should begin to fill.

❑ 7. Open the solenoid drain valve (**SS2** on) when the level (PV) reading reaches 3.0 inches.

❑ 8. Allow the process to become stable.

❑ 9. Set the controller so that only proportional control affects the process.

This involves setting the integral time (RSET MIN) to a very high value (e.g. 50) and setting derivative rate (RATE MIN) to zero.

Setting the integral time to a high value does not completely eliminate the integral action. However, it does minimize its effects adequately for this method.

❑ 10. Set the proportional gain (GAIN) to **1**.

❑ 11. Create an upset by bumping the SP for a few seconds. Then, return the SP to its original setting.

❑ 12. Perform the following substeps to record the process response and create a reaction curve.

A. Check the response of the system by recording the value of the PV every 5 seconds using a table similar to the one in figure 54.

This data allows you to plot a response curve for the process.

PROPORTIONAL-INTEGRAL CONTROL RESPONSE							
TIME (seconds)	PV READING	TIME (seconds)	PV READING	TIME (seconds)	PV READING	TIME (seconds)	PV READING

Figure 54. Table to Record Response

B. Create a graph of PV vs. time, similar to figure 55, on a piece of graph paper.

You will use this to plot the response of the system.

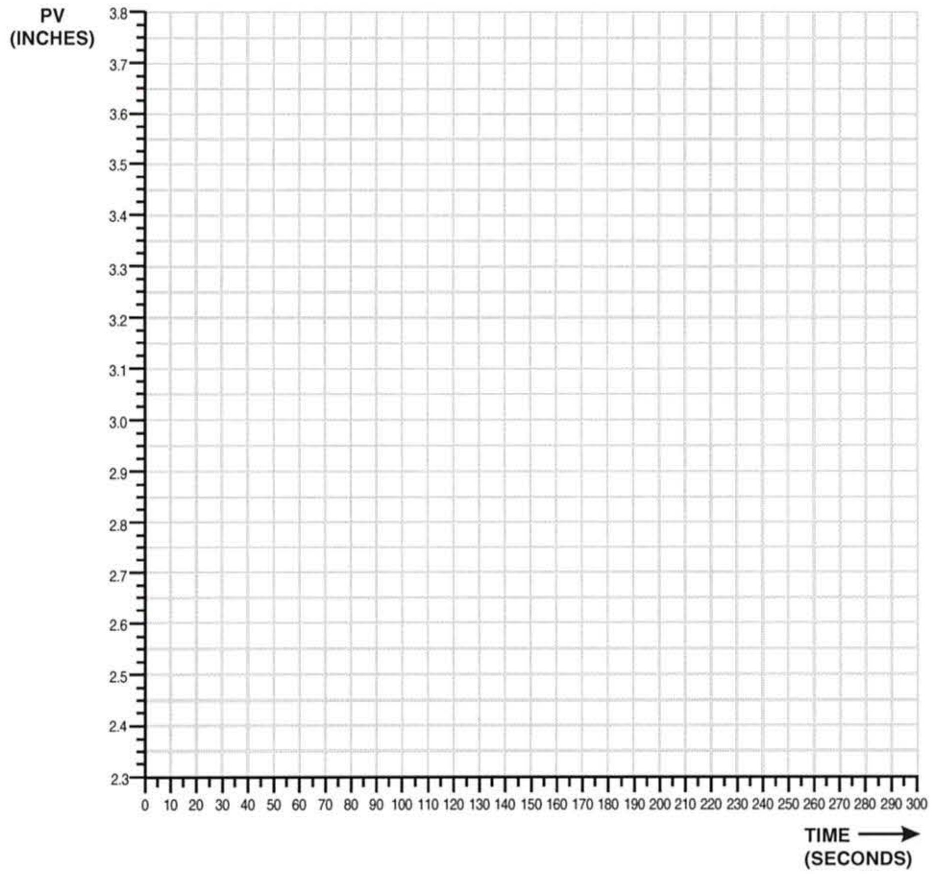

Figure 55. Graph of PV vs. Time

C. Plot the response using the data you collected in substep A.

D. Determine if the response is a stable sine wave.

Remember, you are looking for a response curve that shows continuous cycling, like the one in figure 56.

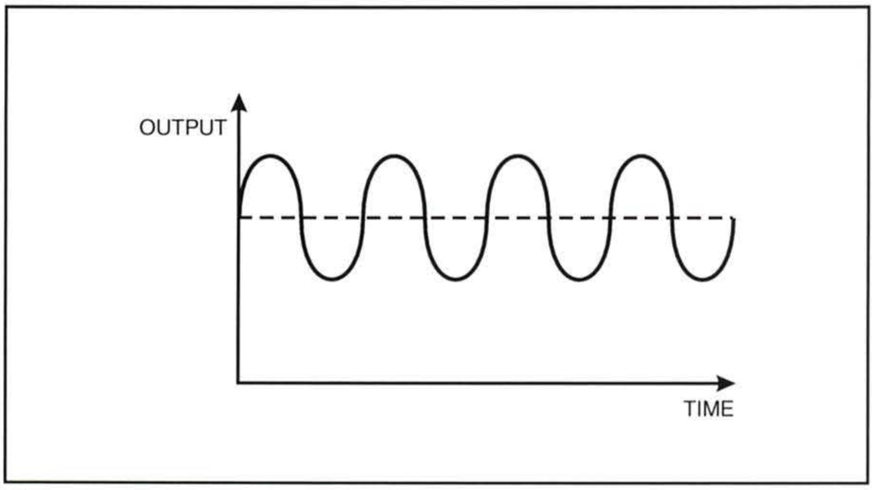

Figure 56. Response Curve Shows Continuous Cycling

If the response curve is damped out, as shown in figure 57, increase the proportional gain and repeat step 12. Repeat this process until you get the desired response.

NOTE

Make changes in the proportional gain in increments of 5 until you get close to desired response. Then, use smaller increments.

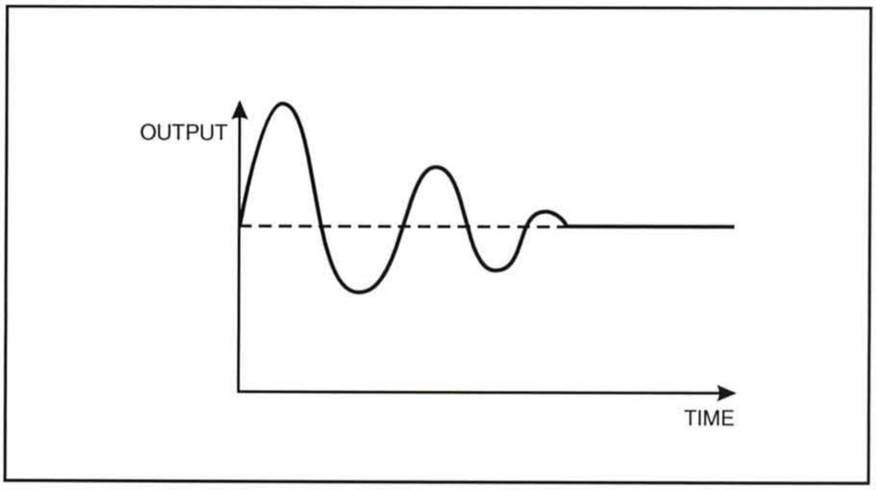

Figure 57. System Response Damped Out

If the response curve shows an unstable system, as figure 58 shows, decrease the proportional gain and repeat step 12. Repeat this process until you get the desired response.

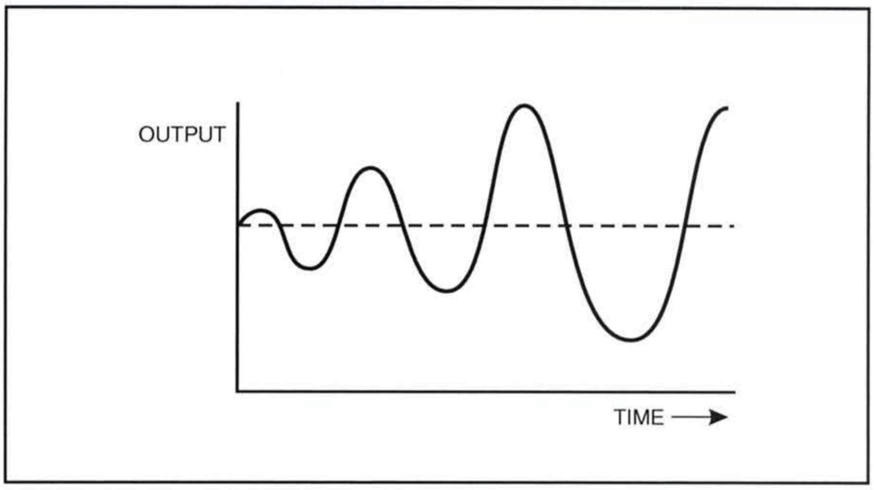

Figure 58. System Response Damped Out

❑ 14. Perform the following substeps to determine the ultimate gain and ultimate period.

A. Record the proportional gain value from the controller display. This is the ultimate gain.

K_u = ______________________

B. Determine the ultimate period by measuring one cycle of oscillation, as figure 59 shows.

This is the ultimate period.

P_u = ______________________

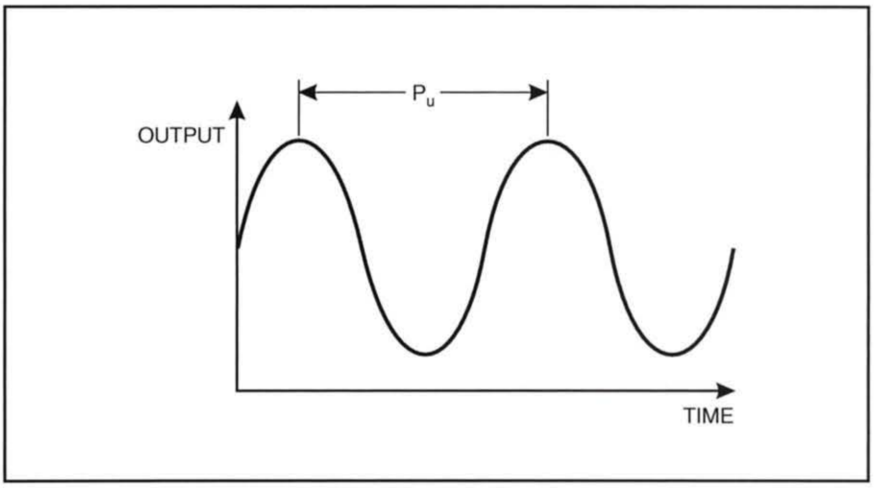

Figure 59. Measuring Ultimate Period

❑ 15. Perform the following substeps to calculate the controller settings to tune the level control loop using the ultimate gain method.

Assume you will use PI control.

A. Calculate the value for the proportional gain (K_p), using the appropriate equation from the table in figure 60.

K_p = ______________________________

PID EQUATIONS - ULTIMATE GAIN METHOD	
CONTROLLER MODE	**EQUATIONS**
Proportional Only (K_p = Proportional Gain)	$K_p = 0.5 \times K_u$
Proportional + Integral (T_i = Reset Time)	$K_p = 0.45 \times K_u$ $T_i = Pu / 1.2$
Proportional + Derivative (T_d = Derivative Rate	$K_p = 0.6 \times K_u$ $T_d = P_u / 8$
Proportional + Integral + Derivative	$K_p = 0.6 \times K_u$ $T_i = 0.5 \times P_u$ $T_d = P_u / 8$

Figure 60. PID Equations for Ultimate Gain Tuning

B. Calculate the value for the integral time (T_i), using the appropriate equation from the table in figure 60.

T_i = ______________________________

❑ 16. Perform the following substeps to tune controller using the settings you calculated in step 15.

A. Place the PID controller in the SETUP mode and set the proportion gain (GAIN) to the value you calculated in step 15A.

B. Set the integral setting (RSET) to the value you calculated in step 15B.

C. Make sure the derivative setting (RATE MIN) is set to zero to eliminate the derivative action.

D. Press the **Lower Display** key to return the controller to the control display mode.

❑17. Perform the following substeps to test the response of the process.

A. Make sure the controller is in the automatic mode.

B. Open the solenoid drain valve (**SS2** on).

C. Start the circulation pump (**SS1** on).

D. Record the value of the PV every five seconds in a table similar to the one in figure 61 until the system becomes stable.

This data allows you to plot a response curve for the process. If the controller is properly tuned, the response curve should indicate quarter wave decay.

PROPORTIONAL-INTEGRAL CONTROL RESPONSE							
TIME (seconds)	PV READING	TIME (seconds)	PV READING	TIME (seconds)	PV READING	TIME (seconds)	PV READING

Figure 61. Table to Record Response

E. Create a graph of PV vs. time, similar to figure 62, on a piece of graph paper.

You will use this to plot the response of the system.

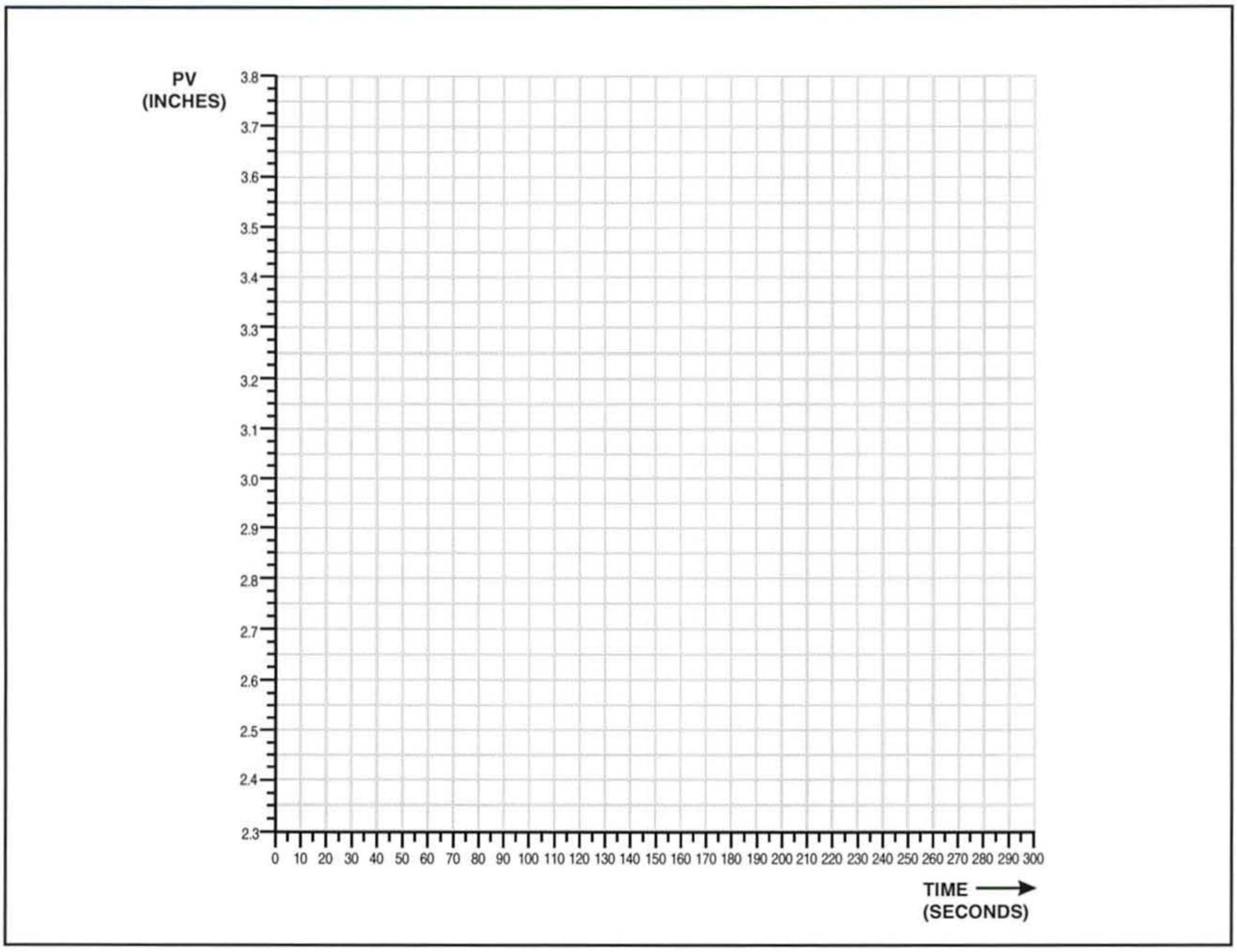

Figure 62. Graph of PV vs. Time

F. Plot the response using the data you collected in substep D. Your response curve should be similar to the one in figure 63.

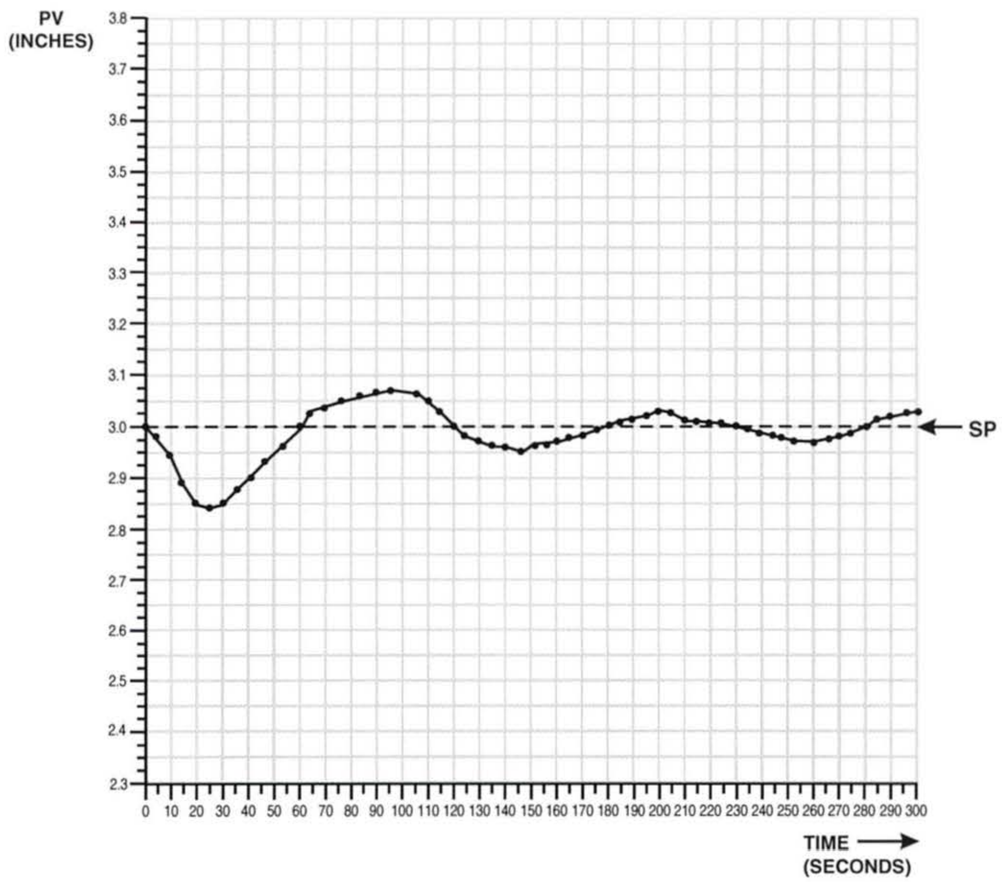

Figure 63. Response of the System (Quarter Wave Decay)

If you do not get the desired response (quarter wave decay), go back, check your calculations and retune the controller. Then, plot a new response curve.

❑ 18. Perform the following substeps to shut down the T5552.

A. Place the selector switch **SS1** in the **OFF** position (up). This will stop the circulation pump.

B. Place the selector switch **SS2** in the **OFF** position (up). This will close the drain solenoid valve.

C. Switch the controller to the manual mode.

D. Open both of the manual drain valves on the process tank to completely drain the tank. When the tank is empty, close both valves.

E. Turn off the main circuit breaker.

F. Disconnect the control circuit.

SEGMENT 4

SELF REVIEW

1. Two common closed-loop tuning methods are the ____________________ method and the "short cut" method.

2. Closed-loop tuning is used frequently in reactor pressure loops and temperature loops to prevent process ________________.

3. The ____________________ method is the closed-loop tuning method developed by Ziegler and Nichols.

4. The ultimate gain is the value of the proportional gain that causes a stable ____________________ response.

5. If the reaction curve damps out, the gain is too __________.

6. The ultimate ______________ is a measure of the time it takes to complete one cycle of the process oscillation.