ENERGY
MANAGEMENT
SERIES

16

FOR INDUSTRY
COMMERCE
AND INSTITUTIONS

Automatic Controls

Energy, Mines and Resources Canada
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PREFACE

Much has been learned about the art and science of managing energy during the past decade. Today, energy management is a seriously applied discipline within the management process of most successful companies.

Initially, in the early 1970's, energy conservation programs were established to alleviate threatened shortages and Canada's dependency on off-shore oil supplies. However, dramatic price increases quickly added a new meaning to the term ''energy conservation'' — reduce energy costs!

Many industrial, commercial and institutional organizations met the challenge and reduced energy costs by up to 50%. Improved energy use efficiency was achieved by such steps as employee awareness programs, improved maintenance procedures, by simply eliminating waste, as well as by undertaking projects to upgrade or improve facilities and equipment.

In order to obtain additional energy savings at this juncture a greater knowledge and understanding of technical theory and its application is required in addition to energy efficiency equipment itself.

At the request of the Canadian Industry Program for Energy Conservation, the Commercial and Institutional Task Force Program and related trade associations, the Industrial Energy Division of the Department of Energy, Mines and Resources Canada, has prepared a series of energy management and technical manuals.

The purpose of these manuals is to help managers and operating personnel recognize energy management opportunities within their organizations. They provide the practitioner with mathematical equations, general information on proven techniques and technology, together with examples on how to save energy.

For further information concerning the manuals listed below or regarding material used at seminars/workshops including actual case studies, please write to:

Industrial Energy Division
Energy Conservation Branch
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INTRODUCTION

Automatic Control is the name given to a broad range of hardware that is used to maintain controlled parameters such as temperature, pressure and level at a desired value under all operating conditions. Most Industrial, Commercial and Institutional facilities benefit from the use of automatic controls. The purpose of this module is to demonstrate how automatic control can improve the performance of many types of facilities while saving energy.

Automatic control provides many benefits and the reason for its use will vary according to application circumstances. The more common reasons for its use are listed below.

- Some processes could not be operated without automatic control. This might be because of process complexity, number of control tasks, speed of changes, or difficulty in interpreting measurement time lags and the required corrective action.
- More accurate and consistent operation with the use of automatic control results in better quality product and fewer rejects.
- Manpower can be relieved of the tedious task of minute by minute observations and process adjustments. This can make personnel available for more interpretative tasks.
- Automatic control consistently responds to the process disturbances in accordance with the "tuning" of the system. Conversely, operator reactions can vary according to influences such as alertness, attitude, and ability to interpret consistently within a shift and between shifts.

The foregoing benefits all represent dollar savings for the organization. Normally the savings do not result directly from automatic controls, but from the improved performance of equipment or processes to which they are applied. These could be in the form of a lower cost per unit of production, less waste, a superior product, or lower labor costs. Many of these benefits can be directly or indirectly translated into energy savings.

This module has been divided into the following sections to describe the concepts, purposes and uses of automatic control.

- *Fundamentals* of automatic control including the terminology, forms of control, and guidance for creating systems.
- *Equipment/Systems* which describes the types of automation which are available.
- *Energy Management Opportunities* are described with examples to demonstrate the diverse ways in which automatic controls can be used to save energy and dollars.
- *Appendices* which contain a glossary, tables, conversion factors and a checklist to assist in making Energy Management Opportunity assessments.

FUNDAMENTALS

The purpose of this module is to explain the concepts and principles of automatic control. This is a non-mathematical overview of the theory and practical considerations of automatic control. An understanding of basic instrumentation is desirable, and the reading of Measuring, Metering and Monitoring, Module 15, is a prerequisite to using this module.

Benefits

Automatic controls are commonly used in the Industrial, Commercial and Institutional sectors. The prime reasons for this acceptance are listed below.

- Precise and consistent operation which results in better product, greater throughput, fewer rejects, and fewer complaints.
- Operating personnel have more time to monitor other parts of the facility and perform equipment maintenance.
- Reduced costs, because of improved performance and less operator involvement.

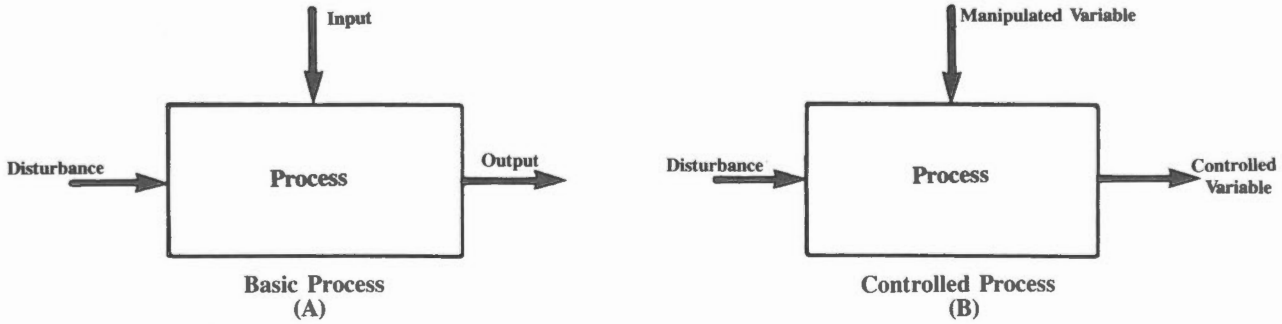
All of the foregoing benefits translate, directly or indirectly, into savings, a significant portion of which is related to energy.

Control Basics

Process Terminology

A universal process description is provided schematically in Figure 1. A *process* is a plant facility or operation where there is a physical or chemical change of matter, or conversion of energy. A process could be the controlled environment in a building, a heat exchanger or a boiler.

In a basic process (Figure 1A) the material subjected to the change is the *input*, and the resultant product is the *output*. There are always one or more *disturbances* which affect the operation of the process. Automatic control implies a controlled process (Figure 1B). The process output represents the desired final product having certain characteristics or specifications, so it is called the *controlled variable*. The process input, which must be varied to satisfy the controlled variable requirements and to offset the disturbances, is called the *manipulated variable*. *Disturbances* act on the process to drive the controlled variable away from the desired value. The controlled variable should be maintained at the desired value for all disturbances. The *set point* of the process is the desired value of the controlled variable.



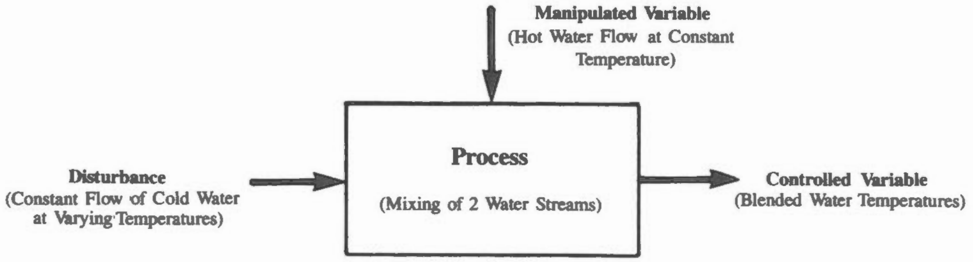
Basic Process
(A)

Controlled Process
(B)

Universal Process
Figure 1

The universal process control description can be easily converted to a specific process example (Figure 2). The universal terms have been retained, and the actual process conditions added, to further explain the terminology. This simple process involves the mixing of two water streams of different temperatures to achieve a desired blended water temperature. The process disturbance is the variation in the temperature of the cold water. The hot water flow rate is varied so that it, in combination with the cold water, provides the desired blended water temperature. Thus, the hot water flow rate is the manipulated variable and the blended water temperature is the controlled variable. The desired blended water temperature is the set point.

The Figure 2 process was described as having a single disturbance. Actually, there could be several simultaneous disturbances such as the identified cold water temperature, cold water flow rate, hot water temperature, and blended water discharge flow rate. Some field checks or calculations may be necessary to ensure that the conditions remain in reasonable balance, so that the controlled variable can be satisfied consistently by changing the manipulated variable. (Refer to “Importance of Process Knowledge” following in this section.)



Process Example
Figure 2

Measurement

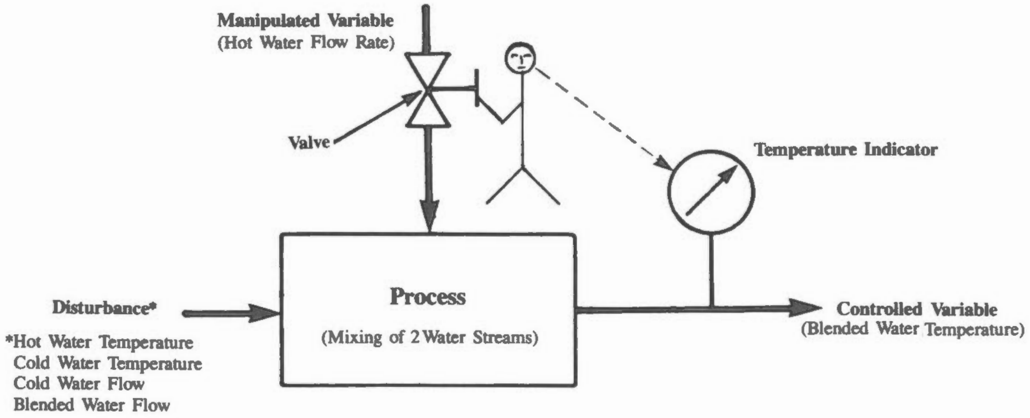
Accurate measurement is a prime requirement for good process control. The measuring element can be an integral part of a control device. This is the case for self-operated regulators and direct-connected controllers which are described under the heading of “Modulating Control”. The majority of automatic control devices do not measure the controlled variable directly. A transmitter is used to sense the process variable and to transmit a signal, proportional to the value of the measured variable, to the controller. This allows devices such as indicators, recorders and flow totalizers to be connected to the same transmitter output signal as the controller. It also permits several controllers and related instruments to be grouped in a central location for operating convenience or to avoid the need for personnel to be continuously located in a hazardous area.

Manual Control

One method of maintaining the water temperature at the set point value would be to install a temperature indicator and a manual valve (Figure 3). The operator can observe the water temperature and, with the set point temperature in mind, adjust the hot water flow rate by positioning the valve. This seems like a simple procedure, but it requires careful and consistent involvement by the operator. A manual control arrangement may not be satisfactory for a variety of reasons.

- The disturbances may be unpredictable with respect to magnitude and timing.
- The operator may not have sufficient time to concentrate on the process disturbances to make the correct adjustments (i.e. the quantity and types of controlled variables to be maintained may exceed the capabilities of process operators).
- Complications, such as time lag, could result in the operator making adjustments later than desired and then by too much. The difference, between when a disturbance occurs and when the controlled variable reflects the change, is called time lag.

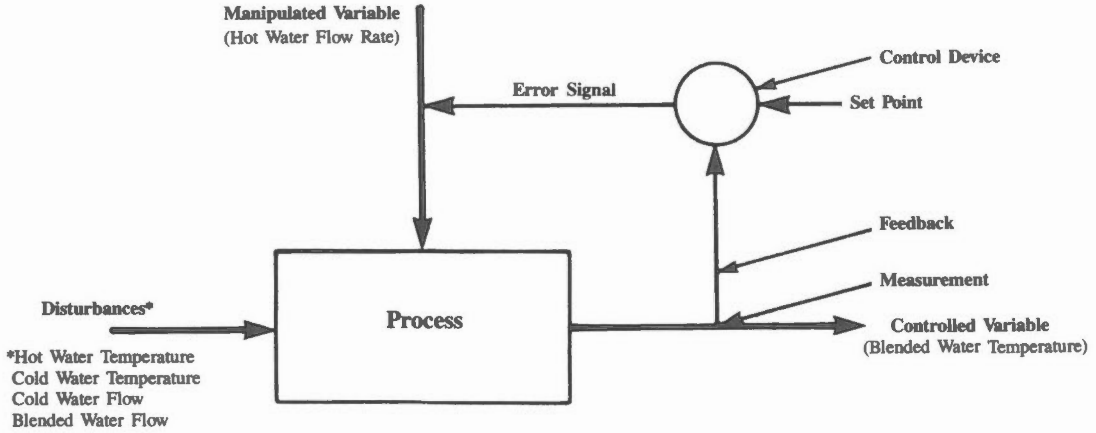
- Differing operator reactions to time lags will cause inconsistent control.
- Inability to keep personnel, who can understand and correctly interpret the process needs, can create problems.
- Lack of consistent operator attention and confusion during shift change periods can result in process errors.



Manual Control
Figure 3

Automatic Control

Automatic control could be used to eliminate the foregoing operator related problems and to provide superior process operation. The same process example can be used to determine how automatic control replaces the operator action on a consistent basis (Figure 4). Associated with the process, there are disturbances, a manipulated variable

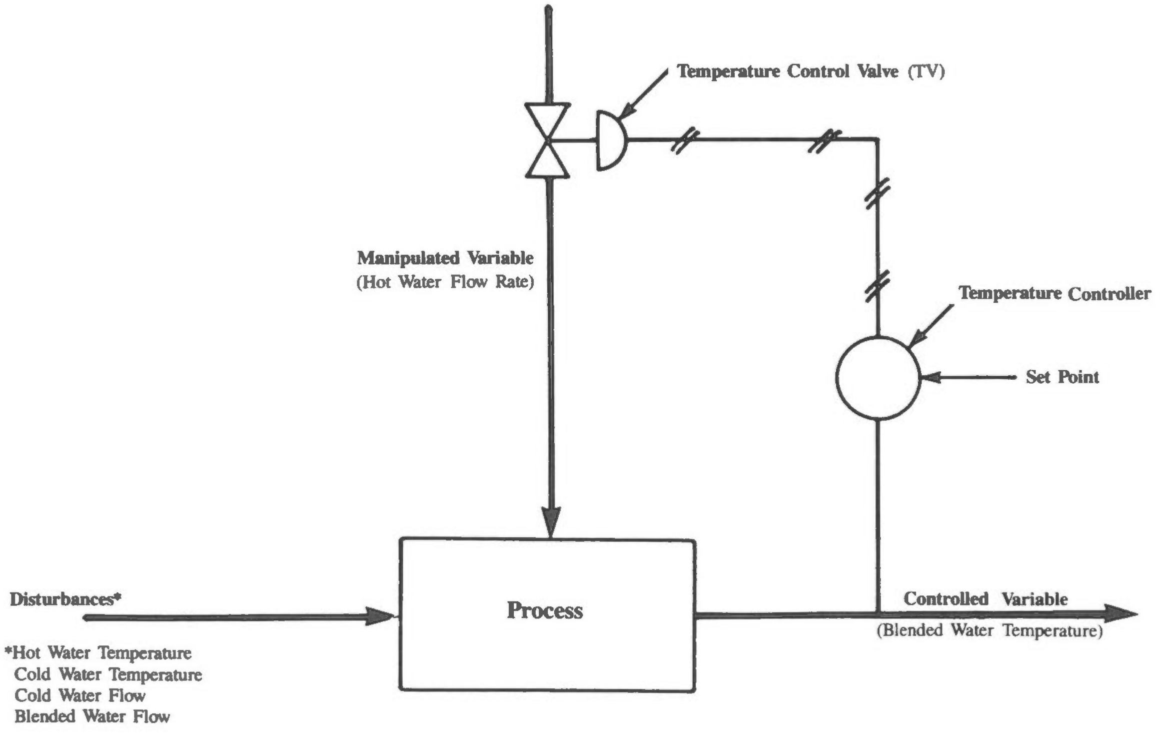


Feedback Control Concept
Figure 4

and a controlled variable. The controller can take many forms, but it must contain:

- A means of measuring the controlled variable to provide the feedback from the process.
- A means of introducing the desired set point.
- A mechanism for generating an output (mechanical, pneumatic, electrical or hydraulic) which is the result of the set point and the controlled variable measurement. The output can be thought of as an error signal (i.e. difference between set point and measured variable), which can be used to change the manipulated variable to eliminate the difference between the set point and the controlled variable measurement. The procedure of comparing the measured variable with the set point to produce a suitable control signal is called *feedback control*.

The feedback control concept can be applied specifically to the same process example by using symbols to represent instrument hardware (Figure 5). The temperature controller (TC) measures the blended water temperature and compares it with the established temperature set point. Based on the temperature measurement and the set point, an output signal would be developed to position the temperature control valve (TV) which would vary the hot water flow to keep the blended water temperature at or near the set point value. The *control valve is the final control element*, which means that it is the device that receives a control signal to directly or indirectly maintain a desired process condition. To summarize, the controller continuously measures the controlled variable, compares this process feedback measurement with the set point and sends a suitable signal to the final control element. In comparing the automatic operation represented by Figure 5 with the manual operation of Figure 3, it can be appreciated how the previously described control benefits can result.



Temperature Control Loop
Figure 5

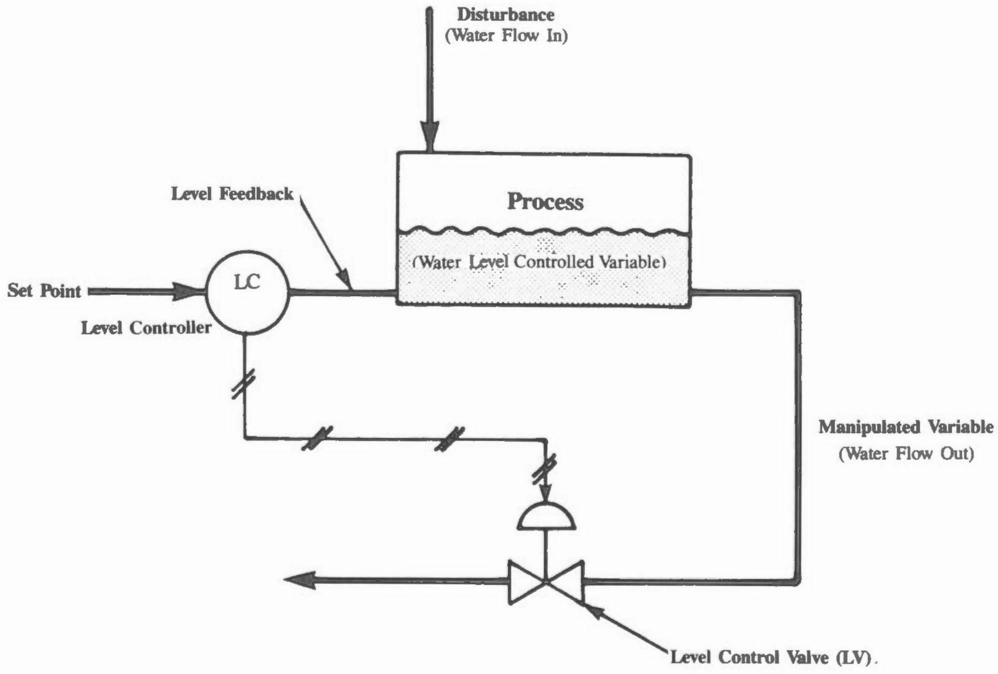
Almost all processes can be separated into the basic elements covered in this section so far. The universal type of schematic (Figure 1) could also represent a process that requires the control of water level in a tank (Figure 6). In this example, the process is a water tank, the controlled variable is the water level, the disturbance is the uncontrolled flow of water into the tank, and the manipulated variable is the flow out of the tank which is regulated by the control valve. The level controller (LC) senses the water level, compares it to the set point and sends a corrective control signal to the level control valve (LV).

There are usually several forms of control that can be selected for a given process application. The objective is to choose the type that provides suitable operation, is convenient for operating personnel, and is cost effective. The common types of control will be covered to assist with the selection and use of automatic controls.

Two-Position Control

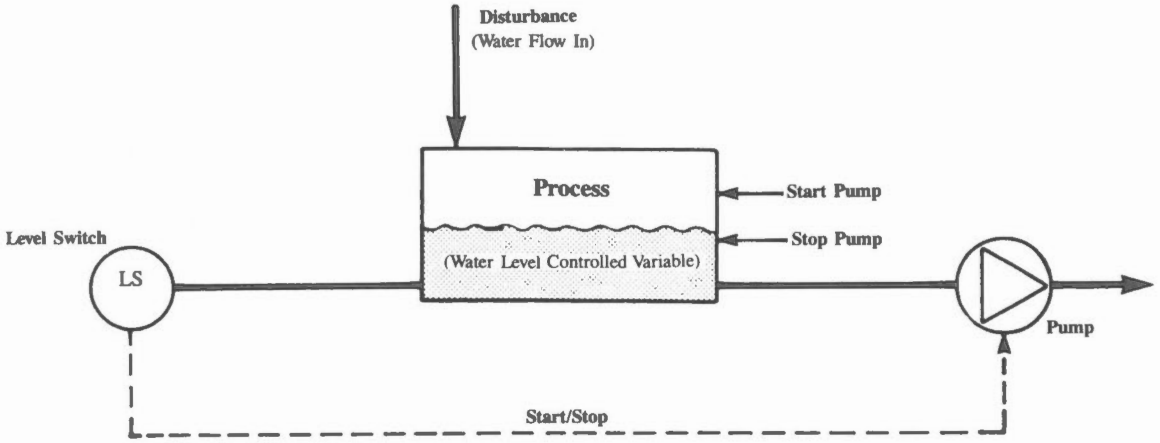
Two-position control is a lower cost form of control which is acceptable for many applications. The common form is one where the two positions represent "on" and "off" modes, while a variation of this might be "high" and "low". This type of controller is a switch that snaps to one position when the measured variable is greater than the set point and to the other position when the measured variable is less than the set point. Thus, the changes take place quickly and by an extreme amount. This may be fully acceptable or not stable enough for good process operation. Two-position control is best suited where:

- The measurement transfer lag is short so that the controlled variable responds quickly to changes in the manipulated variable.
- The capacity of the controlled variable is large enough to prevent excessive cycles between the two positions.
- Continuous cycling is not a problem and a deviation from set point is acceptable.



Level Control Loop
Figure 6

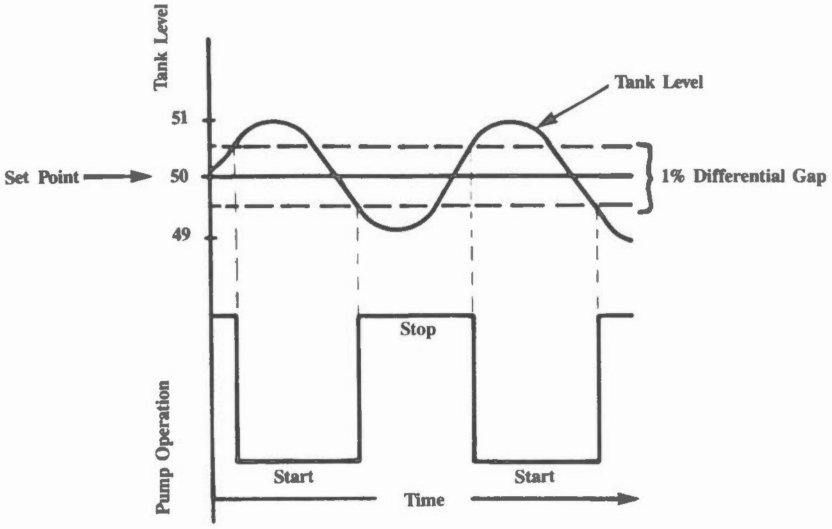
Two-position control also uses the feedback principle to control a process. Figure 7 shows a simple system where the process (tank level) is measured by a level switch (LS) that operates the pump in the tank discharge line. When the level rises to a predetermined point the pump is started. This causes the level to be pumped down to a point where the level switch stops the pump. In time, the tank level will rise to the point where the level switch will again activate the pump, and the cycle will be repeated. The key control characteristic of the level switch is the *differential gap*, which is the amount the controlled variable (water level) must change to cause the level controller (LS) to change from pump-on to pump-off or vice versa. Many control devices have an adjustable differential gap, so that the operation can be tuned to the process needs. The commissioning of this system would involve setting the tank level distance between start and stop points (differential gap) and adjusting the set point according to desired tank level (i.e. should the on/off action occur in the range of 40 per cent or 80 per cent tank level).



Two Position (On/Off) Control
Figure 7

Properly applied, this type of control should be able to maintain the controlled variable within 3 per cent of the upper range limit. If the tank level span was 0 to 5 metres, the variation might then be 0.15 metres (3 per cent of 5 metres). If this represented too great a level variation, then the differential gap might be decreased to 0.05 metres (1 per cent of 5 metres), but this would require the pump to be cycled more frequently. Figure 8 illustrates that the pump starts when the level increases to 50.5 per cent and stops when it drops to 49.5 per cent. The level curve shows how the cycle repeats and how the actual level overshoots the differential gap at the upper and lower operation points. If the level switch was set for 2 per cent instead of 1 per cent differential gap, the amplitude of the tank level variations would increase and the start/stop cycles per unit of time would decrease.

Reference was previously made to the applicability of this type of control depending on the capacity of the process controlled variable. The objective is to maintain adequate control of the controlled variable while avoiding excessive on/off cycles that could damage equipment. In the process example (Figures 7 & 8), there could be suitable capacity if the tank cross sectional area was significant relative to the rate of the flow in and the discharge pumping flow rate. However, to take this example to an extreme, if the tank diameter is only 300 mm, a pump could quickly reduce the level to the lower control point, where the pump would stop briefly before restarting. The operation would be unstable under this condition. A few examples of where two position control has been used successfully are tank and sump level, space heating, and drum steam pressure on small boilers.



Two Position Control of Process
Figure 8

Modulating Control

Concept

Although two-position control is the lowest price method it may be unacceptable in terms of the process. A continuous form of control may be necessary to smooth out the process operation, and to maintain the controlled variable closer to the set point value. Thus, it is important to understand the forms of modulating control that are available, so that the best combination of performance and cost is obtained.

Modulating control is any form in which the manipulated variable can be set to any position within the control range to maintain the controlled variable at set point. In current technology this term is used for certain mechanical and hydraulic controllers, pneumatic and electronic analog controls, and the simulated analog type of control which is achievable with computers. The distinction between analog and digital signals should be clarified before the various control actions are described.

- An analog measurement or control signal is one that can be continuously observed. A conventional watch with hands is an example, in that the hands are always moving to continuously identify the time.
- A digital signal is one where the information is presented in the form of a set of discrete numbers. A digital watch may show hours, minutes and seconds, but it does not provide a continuous indication like the watch with the hands. In practical terms, it does show the time changes as frequently as would normally be needed, and, in fact, the time can be read more accurately than from a watch with hands.

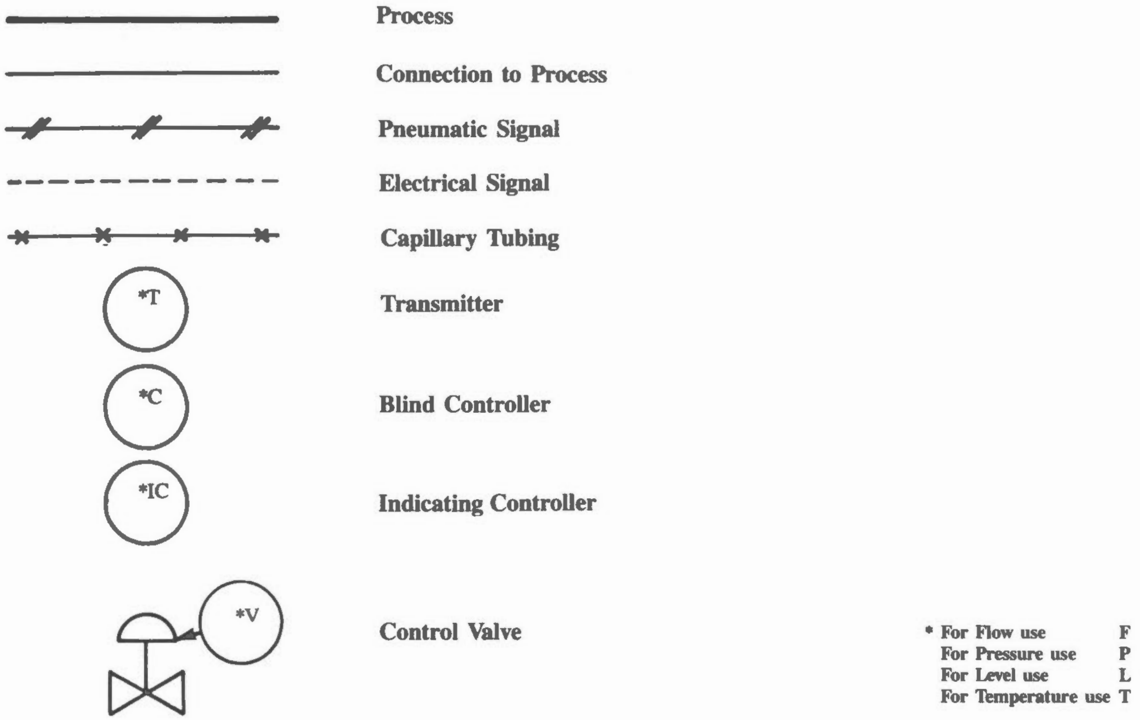
Signal Systems

The basic forms of transmitters are pneumatic and electronic. The considerations for selecting the type of signal include:

- *Pneumatic signals* normally have a signal range of 21 to 103.5 kPa(gauge) that is transmitted through copper or plastic tubing. The most serious limitation is the time delay in transmitting a changing measurement or control signal great distances. The transmission distance for pneumatic control loops should be limited to 150 metres.
- *Electronic signals* are limited to distances of 1500 metres which covers almost all Industrial, Commercial and Institutional facilities. For this reason, plus the additional benefit that the signal is compatible with computers, this type of signal has surpassed the pneumatic system in terms of use. The most common signal is 4 - 20 mA.

An understanding of a few of the basic equipment and signal symbols used for process control schematics can be helpful (Figure 9).

It is now appropriate to review the various forms of modulating control that can be used to maintain efficient operation.



Typical Instrument Symbols
Figure 9

Self-Operated Regulators

A regulator, in automatic control terminology, is a device that measures, controls and throttles in a control loop (Figure 10). In other words, a regulator is self contained and requires no external source of motive power such as air or electricity. Normally it utilizes the pressure of the controlled medium for its motive force.

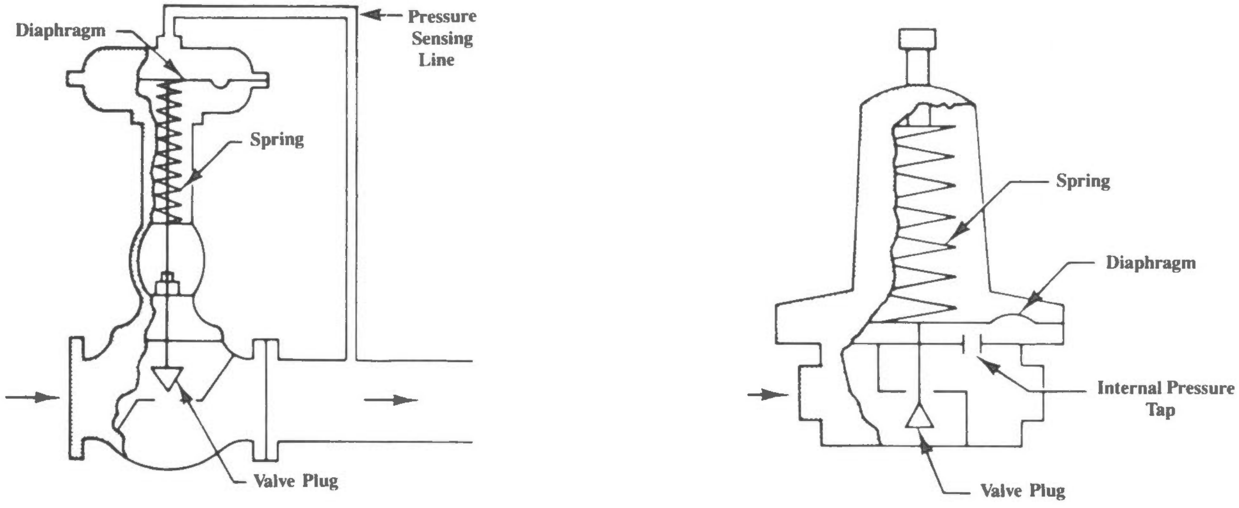
Table 1 summarizes the advantages and disadvantages of self-operated regulators. They usually cost less than the combination of control valves, transmitters and controllers, and they are cheaper to install and maintain. For sizes greater than NPS 6 the economic advantage of regulators disappears and the control valve, controller and transmitter combination becomes financially attractive.

Regulators have a built-in controller and sensor and do not require an air supply. They are not subject to air supply failure and can be installed in locations prohibitive to control valves. Regulators are limited by the materials of construction, pressure and temperature ratings, and they cannot be remotely monitored or controlled. Theoretically, there can be as many types of regulators as there are process properties, but the most common applications are for the control of level, flow, vacuum, pressure and temperature. The two most important types are pressure and temperature regulators.

Direct-Connected Controllers

Direct-connected controllers have a built in process measurement capability and are a logical extension to self-operated regulators. The distinction is that they can provide three additional and significant operating benefits.

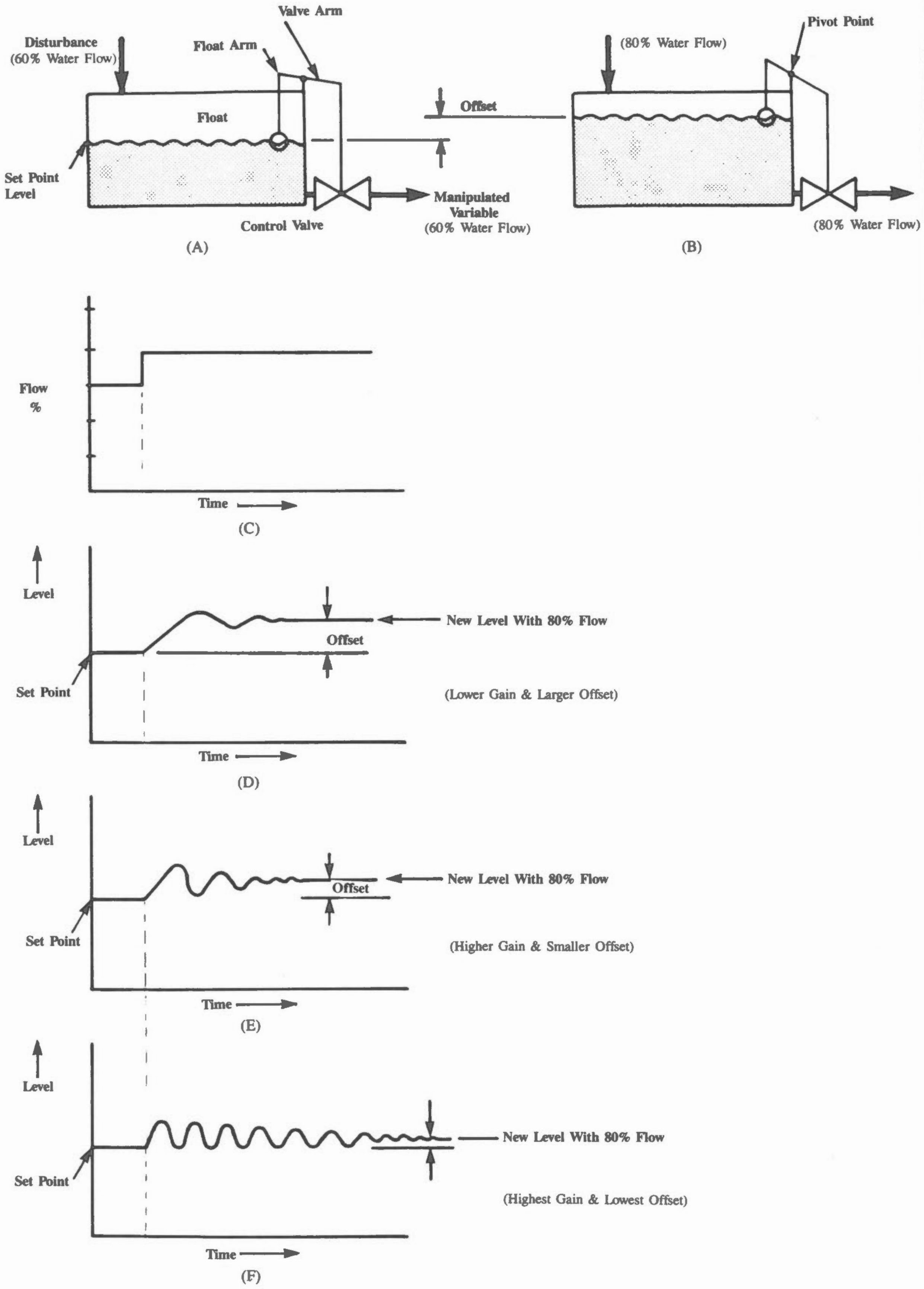
- Multiple control modes that can be selected and tuned for better operation.
- The controller output is a signal which allows the final control element to be located remotely. This permits greater flexibility in the layout of the process and related piping.
- The controller could contain an auto-manual switch to permit automatic or manual control of the final control element.



Self-Operated
Pressure Reducing Regulators
Figure 10

REGULATOR VERSUS CONTROL VALVE
TABLE 1

	Advantages	Disadvantages
Regulator	• Lower cost in small sizes • Size is smaller compared to equivalent control valve • Lower installation costs • Built in controller and sensor • Built in indication of process measurement is available	• Remote control is impossible • Set point adjustment must be made at regulator • Control action is proportional only, thus offset occurs • Materials of construction are limited • Limited applications due to temperature and pressure limitations of the body design.
Control Valve	• Used with remotely located controller with any type of control mode • Wide variety of materials of construction • No limitation in the fail-safe position • Interchangeable between many services and conditions • Wide variety of valve body designs • Variety of actuators	• Greater cost • Installation cost is greater • Power source, usually air, is required • Power source subject to failure • Heavier and more bulky



Proportional Control
Figure 11

Proportional Control

A proportional controller output has a predictable linear relationship with the deviation (error signal) between the set point and the controlled variable. This relationship can be effectively illustrated by the process example and control response curves (Figure 11). The float and control valve arrangement is not a typical form of proportional control hardware, but it is useful to explain the principles involved.

The proportional control action results from the float in the liquid, which is connected by means of linkage to a control valve. The process is first shown with the level at set point and the flows in and out of the tank equal at 60 per cent of design capacity (Figure 11A). The water inflow, which is the disturbance, suddenly increases with a step change to 80 per cent of capacity (Figure 11C) to make the tank level rise. The float rises with the level increase, and this causes the linkage connected to the float to rise and the linkage connected to the control valve to move down. This downward motion of the control valve linkage causes the valve to open proportionally allowing the water flow rate out of the tank to increase. Eventually, the system re-establishes equilibrium (Figure 11B): the float having positioned the control valve so that the manipulated variable (80 per cent water flow out) equals the disturbance (80 per cent water flow in).

The sensitivity (gain) of the controller can be adjusted by changing the float and valve arm lengths. If the float arm was shortened and the valve arm lengthened, 100 per cent control valve travel would occur for a smaller variation in tank level. This would give the controller a greater gain.

There are three level versus time responses shown for low to high gain settings (Figures 11D, 11E, and 11F). It should be noted that there is always some offset in tank level when the disturbance is at a different flow rate than that which existed when the system was set up. This is a characteristic of proportional control and it cannot be avoided. However, the offset is decreased as the gain is increased. Unfortunately, unstable conditions can be created if the gain is too great. Often, this limitation of having some offset is acceptable, and this simple and less expensive type of modulating control can be used.

Gain is a number without units which can be shown in equation form.

$$\text{Gain} = \frac{\text{\% Change Controller Output}}{\text{\% Change Input Error}}$$

Where, (1) For the Figure 11 example, the controller output would be measured in terms of per cent of valve opening.

(2) Error signal = Level Set point — Actual Level

If the maximum tank level variation was 160 mm, then this would be considered to be 100 per cent. If the difference between the set point and actual level was 40 mm then:

$$\text{\% Change Input Error} = \frac{40}{160} \times 100 = 25\%$$

Thus, if a deviation between the set point and actual water level of 40 mm caused the control valve to go through 100 per cent of valve travel the gain would be expressed as:

$$\text{Gain} = \frac{100\%}{25\%}$$

$$= 4$$

This is a fairly high gain which should keep the level offset small. A typical lower gain might require the level error to be 160 mm (100 per cent of maximum variation) to stroke the control valve 100 per cent. The gain of this arrangement can be calculated:

$$\text{Gain} = \frac{100\%}{100\%}$$

$$= 1$$

Proportional band is an alternative term for gain. Proportional band is the inverse of gain and can be expressed.

$$\text{Proportional Band} = \frac{1}{\text{Gain}} \times 100$$

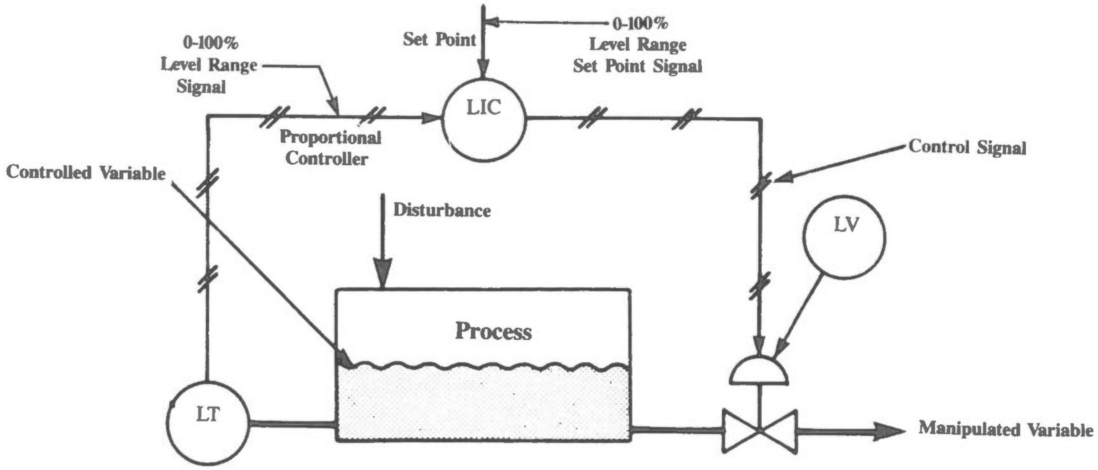
For the previous two gain calculations the equivalent proportional bands are:

$$\text{Proportional Band} = \frac{1}{4} \times 100 = 25\%$$

$$\text{Proportional Band} = \frac{1}{1} \times 100 = 100\%$$

A general type of proportional control loop can be used to demonstrate how gain is determined with a more typical proportional controller (Figure 12). The level transmitter (LT) is designed for a certain range of tank level that causes the transmitter signal to go from 0 to 100 per cent. There is an adjustable set point signal which uses the same signal range as the transmitter and the 0 to 100 per cent variation of this signal represents the same range of tank level as the level transmitter calibration. The proportional level controller has two functions:

- To establish the error signal between the set point and measured variable signals (% set point signal - % measured signal).
- To apply a gain adjustment to the error signal.



Proportional Controller
Figure 12

Assume that the process was in equilibrium when the level transmitter and set point signals were both 40 per cent and the controller output signal to the control valve was 50 per cent. Suddenly the disturbance increased the tank level to 50 per cent of range, the set point remained at 40 per cent and the controller output changed to 80 per cent to open the control valve more. The controller gain can be calculated with the previously presented gain equation:

$$\text{Gain} = \frac{\%\ \text{Change Controller Output}}{\%\ \text{Change Input Error}}$$

$$= \frac{80 - 50}{50 - 40}$$

$$= 3$$

To summarize, proportional control is quite straightforward to use, and the cost is average. The main disadvantage is that there is an offset for all conditions except those existing at the time of calibration. If the offset is not acceptable for the process, the form of control will have to be made more sophisticated. Relative to two-position control, proportional control provides greater opportunity for tuning to smooth out the process operation and achieve more uniform control.

Reset Control

Reset control action is a control technique, which can be used to eliminate the disadvantage of offset that is characteristic of a proportional controller. Reset is more commonly used in combination with proportional control, but it will first be described separately. It is useful to clarify some terms:

- Integral control action is a term that is used interchangeably with reset in the instrumentation industry.
- When reset (integral) control action is used by itself it is usually called proportional speed floating.

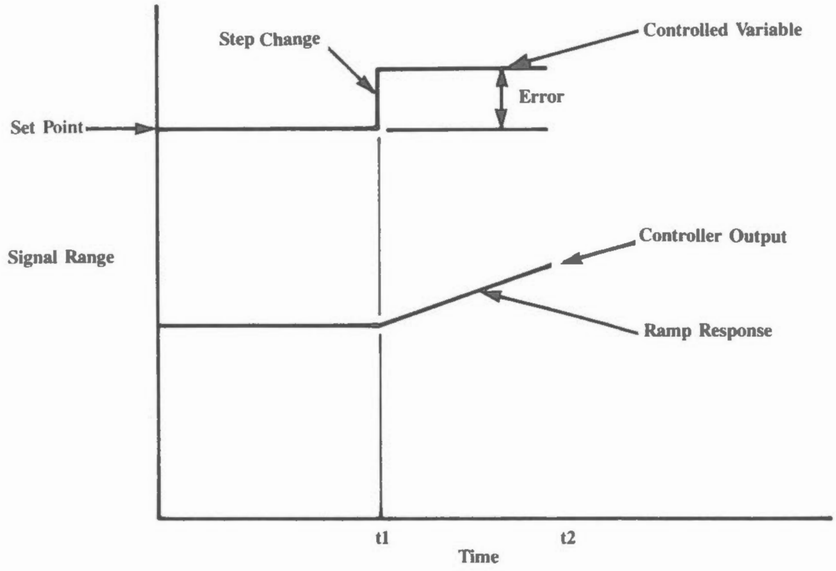
The output of a reset controller varies in accordance with the magnitude of the error signal (set point-controlled variable) and the duration of the error. The term "integral" originates from the mathematical expression that states that the output of the controller is equal to the time integral of the error signal.

The controller response is illustrated schematically in Figure 13. Initially, the controlled variable is at the set point value and the system is in equilibrium. At time t_1 there is a disturbance to the process that changes the controlled variable in the form of a step. This creates a constant error signal in the time period from t_1 to t_2 which results in the controller output changing at a constant rate in an attempt to eliminate the error signal. Figure 13 does not show the controlled variable being brought back to the set point, but this would eventually happen. Basically, the output of this type of controller will change to any value within the output signal range, to alter the manipulated variable so that the controlled variable is maintained at the set point.

The reset action is adjustable and it should be noted that the adjustment on a controller might be indentified in two different ways:

- Reset rate in repeats per minute. This is the number of times that the error signal is duplicated as a change in the controller output signal within one minute. Electronic controllers have a broad range of adjustment of 0.1 to 100 repeats per minute.
- Reset time is the time in minutes that is required for the error signal to be duplicated once in the controller output signal.

Normally, reset control action is used in conjunction with proportional action and this is covered next.



Reset Control Action
Figure 13

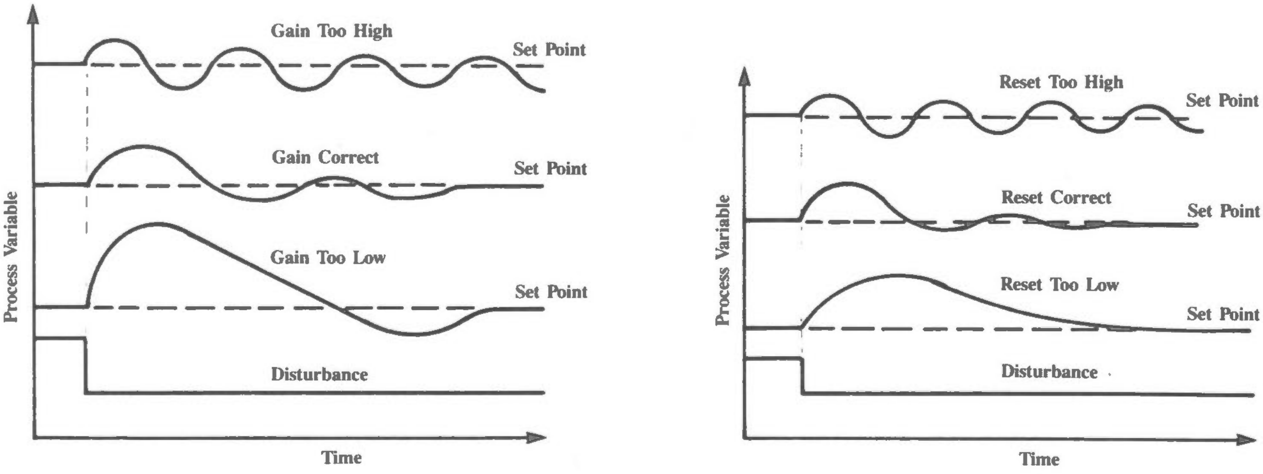
Proportional-Plus-Reset Control

Depending on the manufacturer, this type of controller could be called any one of several names. It is important to recognize the alternative names.

- Proportional-plus-integral.
- Proportional-plus-reset.
- PI control.

Proportional-plus-reset control is the most widely used combination of control modes. The proportional and reset control actions can be considered separately, as previously covered, with the understanding that the output of the two individual modes is summed before leaving the controller. It has been shown that for a step change error signal (set point - controlled variable), the proportional action is also in the form of a step change, while the reset action is in the form of a ramp change. The summing of the two responses means that the controller output immediately changes in the form of a step and then the ramp action starts to drive the controller output further in the same direction. The size of the step portion of the controller output change is a function of the gain setting, and the slope of the ramp is a function of the reset adjustment. The gain action gives the manipulated variable "a kick", then the reset action seeks the new controller output necessary to maintain the controlled variable at the set point value without any offset.

Figure 14 illustrates how the gain and reset settings can influence the manner in which the controlled variable is returned to set point. It is interesting to note that the reaction within the process is almost identical when either the gain or the reset is too high, and it is similar again when these settings are too low.



Proportional-Plus-Reset Controller Response
Figure 14

Rate Control

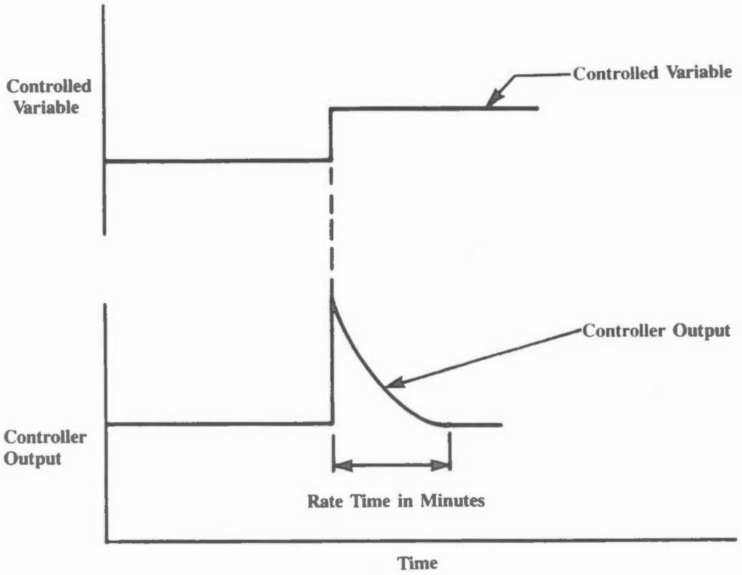
Rate (derivative) control action is normally used with proportional and reset control modes, but it is shown separately to help convey the unique action of this mode of control (Figure 15). Rate action creates a large initial controller output reaction which dissipates with time. Thus, it gives the corrective control action an initial boost allowing the manipulated variable to change quickly and return the controlled variable to normal or near normal. The rate adjustment of a controller, which is a measure of how quickly the initial action is removed from the controller output, might range from 0.1 to 25 minutes.

Rate control is used to counteract the time lags in some processes such as those involving the transfer of temperature changes.

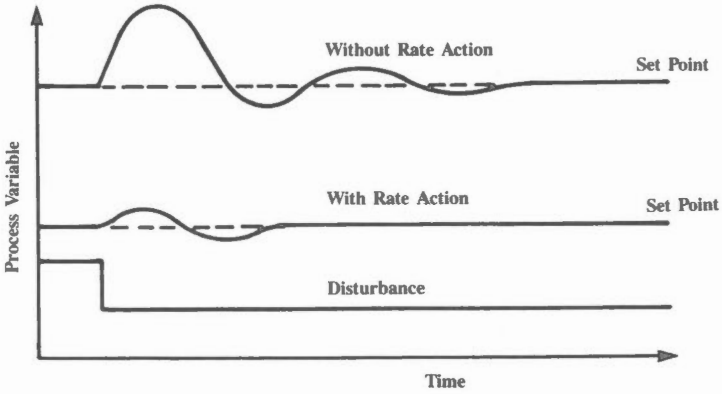
Proportional-Plus-Reset-Plus-Rate Control

This is often referred to as a PID Controller with the letters coming from the combination of control modes (i.e. Proportional, Integral and Derivative). It is also referred to as a three mode controller. A PID controller is normally used with processes having long time lags, and it must be used with discretion because it is difficult to tune successfully. One convenient feature is that, if there is concern about the ability of a PI controller to satisfy the process, a PID controller can be bought and, if the derivative action creates instability, this mode of control can be turned off. The only disadvantage then is the cost paid for an unused feature.

Figure 16 demonstrates how it is possible for the rate action to reduce the initial deviation of the controlled variable from set point and for the faster return of the process to set point.



Rate Control Action
Figure 15



PID Controller Response to Changes in Load With and Without Rate Action
Figure 16

Final Control Elements

Function

The term "final control element" and the function of it have already been introduced in the text and the process schematics. The final control element is used to change the manipulated variable to make the controlled variable equal to the set point.

Control valves are the most common form of final control element. An actuator of some form positions the valve, but the complete assembly can be classed as the final control element.

Control drives and other forms of cylinder operators are used to position linkage that could move dampers, fan inlet louvres, variable speed drives, and many other final control devices. Automatic feeders can also be used as final control elements.

Positioners

There are many hardware types of control valves and some of these are covered in the Equipment/Systems section. They are often equipped with a positioner to obtain the following benefits.

- Improved response of the final control element, particularly in pneumatic systems, by overcoming mechanical friction in seals and bearings, and unbalanced forces on a valve plug.
- Greater power to move the final control element. In the case of a pneumatic system, the air supply to the positioner can be much greater than the control signal, to provide a greater driving force.
- The feedback mechanism between the positioner and the final control element can be used to eliminate the effects of friction and hysterisis.
- Some positioners utilize cams in the feedback mechanism, to modify the characteristics of the relationship between the control signal and the manipulated variable.

Control Valve Sizing

The proper selection of a control valve requires full knowledge of many factors including the process, the user's design criteria, and cost limitations.

A control valve is a variable orifice used to regulate flow of a liquid, gas or vapor. In order for the valve to regulate flow, some energy must be absorbed in the form of a differential pressure across the valve. Thus, in practical terms, a control valve is an energy dissipator. The greater the amount of regulation, the greater the amount of energy absorbed by the valve, owing to the increase of differential pressure across the control valve.

The function of a control valve in a process at the minimum and maximum flow rates can be demonstrated schematically (Figure 17). The pressure losses through the process are lower at minimum flow and higher at maximum flow. The control valve provides the adjustment to the pressure loss profile so that the required system outlet pressure is always satisfied. This explains why the differential pressure across a control valve will be greater at minimum flow capacity and lower at maximum flow capacity. An excessive pressure drop represents an energy loss. However, too low a pressure drop across the valve, relative to the rest of the process pressure drops, can result in poor control.

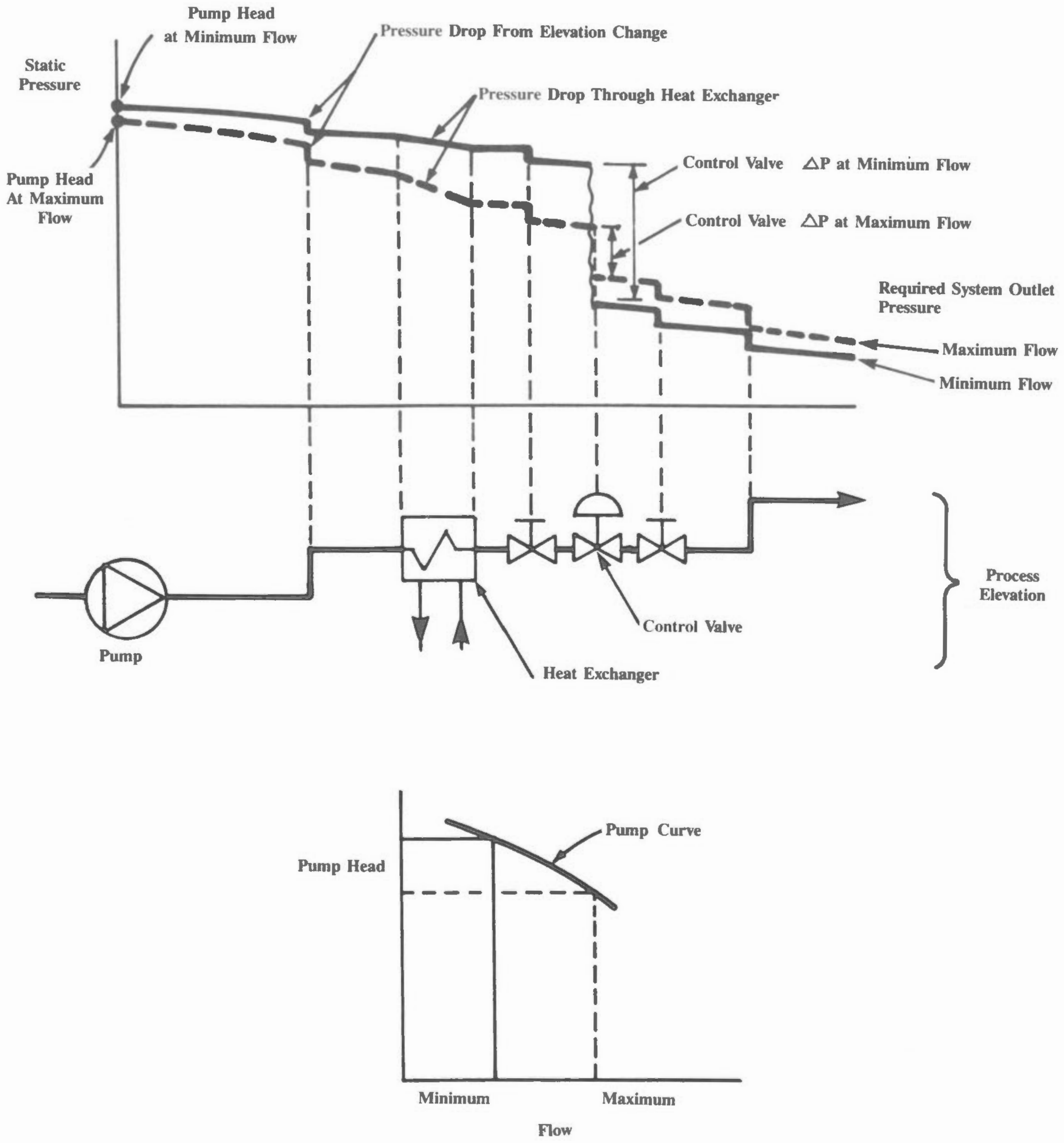
Correct sizing of control valves is necessary to optimize operations, minimize capital cost and provide sufficient capability to control the fluid. Unfortunately, some control valves are sized with rough physical data and many safety factors are used. This often leads to a valve size selection being larger than needed because of the thought that "it is better to be too big than too small". This leads to a problem of poor control because of the valve being nearly closed under normal conditions and to premature wear on parts of the valve plug. Further, oversized valves are expensive and they cannot provide the turndown ratio required for good control.

The control valve must have greater flow rangeability than the process requirements. The process rangeability requirements are simply the range between the maximum and minimum flows. The ratio of the maximum to the minimum is called the *turndown ratio*.

Control valve suppliers can provide valve sizing tables and slide rules, but the final sizing is often calculated by computer. The importance of good design information has already been emphasized and the user of the valve is responsible for ensuring that all sizing data is correct. The valve supplier must be told key information including:

- Material to be controlled and the process conditions such as maximum pressure and temperature, specific gravity, viscosity and percentage solids in a slurry.

- Maximum required flow and the associated pressure drop.
- Minimum required flow and the associated pressure drop.
- Adjacent piping materials.
- Air supply pressure.



Pressure Drop Through Control Valve
Figure 17

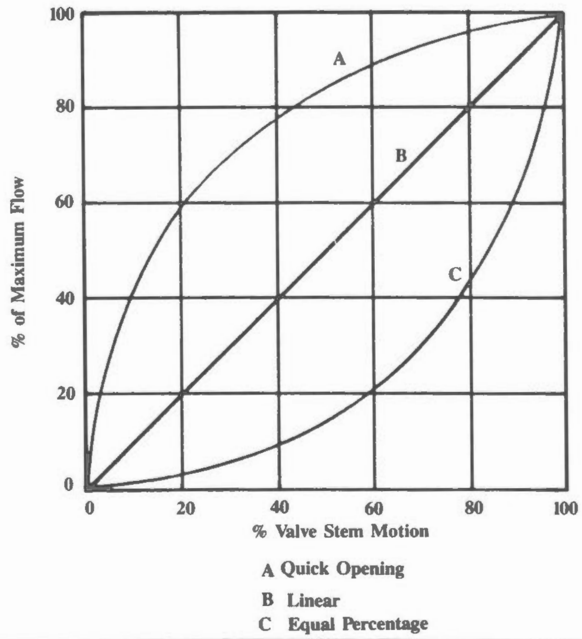
Valve Characteristics

The proper selection of the characteristics of the final control element and/or the field tuning of these characteristics can greatly enhance the performance of a control loop. The safety of the system can be a problem if the final control element is misapplied.

The actual flow characteristics through the control valve should be considered carefully (Figure 18). The quick opening characteristic (A) is often used in self-operated pressure regulators where the process response is immediate. The linear characteristic (B) could provide a desirable form of control when the pressure drop across the valve is a constant. This provides a linear valve stem motion (opening) versus flow relationship. The equal percentage (C) is most common because of the characteristic of providing less flow at the nearly closed position. This characteristic helps to offset the condition in many processes where the pressure drop across the valve is greater when the valve is nearly closed, and less when the valve is more than 50 per cent open. This helps to provide a more linear relationship between valve opening and the resulting flow.

Fail-Safe

In designing a control system, it is important to select the final control element so that the system fails in a safe way if the control signal is lost. This is usually possible with a control valve where a heavy spring closes the valve upon signal or air supply failure. Many processes have separate safety systems that provide additional protection beyond the feature of a fail-safe valve operator.



Valve Flow Characteristics
Figure 18

Control Refinements

The basic control loop components of a transmitter, controller and final control element, have all been described. The many types of controller actions have also been described and this material will assist the reader in establishing suitable control strategies and hardware for the majority of applications. However, there are applications where refinements involving additional hardware or commissioning time can be cost effective. Such options are normally considered when:

- Process disturbances are large and controlled variable deviations from set point are undesirable.
- Process and measurement time lags make good control difficult.

The important governing principle is that the added cost of additional control refinements is only considered if the resulting process improvements make the exercise cost effective. It must be understood that safety is always a mandatory design criterion.

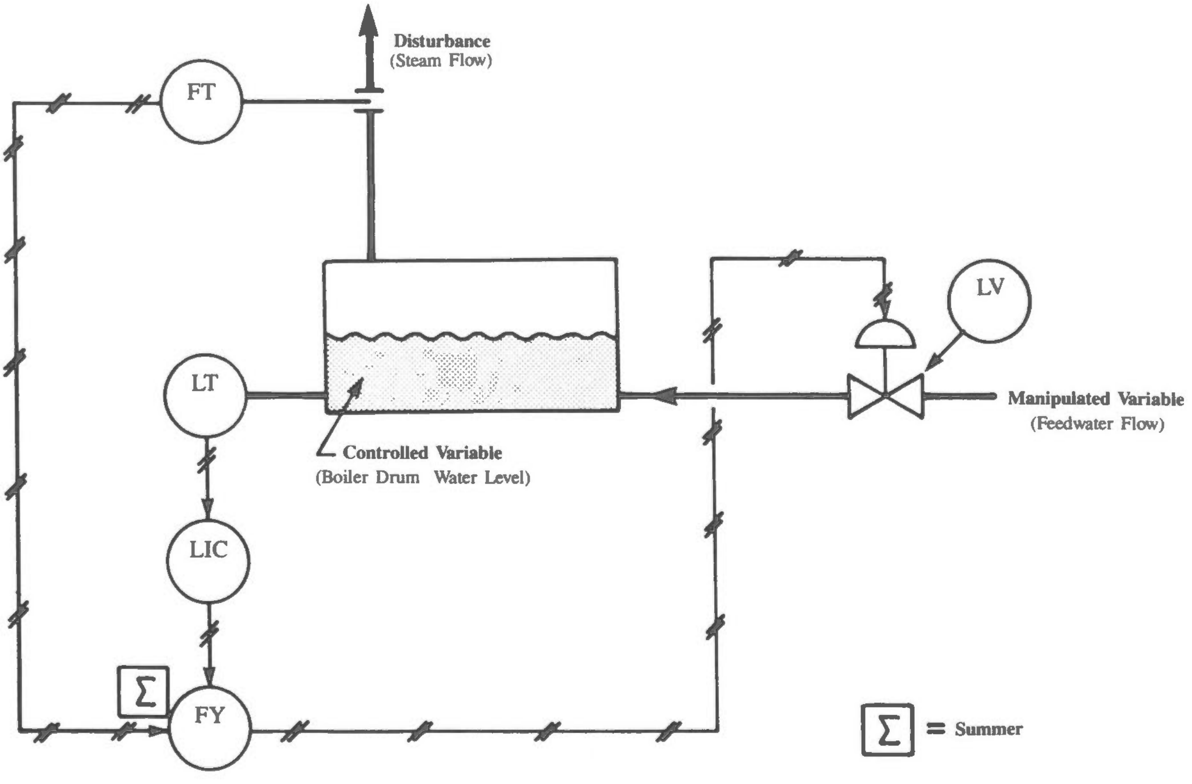
Feedforward Control

Feedforward control is a good example of a control refinement. Sometimes this is referred to as multielement (usually 2 or 3-element) control. The principle can be demonstrated by the level example in Figure 19.

With the feedforward system, as soon as there is a disturbance (steam out), it is detected by the flow transmitter (FT), which sends a signal change through a summing relay to the level control valve (LV). This means that the manipulated variable gets a "kick" as soon as the disturbance occurs so that the feedwater flow-in approximately equals the steam flow-out. Likely, the flow matching will not be exact, but the level controller (LIC) can compensate to eliminate offset in the tank level.

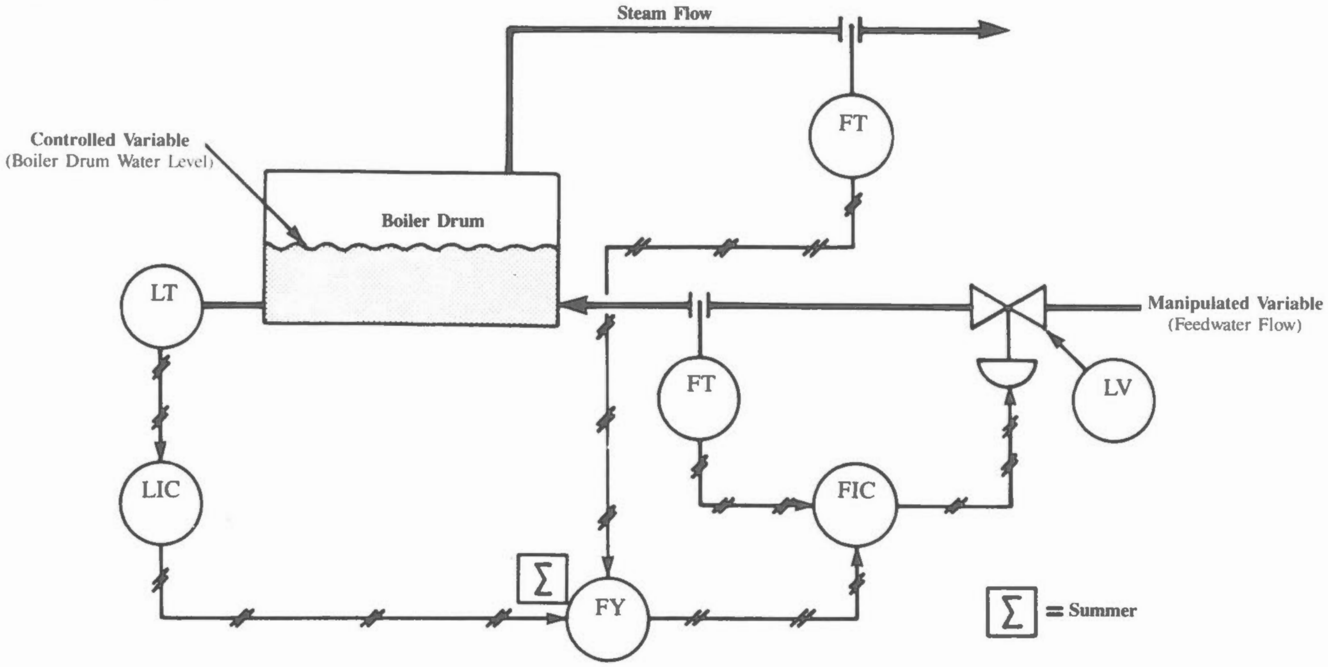
Since the flow transmitter signal is used to set the initial adjustment signal to the feedwater control valve, it is desirable for the change in the flow-in signal to adjust the valve position so that the flow-in equals the disturbance steam flow out. This is where the selection of the proper characteristic control valve is valuable. The control signal to the valve opening relationship can be further refined by putting a positioner, with a characterizing cam, on the control valve. On the basis of commissioning tests, the positioner can then be calibrated so that the change in the steam flow signal approximately reproduces a similar change in the feedwater flow through the control valve. This system is sometimes called a 2-element feedwater control system.

Drum level control on boilers is a common application for 3-element feedforward control. The drum water level measurement can be misleading when the steam demand from the boiler suddenly increases or decreases. When the steam load abruptly increases, the drum pressure quickly decreases. This pressure reaction causes bubbles to form in the boiler tubes below the drum. This will give a high drum measurement reading which overstates the amount of water in the boiler tubes and drum, and it is referred to as "swell" effect. If this were a standard single element control, the feedwater flow to the boiler would be decreased because of the action of an apparent high level condition. This would be undesirable because more water should be admitted to the drum since more steam is being taken away. On a decreasing load, the drum pressure increases, which creates a "shrink" effect causing the wrong action again on a single element control system.



2-Element Feedforward Control Loop
Figure 19

A 3-element boiler drum level control system eliminates the described limitations of a single element system (Figure 20). The three elements are drum level, steam flow and feedwater flow. Essentially, the effect of level control is neutralized during the period when shrink or swell could be causing level measuring "errors". As the "shrink" or "swell" effect subsides, the level controller adjusts the feedwater control valve to eliminate any offset in the drum water level.



3-Element Boiler Drum Level Control System
Figure 20

Cascade Control

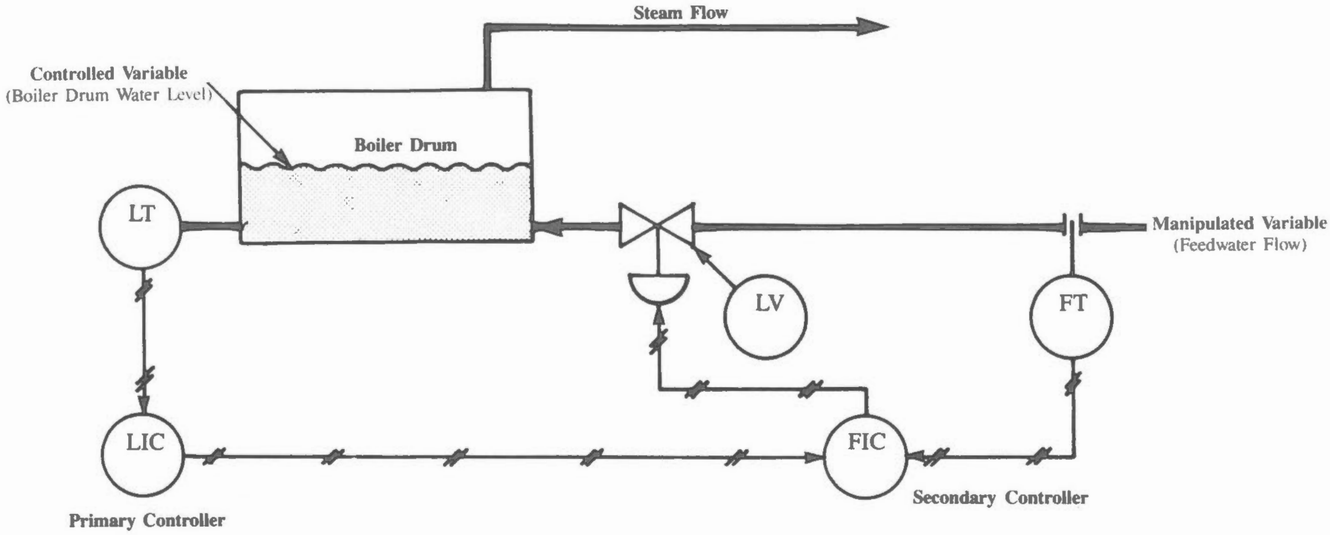
Cascade control is similar to a 2-element feedforward loop in that two measurements are used to control one manipulated variable. However, in cascade control, each measurement goes to a separate controller with the output of the primary controller becoming the set point signal to the second controller (Figure 21). The primary controller is the one associated with the controlled variable that would be used if a simple feedback loop was used. This technique tends to split the process and the associated lags into two parts to improve the process operation. Because of the use of two controllers, it is important that the most logical second measurement is chosen, and that the two controllers be commissioned serially and methodically. This technique is also used to help offset the time lags associated with the process and the controlled variable measurement.

Importance of Process Knowledge

In considering the use of automatic control, it is important to understand the process and how it will respond to disturbances and corrective action. Things to consider when establishing the control arrangement and selecting hardware should include:

- What variable(s) must be maintained and what is the maximum acceptable variation?
- What uncontrolled disturbances exist and what is the magnitude of these changes?
- Is there a significant delay between when a disturbance occurs and when the controlled variable will reflect it?
- How much will the controlled variable change for a typical change in the disturbance input?
- Are there second or third process variables that might be used in the control system to help eliminate process time lag problems?
- Bearing in mind that it is undesirable to make the span of the controlled variable measurement too large, what would be the logical upper and lower range values for the measurement?
- What is the desired rangeability of the manipulated variable and the final control element?
- How predictable is the pressure differential across each control valve at maximum and minimum flow conditions?
- What process conditions must be maintained to ensure safety for all start-up, operating and shutdown conditions?

The foregoing points do not exhaust the list of useful process information, but they do represent a good start. The experience of others who have used the same process can also be a useful guide in assessing the best way to control the process automatically.



Cascade Control System
Figure 21

Energy Audit Methods

Walk Through Audit

A *walk through audit* is a visual inspection of a facility to observe how energy is used or wasted. In most Industrial, Commercial and Institutional facilities a simple walk through will identify potential *Energy Management Opportunities*. The importance of process knowledge for the selection of automatic controls has been emphasized. Thus, in the majority of cases, it will be necessary to do some analysis before coming to conclusions about the cost effectiveness of applying automatic controls. The analysis becomes a part of the second level of audit activity which is called the diagnostic audit.

Diagnostic Audit

In most cases, the justification for the upgrading or addition of automatic controls will not be obvious until the process needs and opportunities have been studied, the savings evaluated and the cost of implementation estimated. This type of analysis is known as a *diagnostic audit*.

The *checklist*, in Appendix D, has been developed to assist with the conducting of a diagnostic audit. Since automatic controls can be applied to almost any process, the checklist must be general in nature. However, the exercise of using it will increase the likelihood of the audit being done thoroughly with meaningful results.

Summary

The key issues in the Fundamentals section are listed.

- Good measurement of process variables is required for automatic control.
- Good process knowledge is essential, and must include a definition of what must be controlled, the value of the controlled variable(s), an analysis of the disturbances and identification of the rangeability of all variables.
- There are many types of control instruments and refining control strategies. It may be necessary to get some assistance in selecting the most cost effective solution.
- The selection and sizing of the final control element is very important.
- A measure of comfort can come from the fact that the control system tuning provides considerable flexibility to compensate for unanticipated conditions and process variations.
- An automatic control system can improve the consistency and quality of an operation, and allow personnel to use their time to perform other tasks such as maintenance.
- The use of automatic controls saves dollars.

ENERGY MANAGEMENT OPPORTUNITIES

Energy Management Opportunities is a term that represents the ways that energy can be used wisely to save money. A number of typical Energy Management Opportunities subdivided into Housekeeping, Low Cost, and Retrofit categories are outlined in this section with text to illustrate the potential energy savings. This is not a complete listing of the available opportunities. However, it is intended to provide ideas for management, operating and maintenance personnel to identify other opportunities that are applicable to a particular facility.

It was previously pointed out that energy savings do not directly result from the use of automatic control equipment. It is the application of instruments to other equipment and systems that creates the saving opportunities. This means that the use of instruments to optimize equipment and process operations should be a background question when studying the other modules. The other modules in this series contain worksheets for the detailed calculations that are required to analyze Energy Management Opportunities. The objective in this section is to provide overview examples of how automatic control facilitates energy and dollar savings. Detailed calculations, which would involve an understanding of other equipment and systems (e.g. HVAC systems, boilers, heat exchangers and air compressors) have been avoided. When properly applied, automatic controls can save energy and dollars, therefore each facility should be evaluated for the opportunities related to the use of control equipment.

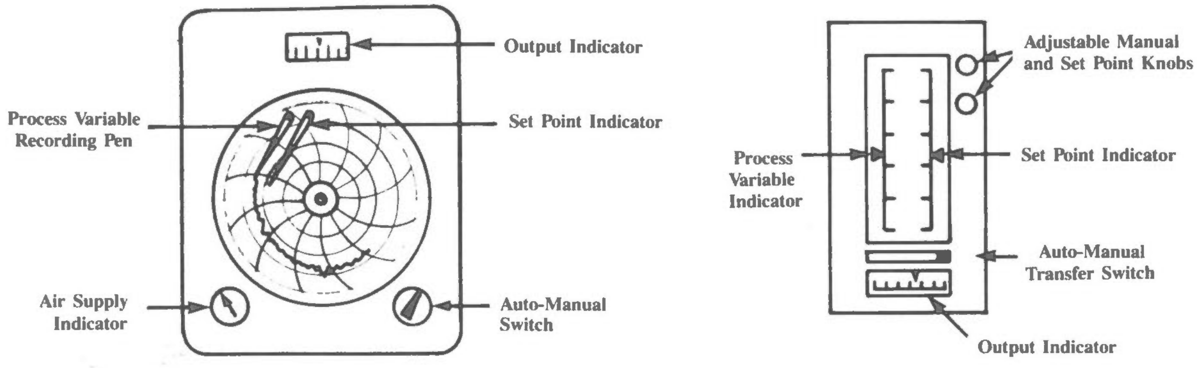
Housekeeping Opportunities

Implemented housekeeping opportunities are energy management actions that are done on a regular basis and never less than once a year. With respect to automatic control, this includes activities such as the periodic calibration of devices, and troubleshooting control problems.

Routine Equipment Inspection and Calibration

Dramatic measuring and control equipment failures can be detected by operating personnel. However, it is more common to experience a gradual deterioration in performance with only subtle indications. Thus, it is important to look for the first signs of off-standard performance, and have a calibration program which eliminates calibration drift before it becomes a significant influence on the process operation. The following opportunities will provide an indication of this activity.

1. Factors which might affect measurement accuracy should be carefully watched because of their influence on the associated control results. For instance, a natural gas pressure which is lower than design conditions will cause the flow measurement to be in error on the high side. Refer to Measuring, Metering and Monitoring, Module 15.
2. The drift in the operation of a controller maintaining the ratio between fuel and air flows to a boiler will result in more excess air in one direction or the possibility of combustibles with an air deficiency. In either case, this unnecessary loss can be detected by observing the oxygen and combustibles recorder or by manually checking the flue gases with an Orsat.
3. Another example of a loop check paying dividends would be the calibration of pressure controls on a dual duct HVAC system to maintain minimum duct static pressure. Refer to Heating, Ventilating and Air-Conditioning, Module 10, for this and other HVAC related examples.
4. Complete control loops should be routinely checked for measurement and set point calibration, final control element operation and overall loop performance. The loop operation may involve a combination of sequencing steps and modulating action.
5. Damper operation, including the operating linkage, should be regularly checked for smoothness of operation and shut-off tightness.
6. For pneumatic controls, the air supply system should be regularly monitored. This would include eliminating



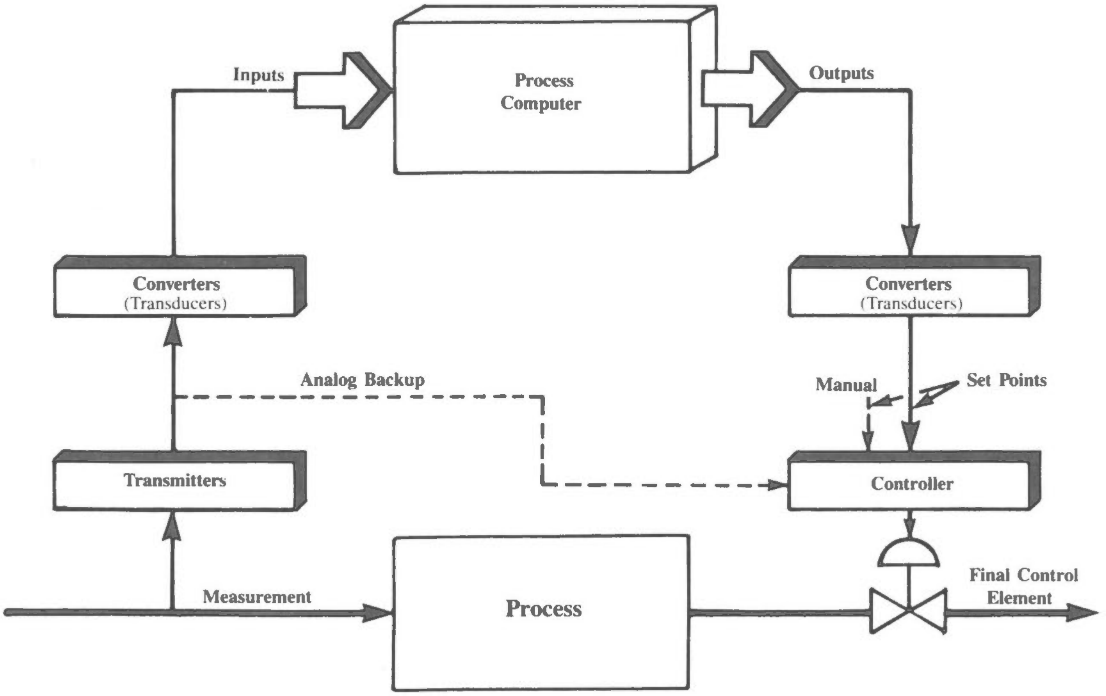
Combined Recorder/Controller

Vertical Scale Controller

Typical Styles Of Controllers
Figure 23

The obvious features to anyone looking at a controller are the display station, auto-manual switching station, plus the adjustable set point and manual set knobs (Figure 23). The auto-manual transfer switch permits the controller to be either in the manual or automatic mode. It is the automatic mode which provides the justification for the device, since in this mode the process measured variable signal can be compared to the set point and any deviation used to modify the controller output in such a way that the deviation is reduced or eliminated.

The display section of the instrument shows information about the set point, process variable and the controller output. These three items of information permit judgements to be made about the acceptability of the process or whether an adjustment is necessary. Most major manufacturers of instruments provide similar features although the method of displaying this information and how the actual transfer between auto and manual is accomplished differs widely. Most controllers can accept another input signal to permit the controller set point to be adjusted from some other external device. The remote set point controller is used in more complicated automatic control systems ranging from cascade loops to those that have the set point established by a computer.



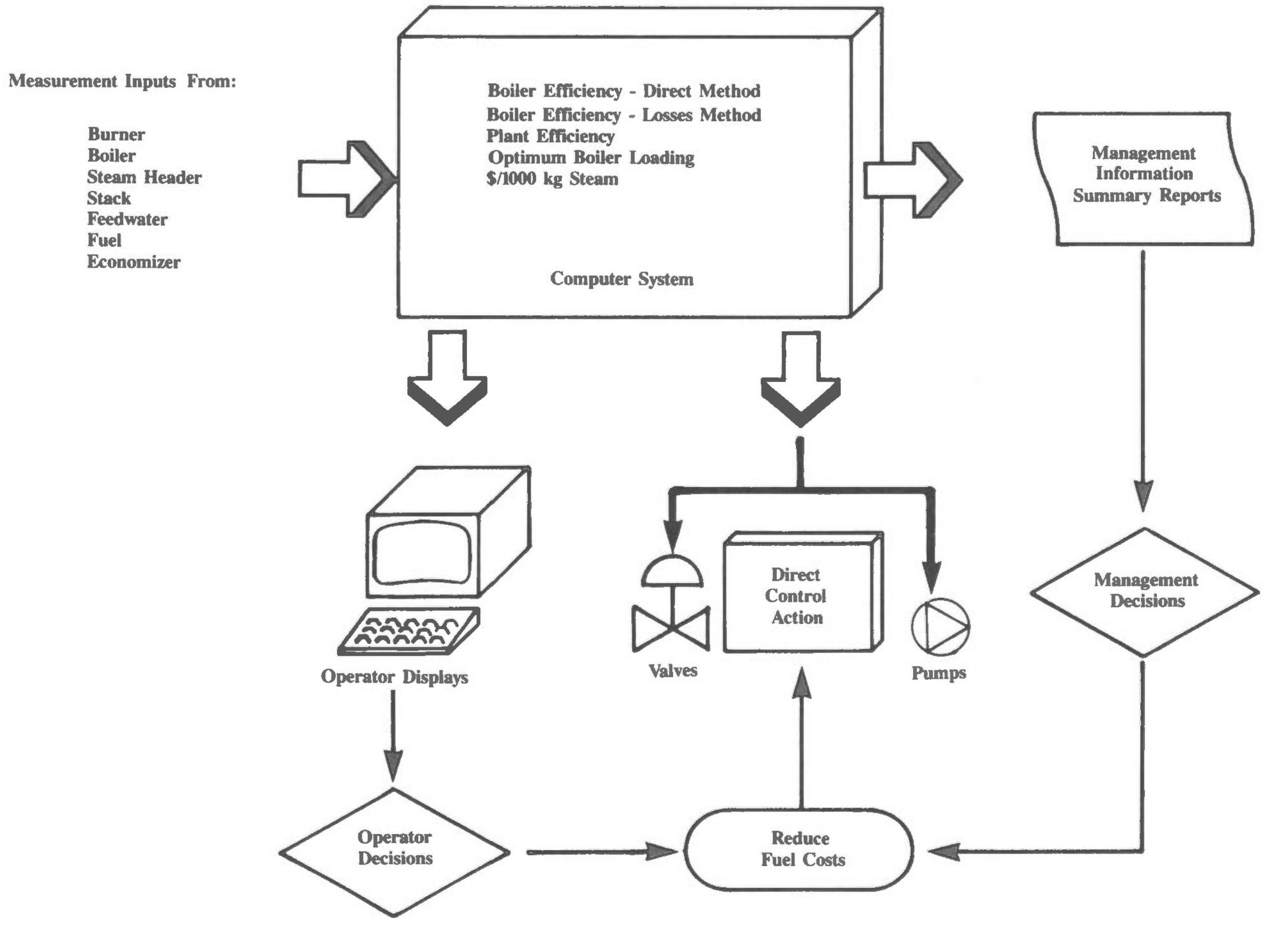
Process Computer Used For Supervisory Set Point Control
Figure 24

Computers

Pneumatic analog computers have been solving automatic control problems since the late 1940s. The need to be able to "compute" in the form of addition, subtraction, multiplication and division is easily accomplished using analog signals opposing one another in motion-balance instruments. They are used primarily for special purpose calculations such as determining the mass flow of gases from flow, temperature and static pressure measurements. They are also used to calculate heat flow from liquid flow rate and temperature difference measurements. Electronic instruments also are capable of analog computation and their use is now widespread.

The term computer generally refers to the digital device which has been developed over the last twenty years. Early digital computers evolved out of the vacuum tube electronics industry and were developed primarily for the engineering and scientific field during the mid 1940s. Later these digital computers were applied to the business and accounting fields for electronic data processing (EDP). Computers were accepted for automatic control use between 1960 and 1970 and today there are thousands in use around the world.

Process computers were initially used in a supervisory capacity (Figure 25). Measurements would provide the computer with data that permitted calculations to determine the best operating conditions. Later the calculated results were used to adjust the set points for pneumatic or electronic analog controllers (Figure 24). These supervised controllers would, in turn, adjust a signal to a valve or final control element and thus change the process conditions toward the optimum desired operation. The computer would "see" such a change and compare the results, just as a human would, and make further adjustments as required. Such a computer control system is known by the term *Supervisory Set Point*.



Energy Management System For Boiler Efficiency And Performance Monitoring
Figure 25

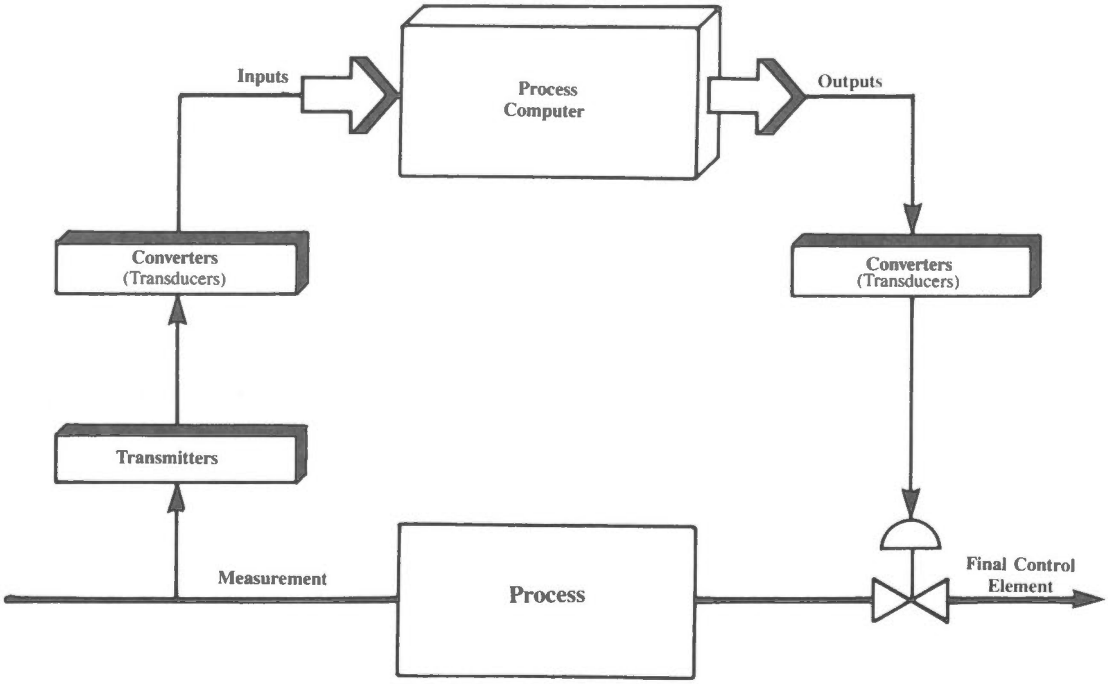
As computers became more reliable, faster, better understood, and less expensive, the digital computer directly adjusted the final control element instead of altering the set point of a conventional analog controller (Figure 26). This form of computer control became known as *Direct Digital Control* (DDC).

Supervisory set point and direct digital control require backup devices which are often pneumatic or electronic analog controllers. Pneumatic backup controls offer simplicity and cost advantages while electronic backup controls provide compatability to the computer input and output signals.

With the tremendous developments that have taken place over the past ten years, minicomputers of the 1970s are outdated by today's equipment. The advent of the minicomputer, followed by the microcomputer, and then the microprocessor has enabled many process control or automation operations to become more economic and flexible.

A computer involved in the control of processing is known as a "Process Computer" and usually it operates in "real time" as distinct from "shared time" often associated with EDP computers. The term *real time* refers to the actual time (of day) that the process is running with input signals of process variables continuously being monitored by the computer. *On-line* is a term frequently used to describe when a computer is monitoring or controlling a process or operation. These two terms are generally used to describe a process computer since it must be on-line continuously to accept input signals.

One of the frequent justifications for computer control is in energy management. Many industries are energy intensive, requiring large amounts of thermal, electrical and mechanical energy. Such industries purchase various types of fuel and convert these to energy sources such as steam by the use of power boilers. Waste products are often converted into energy by means of combustion. Steam is used to supply the thermal requirements for the facility and sometimes to also provide the motive force to drive turbine-generators for in-plant electrical generation.



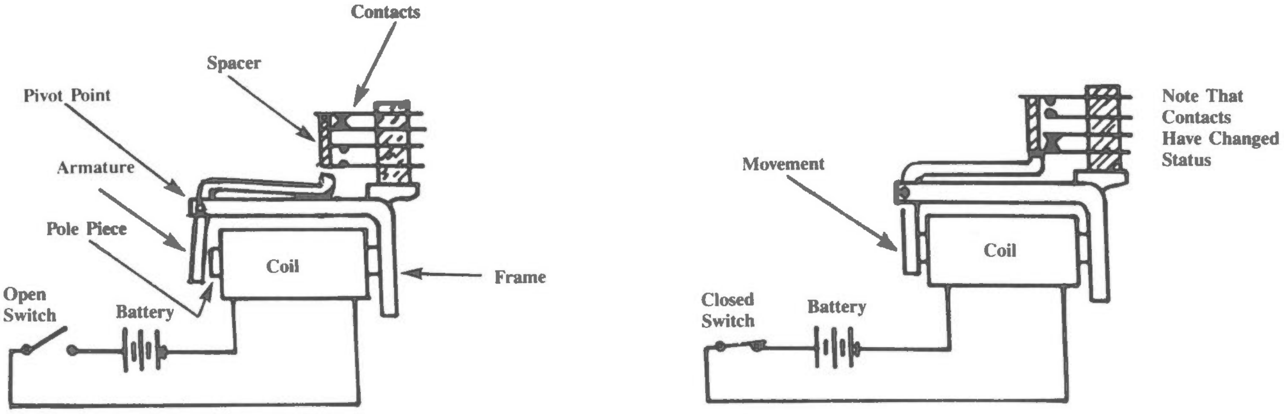
Process Computer Used For Direct Digital Control
Figure 26

Microprocessor based control systems for processes such as boiler plants are now quite common. Typically, they are developed in modular form to allow the system to be tailored to the size and nature of the facility to be controlled. Standard electronic transmitters provide the process information. The following features are commonly used in a boiler plant application.

- Combustion control including automatic recorrection of excess air to ensure optimum performance.
- Multielement feedwater control.
- Sequential logic control for the burner management safety system.
- Single boiler and total plant efficiency calculations to establish the most efficient loading of boilers, and to alert personnel to conditions which may be downgrading the energy utilization performance.

- Periodic log reporting at the end of each hour, shift, day week or month.
- Audible alarms with automatic printouts when a variable goes into an alarm state and when it returns to normal.
- CRT graphic displays to show the status of the system or a subsystem, and to provide trend analysis of selected points from the stored data.

This boiler plant control and monitoring system could also monitor all the purchased forms of energy such as natural gas, electricity, fuel oil, and coal plus any plant-generated energy produced from turbine-generators or waste heat boilers. Similarly, in-plant consumers of energy could be measured and the signals sent back to the energy management computer to be stored and logged. With the energy measurement and production data fed into the computer an automatic energy audit can be generated for a department, production line, facility or building.



Relay In De-Energized State

Relay In Energized State

Electromechanical Relay
Figure 27

Logic Components

Logic components are devices that, when interconnected, will satisfy process switching functions. The components can be electrically or pneumatically driven, and those that are electric can be either electromechanical or electronic devices. Of all those mentioned, only the electronic devices have no moving parts. Logic components can therefore be categorized as devices with either moving or no moving parts.

Moving part logic components include items such as electromechanical relays, timers and stepping switches. They all have something in common in that they open or close an electrical contact or groups of contacts as a consequence of time, or a change in some electrical condition as determined from a signal. These contact closures are wired together in a particular manner to turn on or off items such as, pumps and other motor-driven equipment or signalling devices.

The relays described here are all electromechanical or electrothermal and appear in many different forms. Meter relays and ultrasensitive relays are actuated by low energy signals (a few milliwatts or even microwatts), and are used where only a small signal is available such as the output of a transducer. General purpose or small control relays are used where flexibility in application and operation reliability are essential. Relays in this category may be either AC or DC and can control up to 20 amperes per contact at 120 volt level.

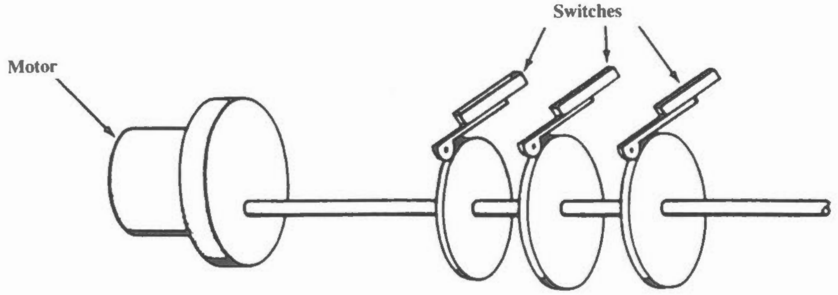
Larger relays are used for electrical power switching and are often AC operated from small general purpose relays. All relays operate on the same electromagnetic forces principle, produced by an electric current flowing through a coil of wire surrounding a pole piece which attracts an armature. The de-energized and energized states of a relay are shown in Figure 27. In devices such as meter relays, the coil itself is moved in a magnetic field.

Timers are defined as devices which initiate action in an electrical circuit at some predetermined time. Timers may be mechanical including pneumatic, hydraulic, clockwork or electric motors, plus electronic or thermal devices.

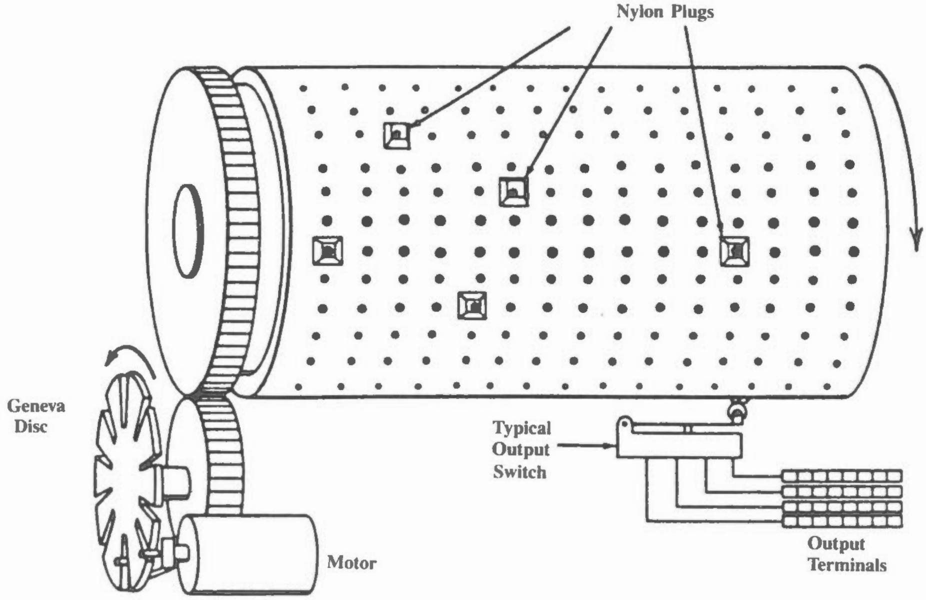
The function of a timer is to initiate action after a known amount of time has elapsed. This action can actuate a number of circuits in accurately timed succession to control reactions or processes at definite intervals.

When a single time interval (either fixed or adjustable) must be established, interval timers are used. These employ either a clockwork mechanism, synchronous motor, calibrated dashpot or other methods to produce some action at a specific interval after the signal is applied to the timer. The range of intervals varies from a few milliseconds to an hour for pneumatic controlled devices, and up to days for electric synchronous motor driven timers.

Programming timers are capable of controlling a number of circuits on a continuing basis where many different actions are required during the cycle time (Figure 28). They have been used for many years to control such things as sequencing a neon advertisement display sign, ingredient mixing, and the cooking process in breweries. Programming timers, in conjunction with relays, have been the backbone of most automatically controlled batch sequence operations.

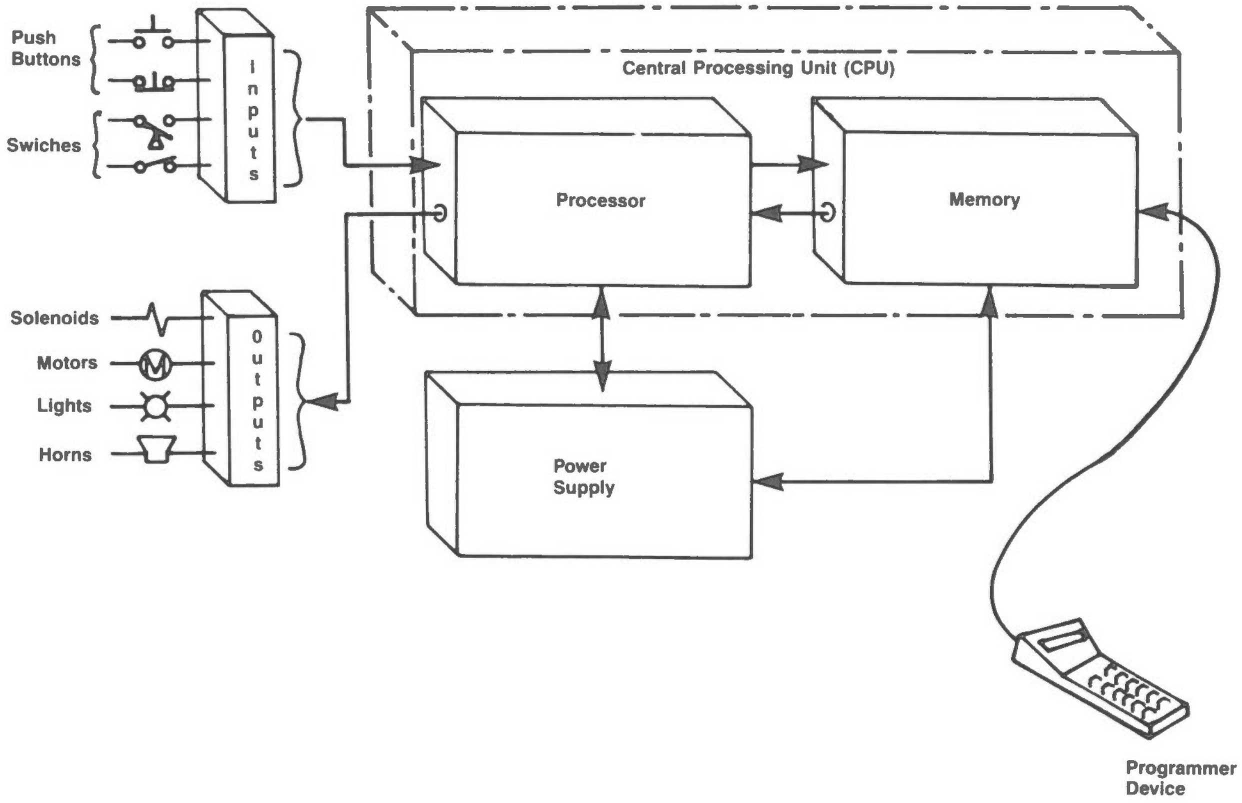


Cam Operated Time (Simplified)



Programmable Drum For Event Sequencing

Programming Timers
Figure 28



Programmable Controller - Block Diagram
Figure 29

Programmable Controllers

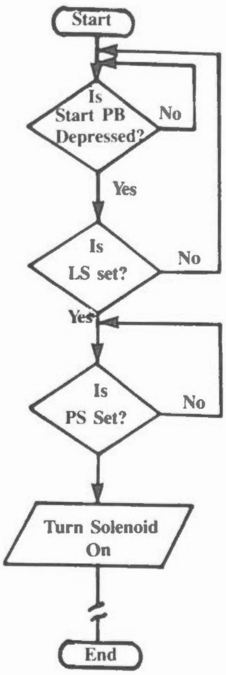
The automotive industry traditionally used many relays, timers, stepping switches and programming timers which required significant relocation and rewiring effort for each new model year. In the late 1960's the market opportunities for programmable electronic hardware to replace other logic types resulted in the development of the programmable controller (PC). This is sometimes called a programmable logic controller which is actually the registered name by one of the 150 manufacturers of these units.

The early programmable controllers were essentially electromechanical relay and timer replacements. This new hardware was more costly, but the system was justified on the basis of lower installation costs with greater flexibility and re-use potential. This benefit is currently greater because of the declining cost of programmable controller hardware. However, the prime reason for the extensive use of programmable controllers is the flexibility in changing the logic of a system, the shorter time to effect changes and the increased suitability for re-use in various facility applications.

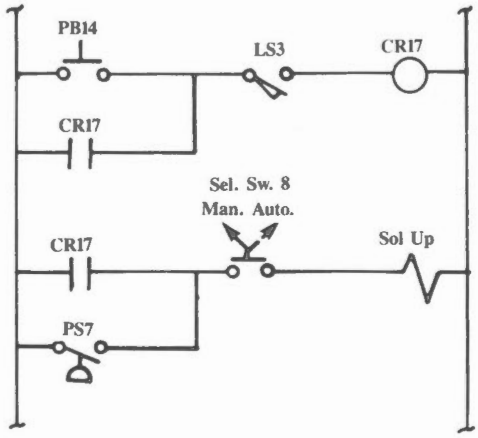
A programmable controller is a solid state device that is used to control a machine or process operation by means of a stored program and feedback from input and output devices (Figure 29). It comprises three basic sections: the *Central Processing Unit (CPU); the Input/Output (I/O) interface; and the power supply*. Programming is not a difficult task to anyone familiar with conventional relay logic. Unlike a computer, where the programming is performed using a special language such as BASIC, FORTRAN or PASCAL, the programmable controller uses a ladder diagram format which is similar to the method used to develop relay and timer circuitry.

There are a number of logic steps to be taken before a PC program can be written and entered into the machine.

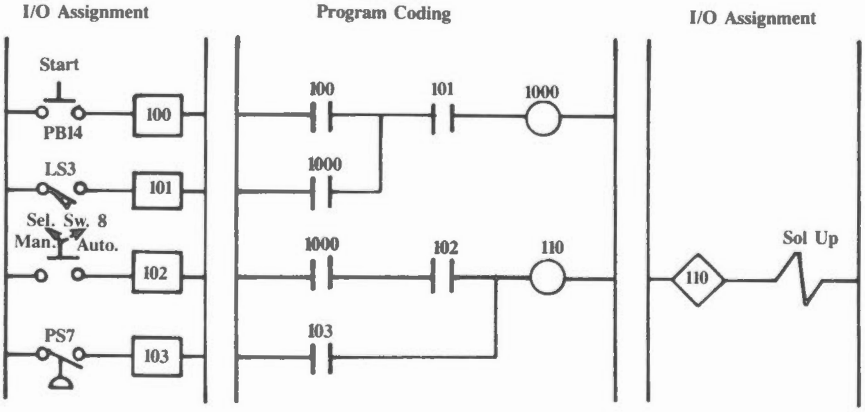
1. Define control task by writing down the sequence of operations in simple word terms.
2. Draw a flow chart to show sequences and the relationships between components and activities.
3. Create ladder-style logic diagrams.
4. Assign identification codes to each input and output signal.
5. Allocate PC addresses for each input and output signal.
6. Create a coded logic diagram using a ladder diagram as a base and adding addresses and other forms of identification to it.



Sample Of A Simple Flow Chart



Part Of A Typical Ladder Style Diagram



Example Of A Typical Coded Logic Diagram

Programmable Controller Logic
Figure 30

At this stage the program is ready to be entered into the PC by means of the programming device. A successful checkout, taking the least amount of time, is a direct reflection of the care taken during the preceding steps. Typical examples of a flow chart, ladder diagram and coded logic diagram are shown in Figure 30.

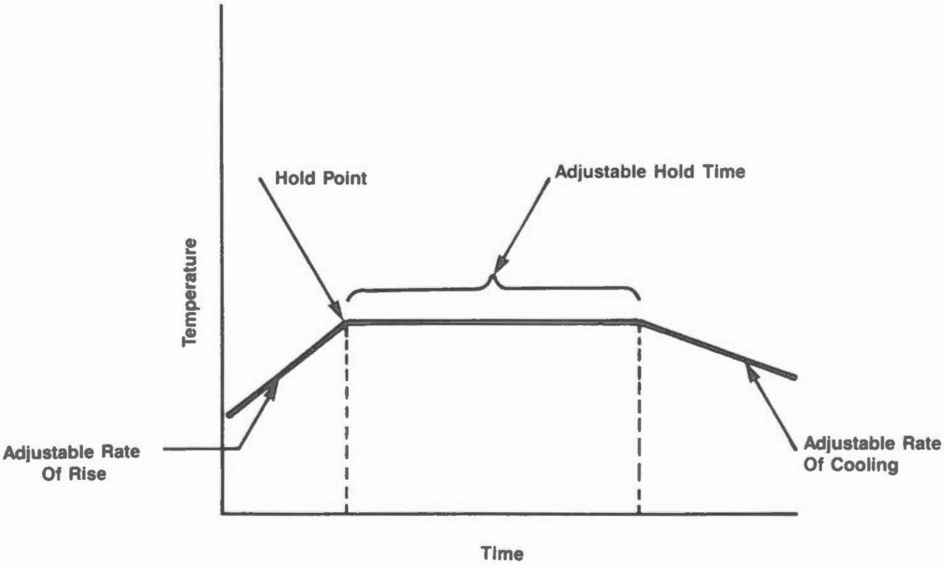
The benefits of a programmable controller compared with other logic components can be summarized as follows:

- Equipment hardware is modular permitting expansion as system needs grow.
- Flexibility in ability to change programs easily and quickly, often without the need for additional components.
- Simple installation owing to the relatively small size and modular construction style. Input/output interfaces can be located in a separate area from the central processing unit to reduce the amount of field wiring.
- Little maintenance is required because of the use of plug-in devices and solid state design. Many PC's have self-diagnostic capabilities to locate the source of problem.

The CPU accepts (reads) input data from discrete devices such as pushbuttons, switches, level or pressure switches, and executes the stored user program from memory. Appropriate output commands are sent to controlling devices such as solenoid valves, motors, lights, and horns. The power supply provides all the necessary voltages required for the proper operation of the system.

The 'Input/Output' interface is the link between the CPU and the equipment or process to be controlled and usually these devices operate at higher electrical voltage levels than the CPU and its power supply.

In order to make a programmable controller work, a programming device is required to permit the entry of the control program into memory. The simplest device is similar to a hand- held calculator connected by a cable to the CPU while more complex programming devices utilize a CRT and microprocessor- based circuitry which provides "intelligence" for sophisticated programming.



Function Generator Program
Figure 31

Function Generators and Computing Devices

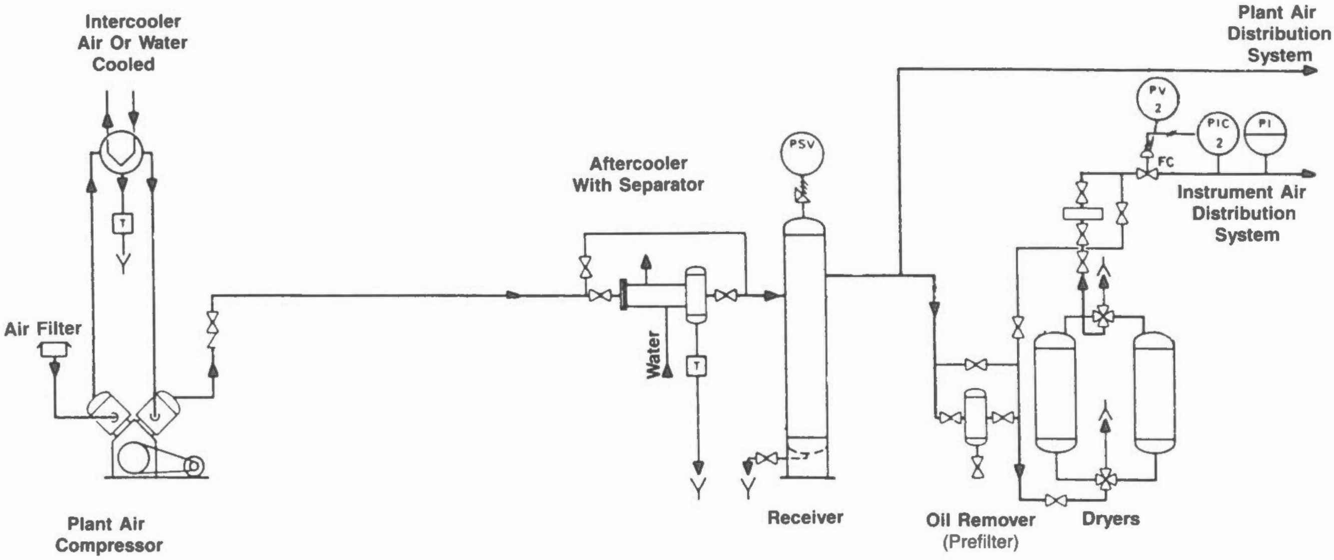
The simplest and least expensive analog time function generator is a cam-type programmer which consists of a motor-driven cam that varies the set point of a controller. These devices are usually installed in a large case instrument housing equipped with a 12" circular chart which records the measured variable. Often, cam programmers are associated with heating or cooling batch processes.

An adjustable ramp and hold programmer is a combination of the previously described cam programmer and some adjustable timers used to set the 'hold' or 'rate of rise' periods. A typical rate of rise - hold - rate of cooling program is shown in Figure 31. This type of function generator is often used for cooking processes where for process reasons the rate of rise of product temperature is important.

Computing relays are analog devices which provide a variety of functions. Electronic and pneumatic types are available and can perform the following typical functions.

- Multiply, A x B = C
- Divide, A/B = D
- Add, A + B = E
- Subtract, A - B = F
- Average, (A + B + C + D)/4 = G
- Square Root Extracting, Integration, and Characterization

Function generators and computing devices are diverse and widely used, since over many years specialized devices have been made to fit the market needs.



Plant Instrument Air System
Figure 32

Power Supplies

All instrumentation require some form of power. Pneumatic control equipment requires clean, oil and water free air, while electronic instruments require a reliable electrical power distribution system.

Pneumatic air supply (Figure 32) is often taken from the main compressed air system, downstream of the main air receiver vessel, and operates at a pressure of approximately 700 kPa(gauge). A dual tower desiccant air dryer removes most of the moisture down to a dewpoint of -40°C and an after-filter ensures that desiccant particles do not enter the distribution header. The distribution header, usually a NPS 2 galvanized pipe, is often a "ring-main" design from which individual tap off points are taken from the top of the pipe. All low points have drain valves to allow the blow down of moisture. At the air-consuming instrument or final control element an air filter/regulator is installed to remove any contaminants which would otherwise clog small orifices, and to reduce the pressure to a working pressure of about 140 kPa(gauge).

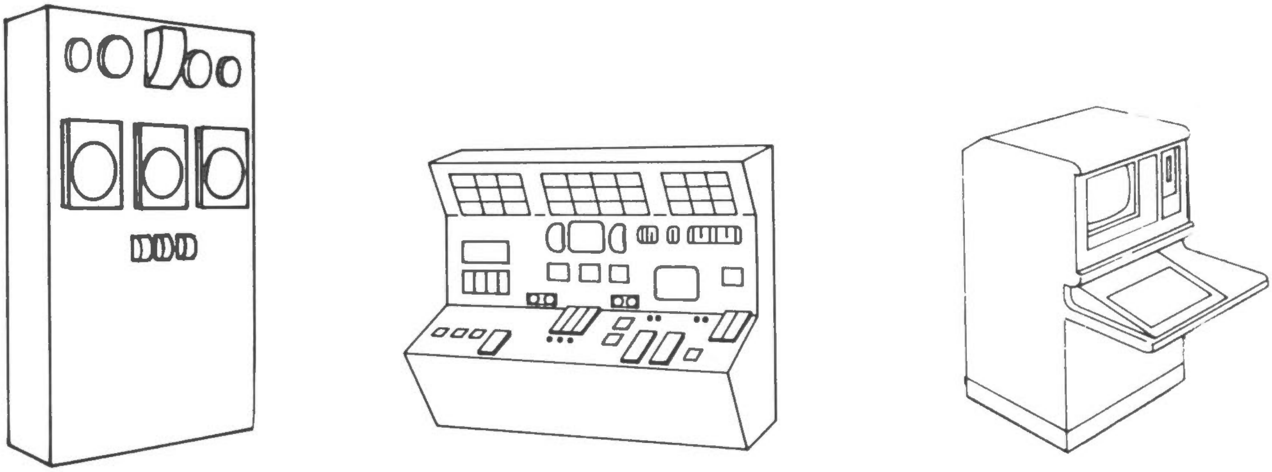
One of the common sources of automatic control problems is poor quality air resulting from incorrectly installed or poorly maintained instrument air supplies. The energy losses related to air leakage can be significant.

Electrical power supplies for instruments should be taken from a reliable source. Upon power failure, there should also be automatic switch-over to another source. Most of today's instruments operate off a standard 117 V, 60 Hz supply. A momentary loss of electrical power to computers or microprocessor based equipment can cause loss of control and, sometimes, data. A standby uninterruptable power supply eliminates this problem and is often specified as an essential item by the control equipment supplier. These units are available as packaged products from the power distribution supply industry. Generally, automatic control equipment are not large consumers of energy.

Control Panels

A control panel centralizes all of the control equipment required for safe and efficient operation of the plant or facility. The instruments generally found on a control panel include recorders, controllers, indicators, alarm annunciators, pushbuttons, selector switches and pilot lights.

Panel styles are varied (Figure 33) and determined by factors such as available space, need for a graphic display of the operation, and the number of monitoring and control instruments. A flat faced panel extending from floor to ceiling is the most economical and widely accepted form of panel. Variations include sloping front sections to improve visibility for a standing operator. In contrast, consoles and console desks provide a lower profile and offer a work surface for a sitting person. Control panels are almost always custom designed for the particular application.



Vertical Panel

Sloping Front Panel

Operator Console

Typical Panel Shapes
Figure 33

Final Control Elements

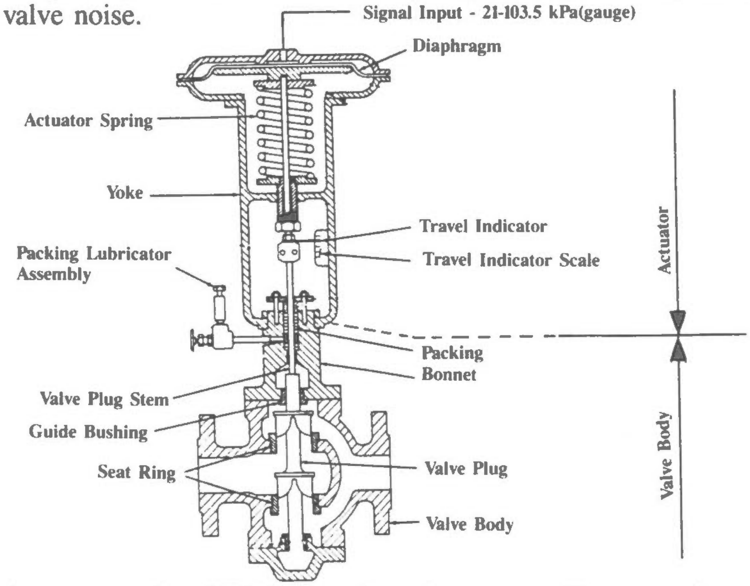
Control Valves

In order that the topic of control valves can be better understood the following is a brief listing of some of the terminology used.

- *Valve* is a pressure-dissipating device designed to modify the flow of fluids in pipes.
- *Control valve* is a valve designed for control purposes which uses an actuator that positions the valve in response to an external signal.
- *Regulator* is a control valve which has an integral mechanism that provides sufficient motive force to operate it without need for an external source of control signal and power.
- *Hand valve* is a valve with a manual operator, lever or handle.
- *Actuator* is a device mounted on a valve body to position the valve according to a remotely generated signal.
- *Valve body* is the part of the valve containing the flowing fluid and the plug which modifies the flow of fluids through the valve.

A control valve consists of two major subassemblies, a valve body and an actuator (Figure 34). The valve body contains the fluid and consists of a body, valve plug, seat ring and guides. The bonnet and valve stem are also part of the valve body. This subassembly must meet all of the applicable pressure, temperature and corrosion requirements of the process system. The internal trim (valve plug, seat ring and guides) controls the fluid, provides the flow characteristic and accomplishes the shutoff requirements. The actuator moves the valve plug in response to a signal (usually air) from a separate controlling instrument.

The globe style valve body is most common. It can be single or double-seated, cage or stem-guided. Single-seated valves are usually employed where tight shutoff is required, or in small NPS 1 sizes and below. Double-seated globe valves are often employed in pressure reducing applications where tight shutoff is not an important consideration. Cage-guided globe valves are probably the most common body and trim style in use because of the flexibility of the available flow response versus stem-travel characteristics. Cage valves often have streamlined body passages to permit increased flow capacity for a given body size, and special trim parts can be installed to reduce valve noise.



Control Valve
Figure 34

In sizes greater than NPS 3 butterfly valves are used because of cost advantages over globe valves. The butterfly valve has less rangeability than a globe type, but can provide good control with low differential pressures. Susceptibility to choking, cavitation and noise generation limits the use of these valves. Cavitation is a two stage phenomenon, the first stage of which is the formation of vapor bubbles within the liquid. The second stage is the collapse of these bubbles into the all-liquid state. This phenomenon affects valve-sizing procedures and limits the life expectancy of the valve.

The eccentric rotating plug valve, which is a rotary valve with a mushroom-shaped plug, is a good alternative to the globe valve. For a given size, this type of valve provides more flow capacity than a globe valve and less than a butterfly, while the cost is less than the globe type and more than the butterfly. Often, this style has a flangeless body which is clamped between pipe flanges.

For a given size, ball valves offer a high flow capacity and virtually unobstructed fluid flow. Thus, they are suitable for fibrous or slurry services since there is little chance of process material build-up around cavities and shafts. Rangeability of this valve is limited, but can be increased by use of a specially contoured opening in the leading edge of the inlet face of the ball. An additional advantage of the ball valve is its inherent ability to be a tight shutoff device.

Diaphragm valves are used for corrosive and hazardous liquids, gases and high purity products in the food and beverage industry. The valve is opened and closed by moving the centre of the diaphragm away or towards the fluid passage in the valve body. Tight shutoff is inherent with this design and its simple construction permits easy maintenance. The main limitation is the relatively low maximum pressure of 1000 kPa(gauge) and that little control is available beyond 50 per cent valve opening.

Pinch valves are a low cost and simple device. They are widely used to control the flow of abrasive materials such as slurries encountered in the mining industry. The main body and 'trim' is a reinforced rubber tube inside a cast metal case. There is space between the tube and the case which can be pressurized with air to pinch the tube and restrict the flow. These valves are special application devices designed to overcome corrosion and erosion problems associated with hard-to-handle fluids and slurries.

Control Valve Actuators

There are many types of actuators for control valves. Requirements, such as suggested by the following list, dictate the final selection.

- Operating media available, air or electric.
- Thrust requirements.
- Length of stroke.
- Speed of stroke.
- Control valve body style.
- Required valve position upon air or electric supply failure.

The spring-opposed diaphragm with air as the operating medium is the commonly used type of control valve actuator. Actuators are usually classified as direct acting (increase in signal air pressure extends actuator stem) or reverse acting (increase in signal air pressure retracts actuator stem). Selection of direct or reverse action is usually based upon fail-safe requirements of the valve, with reliance on the spring to drive the valve to the safe position in the event of an air failure.

Usually piston or cylinder actuators are used where valve designs with long strokes or high forces are encountered. The piston or cylinders can be hydraulic, air or gas-operated. Single and double-acting piston actuators are available. Fail-closed, fail-open or fail-last-position can be readily achieved with piston or cylinder actuators. A variation of this type of actuator is the electrohydraulic operator which uses a continuously running electric motor to drive a pump and supply hydraulic pressure for the piston.

Electric motor actuators are used where air is not available and speed of response is not critical. The electric motor is connected to the valve shaft by means of a gearbox in order to develop the required torques. The stroking times for the valve to go from fully closed to fully open can often be as long as 30 seconds. Thus, the application of motor driven control valves for automatic control is limited.

Positioners

Control valves have inherent operating characteristics which hinder precise positioning under varying operating conditions. Factors such as the pressure differential across the valve seat, over-tightening of packing, and viscous or fouling service can create additional forces that prevent the valve from assuming the position demanded by the controller.

The valve positioner compares the valve stem position with the demand generated by the controller. If the valve stem is incorrectly positioned, the positioner either adds or exhausts air from the actuator until the correct valve stem position is obtained.

Positioners are available for either pneumatic or electronic signal input. The electropneumatic positioner accepts the input from an electronic controller and using air as the driving force positions the control valve.

Valve Accessories

Handwheels can be mounted as an accessory to most types of control valves. They provide the means to override the control system and manually operate the valve. Various designs are available, some that allow valve travel in either direction without relying on the valve spring for the return stroke, while others use a clutch and pin arrangement which must be disengaged when not in use.

Solenoid valves are commonly used to disengage the automatic signal to permit the control valve to assume the fail-closed position. This feature is useful in batching operations and is also used in emergency interlocking circuits where the de-energizing of a solenoid coil drives the control valve into a safe position.

Valve mounted electropneumatic transducers convert electronic signals into pneumatic signals enabling electronic controllers to be compatible with pneumatically controlled final control elements.

Pneumatic booster relays are used to increase the speed of response of a control valve and are particularly useful when the valve is located more than 50 metres from the pneumatic controller.

Control Drives

Control drives position regulating devices such as dampers, fan inlet vanes, lever-operated valves such as butterfly valves, governors, variable speed drives, and fuel valves for smaller boilers. They are also called damper motors and damper operators. There are many variations in the available hardware but not to the extent of control valve choices.

Control drives can be used for two-position operation or full modulating control. The pneumatic units consist of cylinders or diaphragm actuators. The listed signal and power supply combinations provides an appreciation of the available variations.

- Pneumatic signal and air driven.
- Electric signal and air driven.
- Electric signal and motor driven.
- Two-Position electric or pneumatic signal with air drive.
- Two-Position electric signal (contact closure) and electric drive.

The described potential applications vary substantially in torque requirements, but this is generally satisfied with the continuous torque ratings which range from 1 to 7500 Nm. The accessories support a great variety of monitoring and automatic control requirements.

Variable Speed Drives

Many items of equipment use some form of variable speed drive to allow changes in the speed of driven equipment. The drives subdivide into the following basic categories.

- Those in which the speed of a direct or alternating current electric motor is varied.
- Hydraulic or pneumatic drives where the flow of oil or air to the vane type motor is varied to change the motor speed.
- Those in which the sides of a variable speed pulley are separated or moved together to vary the pulley pitch diameter and thus the speed of the driven pulley.

All of these drives can be controlled by an automatic control signal to change the speed of the driven equipment.

Automatic Feeders

Batch and continuous processes require different kinds of material feed control. Some of the automatic feeder devices can be used for either type of process, but the nature of the process is a reasonable way to separate the description of feeders.

Batch processes require predetermined weight or volume of material and the processing does not begin until everything has been added. Gravimetric weighing devices can be used to weigh a fixed amount or a volumetric feeder can be used to establish volume units with the increments of material counted to suit the batch. Thus, this type of feeding is basically a measurement action with some form of counting.

Continuous processes require that the material be established on the basis of volume or weight per unit of time. The measurement of volume or weight per unit of time can be used in a control loop with the output control signal changing the product feed rate. There are a variety of devices that could respond to this control signal and most vary the feed rate by changing the speed of something. Devices that can be speed-adjusted to vary the feed rate would include all types of conveyors, star feeders, vibrating feeders, apron feeders, rotary tables, and rotary vanes.

Metering pumps are a form of feeder. An example would be the dosing of chemicals into boiler feed water to control corrosion. Each cycle or stroke of the pump injects a fixed, known volume of liquid. Dosing rates may be varied through the use of a variable speed drive or by varying the stroke length.

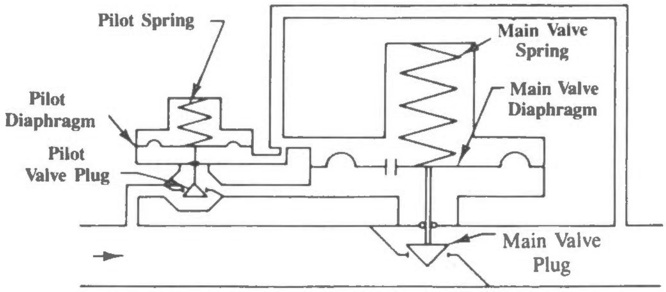
Self-Operated Regulators

The self-contained pressure regulator was first developed in the late 1800s and generally consists of a plug, seat, stem, diaphragm, spring and casing (Figure 10). The diaphragm is the "brain" of the pressure regulator, in that it enables the set point, which is represented by a spring force, to be compared with the regulated pressure. The resulting force difference positions the valve plug to alter the fluid pressure. This balancing of the two internal forces alters the valve opening to reduce the error between the spring setting and the fluid pressure until equilibrium has been reached. Thus the diaphragm is a feedback device, an error detecting mechanism, and an actuator.

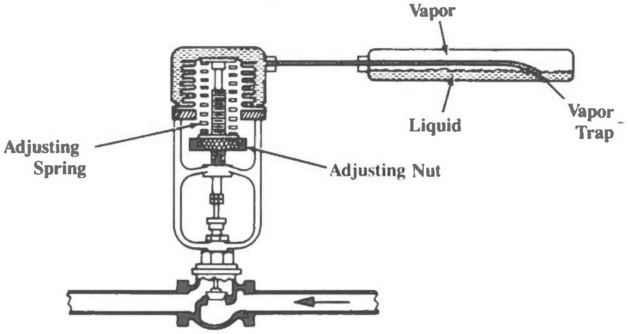
The pilot-operated regulator is a variation of the spring-loaded regulator and is a two-stage device (Figure 35). The first stage pilot is a spring-actuated regulator that controls the pressure on the diaphragm of the main regulating valve. The advantages are that the actuating fluid operating the first stage regulator is at the upstream pressure, providing a higher force to the actuating mechanism, and that the valve stem travel is short, which reduces the offset (difference between desired and actual pressures). Hence the pilot-operated regulator provides accurate regulation for a wide range of pressures and flow capacities. The pilot (first stage) regulator can be an external or internal part of the main regulator.

Temperature regulators physically differ from pressure regulators in many different ways. The actuator portion of the regulator is often a bellows mechanism connected through capillary tubing to a sensing bulb. The sensing bulb, capillary and bellows are a filled, sealed system using a vapor, liquid or hot chamber system. The two most commonly used fills are vapor and liquid.

The operation of the vapor temperature regulator is illustrated in Figure 36. The actuator is partially filled with a volatile liquid that is chemically stable at temperatures above the range of the regulator service. The sensing bulb contains the liquid-vapor interface. Thus the pressure within the actuator bellows is the vapor pressure of the "fill liquid". This vapor pressure, increasing with rising temperature, acts on the bellows against the force of the spring adjustment to produce the motive force required to move the valve plug.



Pilot Operated Pressure Regulator
Figure 35



Temperature Regulator
Figure 36

Systems

The objective of this section is to provide additional process control system descriptions which will help to consolidate the foregoing material. Automation systems are sometimes too diverse and complicated to understand without prior instrumentation background. However, this module should create certain reactions:

- An interest in the potential of automatic controls.
- Convictions that automatic controls can save dollars.
- Sufficient confidence to talk to others about automation systems to assess the technical and financial implications of using them in a specific facility.

Controlling a Process

Often there are many control solutions to a specific process operating problem. Proper analysis of the process will help to eliminate some of the less suitable control system possibilities. The questions regarding the process operation will vary with the process, but the following list provides an indication of the required detail.

- What are the process objectives?
- What is the major process equipment and its operation?
- How predictable are the process parameters?
- What variable(s) must be maintained and what is the maximum acceptable variation? Are there financial benefits in reducing the variations in the controlled variable (i.e. is there merit in buying a more expensive control system to obtain better control)?
- What uncontrolled disturbances exist and what is the magnitude of them? Should these be measured and monitored?
- Is there a significant delay between when a disturbance occurs and when the controlled variable will reflect it?
- How much will the controlled variable change for a typical change in the disturbance input?
- Are there second or third process variables that might be used in the control system to help eliminate process time lag problems?
- Are there any measurement problems?
- What is the desired rangeability of the manipulated variable and the final control element?
- What process conditions must be maintained to ensure safety for all start-up, operating and shut-down conditions?

Multiple Control Solutions

Normally, a process can be successfully controlled in more than one way. By being able to answer all of the questions in the foregoing section it should be easier to select the most logical and cost effective control solution. A heat exchanger process can be used to demonstrate seven different control solutions to a common problem (Figure 37).

The basic process is illustrated in Figure 37A. A process fluid is heated by steam in a heat exchanger. The objective is to maintain a certain hot fluid temperature by means of varying the amount of steam to the heat exchanger. The most rudimentary form of control would be to position the steam valve manually. The operator must provide the control feedback in this case.

The least expensive control solution will be the on-off temperature control (Figure 37B) or the self-operated temperature regulator (Figure 37C). The on-off approach utilizes a temperature switch (TS) with contacts that snap open or closed as the temperature goes above or below the desired temperature set point. When the temperature drops below the set point, the switch contact closes and the solenoid valve (S) is energized. This opens the valve and admits steam. When the temperature rises above the set point, the switch contact opens and the solenoid valve closes.

Figure 37C illustrates the operation of a self-operated temperature regulator (TCV). The pressure in the filled thermal system increases and decreases according to the sensed fluid temperature. Thus, as the temperature goes above set point, the increasing pressure to the topworks on TCV positions the inner valve to reduce the flow of steam. The operation should be smoother than the on-off control, but both systems will have some offset between the actual temperature and the desired set point value.

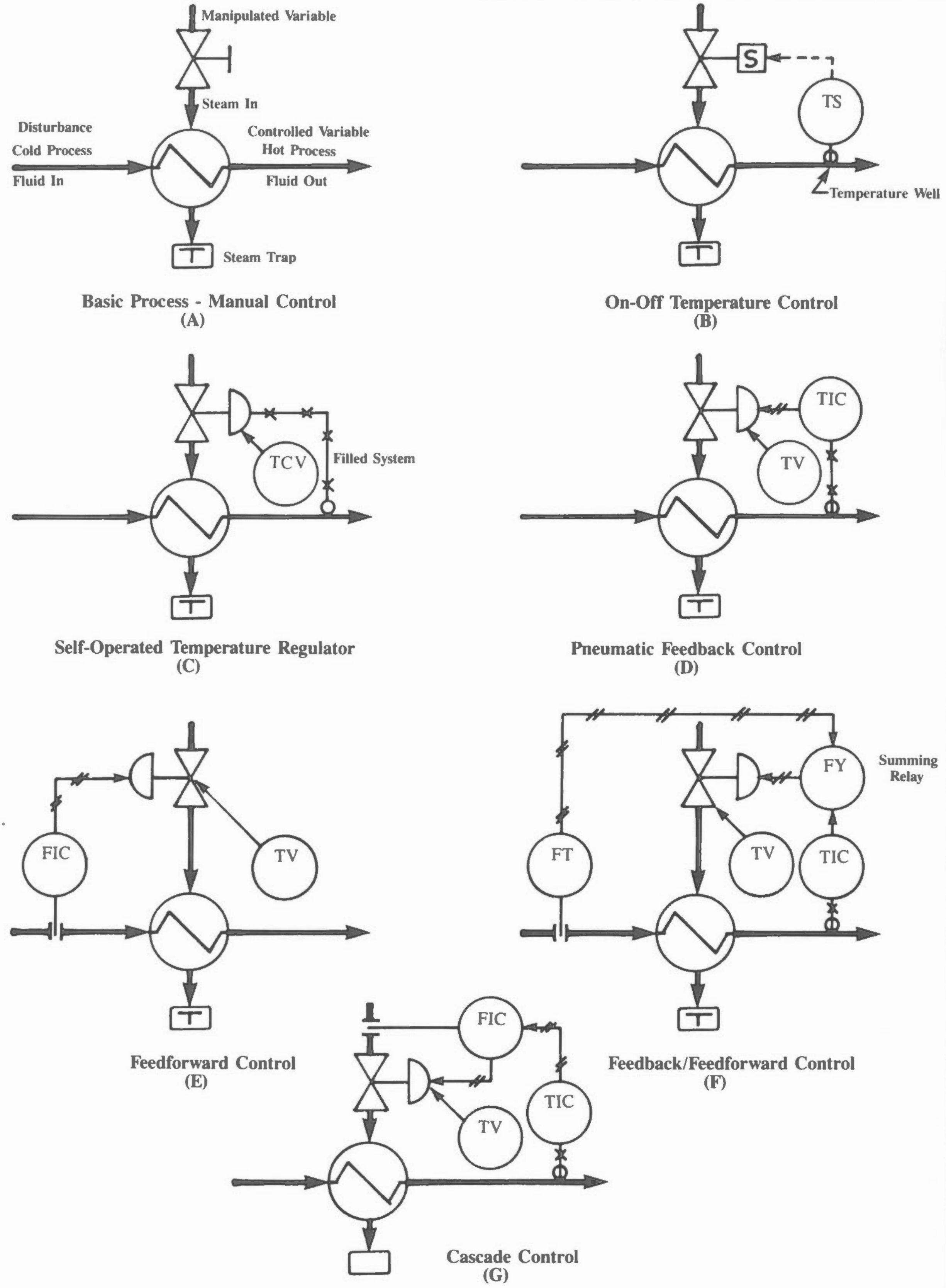
Figure 37D represents a common pneumatic feedback control loop. It is more flexible to commission than the Figures 37B, or C systems. Depending on the control modes selected it could be capable of eliminating offset. It permits flexibility in the location of the controller (TIC) and control valve (TV).

Feed forward control is the term used to describe a control system in which corrective action is based on the measurement of a disturbance input to the process. It should be noted that Figure 37A, incorporates manual feedback while Figures37 B, C and D use automatic feedback. Figure 37E suggests an arrangement where the variable flow of process fluid to the heat exchanger is used to establish the steam flow. In theory, this means that the change is detected before it influences the temperature of process fluid leaving the heat exchanger, and this is good. However, without feedback the operating conditions would undoubtedly change with time and the temperature control results would be unsatisfactory.

Feedback and feedforward principles can be combined to advantage (Figure 37F). This control loop combines the features of loops D and E. Thus, any process fluid flow disturbances are immediately detected by the flow transmitter (FT) which sends a signal through the summing relay to the control valve (TV). With the proper hardware selection, including valve sizing, this should eliminate most of the potential process upset. Temperature controller (TIC) would only then detect minor temperature variations which reflect the inadequacy of the feedforward loop. Controller (TIC) could eliminate any offset by modifying the signal to the control valve (TV).

Cascade control is the term used to describe a system where automatic controllers are arranged as a series of stages in which the output of one stage becomes the input of the next. Usually this form of control is limited to two stages where the output of the first stage controller becomes the set point input to the second stage controller. In a cascade control system, one controller (commonly called the primary or master) is actuated by the process variable, which is to be regulated to a constant value, and a secondary controller is actuated by a variable that can cause changes to the primary variable. The primary controller output adjusts the set point of the secondary controller which, in turn, operates a final control element.

Cascade control, if properly applied and installed, can reduce the effect of time constants in the loop, and eliminate the effect of disturbances in the secondary variable before they enter the primary process loop. Figure 37G shows the principle with the same heat exchanger process. The heat process fluid temperature control loop (TIC) establishes the set point for the steam flow control loop (FIC). This can help to reduce disturbances caused by the steam supply system and provide feedback control on other disturbance sources.



Basic Process - Manual Control
(A)

On-Off Temperature Control
(B)

Self-Operated Temperature Regulator
(C)

Pneumatic Feedback Control
(D)

Feedforward Control
(E)

Feedback/Feedforward Control
(F)

Cascade Control
(G)

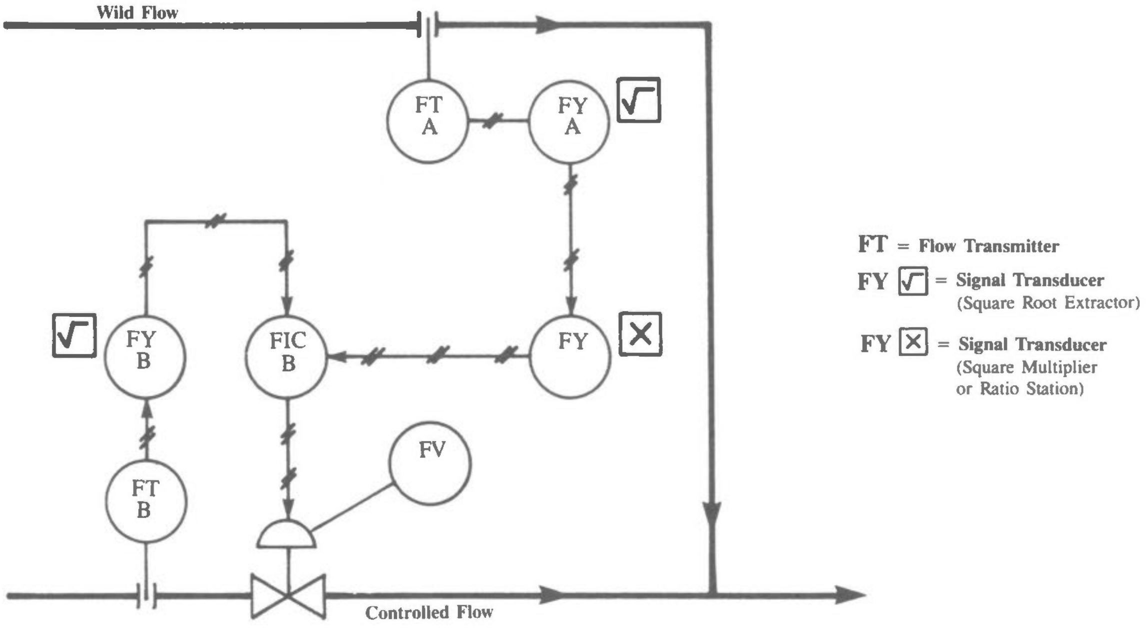
Multiple Control Solutions
Figure 37

Flow Ratio Control

Flow ratio control is the control of one process flow to maintain a fixed ratio with another process flow (Figure 38). The set point of the controlled flow is usually set by a device which multiplies the measured value of the uncontrolled (wild) flow by the desired ratio. The measured flow signals must have the same linear or square root characteristics.

$$\text{Desired Flow Ratio} = \frac{\text{Controlled Flow Rate}}{\text{Wild Flow Rate}}$$

There are many variations of ratio control systems used in a wide variety of applications from the blending of gasolines to the proportioning of chemical reagents in water treatment plants. A transmitting flow meter must be installed in each flow stream (Figure 39). The two signals are received by the control system which transmits an output signal to a valve located in the "controlled" line. The valve provides the means of manipulating the desired ratio of flows.



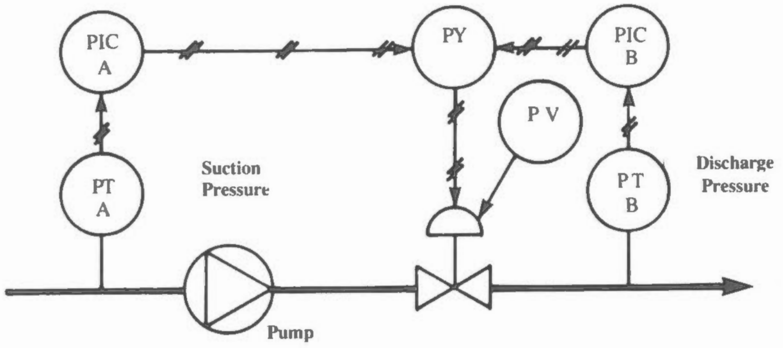
Flow Ratio Control
Figure 38

Override Control

Override control is defined as a control system in which two process variables are related in such a way that either can be controlled by the same manipulated variable. One of these variables is controlled at a selected set point, provided the second variable is on the "safe" side of its set point. If the second variable approaches its set point, control is automatically transferred so that it will not go beyond set point. At the same time, the first variable falls away from its set point in a safe direction.

An example of a typical override control system is an automatic suction and discharge pressure control system for a pipeline pumping station (Figure 39).

The throttled discharge pressure is controlled at 700 kPa(gauge), providing the suction pressure does not fall below 7 kPa(gauge). If the suction pressure drops toward 7 kPa(gauge), control is automatically transferred to the suction pressure controller which then operates the same control valve. The discharge pressure reduces to some value less than 700 kPa(gauge) and the pump suction pressure is maintained at 7 kPa(gauge). This condition will remain until discharge pressure rises to 700 kPa whereupon the control switches back to the discharge pressure controller. Thus, the override control system prevents the pump suction pressure from dropping to where cavitation might take place because of the suction pressure approaching the fluid vapor pressure.



Override Control
Figure 39

Batching Control Systems

Batch control systems can be event, time or measurement-related, or a combination of all three. Additionally, batching systems can be analog or digitally measured, and can have deliberate pauses to allow for human intervention. Finally, the type of control can also be analog or digital using computers, programmable controllers, relays and timers in conjunction with most types of measuring equipment. In short, batching control systems are as varied as the needs. Two systems are rarely the same.

ENERGY MANAGEMENT OPPORTUNITIES

Energy Management Opportunities is a term that represents the ways that energy can be used wisely to save money. A number of typical Energy Management Opportunities subdivided into Housekeeping, Low Cost, and Retrofit categories are outlined in this section with text to illustrate the potential energy savings. This is not a complete listing of the available opportunities. However, it is intended to provide ideas for management, operating and maintenance personnel to identify other opportunities that are applicable to a particular facility.

It was previously pointed out that energy savings do not directly result from the use of automatic control equipment. It is the application of instruments to other equipment and systems that creates the saving opportunities. This means that the use of instruments to optimize equipment and process operations should be a background question when studying the other modules. The other modules in this series contain worksheets for the detailed calculations that are required to analyze Energy Management Opportunities. The objective in this section is to provide overview examples of how automatic control facilitates energy and dollar savings. Detailed calculations, which would involve an understanding of other equipment and systems (e.g. HVAC systems, boilers, heat exchangers and air compressors) have been avoided. When properly applied, automatic controls can save energy and dollars, therefore each facility should be evaluated for the opportunities related to the use of control equipment.

Housekeeping Opportunities

Implemented housekeeping opportunities are energy management actions that are done on a regular basis and never less than once a year. With respect to automatic control, this includes activities such as the periodic calibration of devices, and troubleshooting control problems.

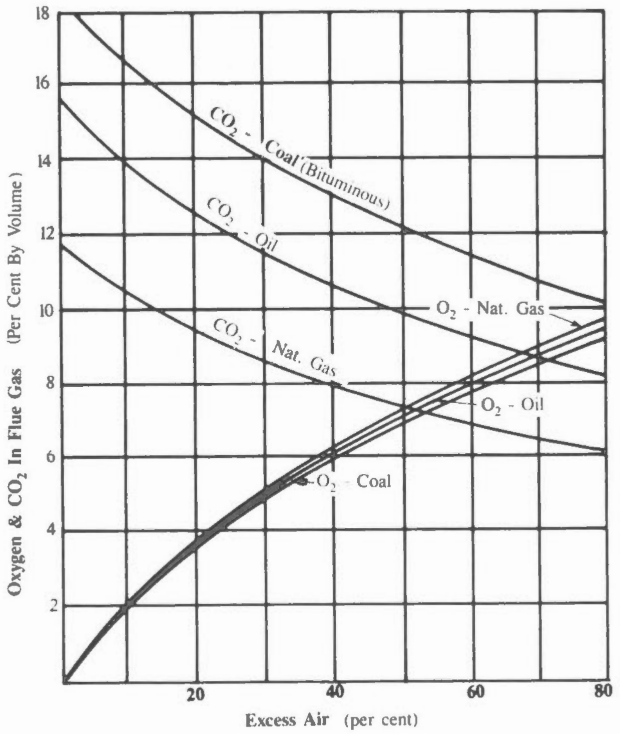
Routine Equipment Inspection and Calibration

Dramatic measuring and control equipment failures can be detected by operating personnel. However, it is more common to experience a gradual deterioration in performance with only subtle indications. Thus, it is important to look for the first signs of off-standard performance, and have a calibration program which eliminates calibration drift before it becomes a significant influence on the process operation. The following opportunities will provide an indication of this activity.

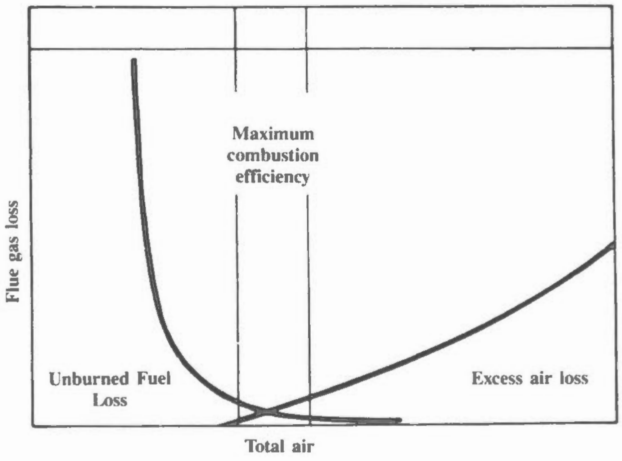
1. Factors which might affect measurement accuracy should be carefully watched because of their influence on the associated control results. For instance, a natural gas pressure which is lower than design conditions will cause the flow measurement to be in error on the high side. Refer to Measuring, Metering and Monitoring, Module 15.
2. The drift in the operation of a controller maintaining the ratio between fuel and air flows to a boiler will result in more excess air in one direction or the possibility of combustibles with an air deficiency. In either case, this unnecessary loss can be detected by observing the oxygen and combustibles recorder or by manually checking the flue gases with an Orsat.
3. Another example of a loop check paying dividends would be the calibration of pressure controls on a dual duct HVAC system to maintain minimum duct static pressure. Refer to Heating, Ventilating and Air-Conditioning, Module 10, for this and other HVAC related examples.
4. Complete control loops should be routinely checked for measurement and set point calibration, final control element operation and overall loop performance. The loop operation may involve a combination of sequencing steps and modulating action.
5. Damper operation, including the operating linkage, should be regularly checked for smoothness of operation and shut-off tightness.
6. For pneumatic controls, the air supply system should be regularly monitored. This would include eliminating

air leaks, blowing liquid from the system at drain valves and checking the condition of filter media. Refer to Water and Compressed Air Systems, Module 12.

7. It is also possible for a control loop with well calibrated and tuned components to be improperly operated because of operator confusion or carelessness. Routine checks of equipment operation and discussions with operating personnel may uncover situations which require supervision.



Per Cent Oxygen and CO_2 Versus Excess Air
Figure 40



Zone of Maximum Combustion Efficiency
Figure 41

Optimizing Control System Performance

The foregoing housekeeping activities may have resulted in the control loops performing to the plant standards. However, the standards for control loop performance may have been established when there was less emphasis on saving energy and dollars. An opportunity may be created by optimizing controls as a separate activity, to focus attention on loop performance. A random sample of examples is provided to stimulate thinking about opportunities available in Industrial, Commercial and Institutional facilities.

1. Inspect thermostats and relocate them if they are positioned on outside walls or in drafts.
2. In the heating season lower the thermostat setting because each degree reduction saves about two and a half per cent of the related heating energy.
3. During unoccupied periods set thermostats lower.
4. Raise building thermostat settings during the cooling season.
5. In multizone HVAC systems, set control to reduce hot deck and increase cold deck temperatures consistent with the loads of critical zones. While this will lower energy consumption, it must be noted that it will also reduce the heating and cooling capabilities of the system.
6. Adjust and balance heating and cooling control systems to minimize cooling and overheating which results from poor zoning, poor distribution and poor control system operation.
7. A boiler is a reasonably complex process which is common to many plants, and it can be used as an example. Figure 40 shows that the ideal amount of air to combine with fuel in a combustion process is a narrow range defined as “the zone of maximum combustion efficiency”. Surplus combustion air unnecessarily adds to the excess air loss of the flue gases up the stack, while insufficient air results in unburned fuel

loss plus the potential of establishing explosive conditions. The fuel-air ratio establishes the total air value and the per cent oxygen in the flue gases indentifies the amount of excess air (Figure 41). Because of the conservatism of plant operators and control equipment personnel it is quite usual to find high excess air. The leverage between the cost of making safe and efficient adjustments and the resulting fuel savings can be substantial. The savings will depend on the temperature of the flue gases, but a typical reduction of 1 per cent oxygen results in a 5 per cent excess air reduction and fuel savings in the order of ½ of 1 per cent. Refer to Combustion, Module 5 for more details.

8. Adjust controls to prevent simultaneous operation of heating and cooling systems to achieve desired temperature.

Low Cost Opportunities

Implemented low cost opportunities are Energy Management actions that are *done once and for which the cost is not great*. This creates a separation from the housekeeping activities which must be repeated regularly. The third and final classification of an energy management opportunity is retrofit and this is intended to cover any changes too large to be defined as low cost. The distinction between low cost and retrofit energy management opportunities will depend upon the size and nature of a facility, and must be established by the company or institution.

Two-Position Control

The Fundamentals section identified that two-position control devices are commonly used because of their relative low cost. There is great diversity in the types of two-position controllers, but the following will provide an overview of the opportunities which may be available to save energy and dollars.

1. Install thermostats for control of all heating equipment.
2. Consider installation of night set-back and morning start-up controls for scheduling the heating and cooling operations for each HVAC zone on the basis of occupancy patterns. This would include an analysis of when start-up should take place to ensure comfort for occupants when they arrive for work.
3. Consider installation of key-lock plastic covers over thermostats to prevent building occupants from adjusting settings.
4. Install photocells to control outdoor or perimeter lighting.
5. Consider installing a master switching system, using low voltage switching to permit an operator at one or more stations to turn off lighting at the end of occupied periods. Seven-day timers can also be used to program lights automatically.
6. Lights are often left on after all personnel have left an area. One solution involved installing a sensing device at the truck exit to establish when a truck vacated an area. A timer was actuated by this sensor and, after a short time-out period, most of the lights in that area were turned off.
7. Consider the installation of automatic door closers on personnel and vehicle doors connecting to the outdoors.
8. Install warm-up cycle controls on air-handling units that have an outside air intake, to permit outside air dampers to remain closed during building warm up or cool down.
9. Add automatic timers for night and weekend temperature set point operation for all infrequently occupied areas.
10. In some cases, the installation of a very simple and inexpensive control can result in dramatic savings. An example of this is a small bakery that was running a continuous baking line. The product was packed directly from the bakeoven discharge conveyor. Any product missed by the operator went to scrap. The wasted product exceeded 20 per cent of production. A photoswitch was installed beyond the operator, to sense product on the belt. Whenever product passed the packaging operator the belt stopped automatically to allow the product to be retrieved. This reduced the waste to less than 5 per cent of production.
11. Measurement is always required for a control system, but this is an example of a control system being required for an accurate and high rangeability measurement system. When steam flow measurement is used for billing purposes it is important that the measurement be accurate at low and high flow rates. When the expected steam use variations exceeds the rangeability of steam flow meters, the solution is to put a low range meter in parallel with a high range meter. An automatic selecting control circuit is then used to select the appropriate meter for the flow rate and use its output for billing purposes.

Modulating Control

Modulating control is normally more sophisticated than two-position control, but its complexity varies considerably from self-operated regulators to centralized control systems. This diverse control equipment is in turn applied to the various Industrial, Commercial and Institutional applications, thus the following list only "scratches the surface" of potential opportunities.

1. Consider water flow and temperature regulators for showers.
2. An uncontrolled amount of water was being used to rinse components in a manufacturing process and then allowed to overflow to a drain. An adjustable self-operated flow regulator was installed to allow the lowest acceptable flow rate to be established and maintained.
3. For applications such as heavy-oil heating systems convert two-position control to self-operated temperature regulator control. This would have to be justified, but the reasons might include the elimination of unacceptable temperature variations or the smoothing out of the steam demand.
4. Convert from batch to continuous operation. Benefits may include more uniform process conditions, greater throughput using the same size process equipment, and heat recovery between stages.
5. Add better HVAC controls to prevent simultaneous heating and cooling to satisfy temperature requirements.
6. Replace HVAC air-handling systems, dampers and operators which do not perform satisfactorily.
7. Add the necessary equipment and controls to convert a constant-volume-air-handling system to a variable-air-volume type.
8. In a multizone HVAC system, consider installing automatic control valves to regulate hot and cold deck temperatures according to demand. When properly installed, and with all hot deck or cold deck dampers partially closed, the control will reduce hot deck and increase cold deck temperatures progressively until one or more zone dampers are fully open.
9. Consider converting single-zone, single-duct systems to variable-volume by adding variable-air-volume boxes at each branch. Fan volume must be controlled according to demand.
10. Provide volume control for the supply air fan and reduce capacity, preferably by speed reduction, when hot deck and cold deck air quantities can be reduced and still meet peak loads. Reducing heat loss and heat gain provides an opportunity to reduce the amount of circulated air.
11. Change dual-duct systems to variable-volume when energy analysis is favorable and the payback in energy saved is sufficiently attractive. Do this by adding variable-air-volume boxes and fan control.
12. Use fan-inlet-vortex-dampers with operators, or fan variable speed drives to reduce air flow for low demand conditions.
13. Consider installing economizer-cycle and/or enthalpy-control to air handling units in offices. This will minimize cooling-energy requirements by using proper amounts of outdoor and return air to permit "free cooling", when possible with outside air.
14. Large electricity users pay for electricity by a combination of consumption and demand charges. Demand charges do not represent energy benefits to a facility and should be avoided. Explore the possibility of a peak-demand controller to reduce the peak electrical demand and so reduce the demand charges. Refer to Electrical, Module 3 for more details.
15. The relationship of boiler excess air to fuel savings was discussed in the housekeeping examples in the context of control equipment calibration. The existing control system may be so rudimentary that a superior system could be justified on the basis of fuel savings. This might be achieved by upgrading a simple positioning system to a fuel-flow/air-flow control system. Another example would be an existing fuel-flow/air-flow combustion control system that could be upgraded to incorporate automatic oxygen recorrection. In both control system upgrade situations the objective is to maintain optimum conditions as shown in Figure 40.
16. Continuous boiler blow down limits the dissolved and suspended solids in the boiler water system. The blow down rate can be eight per cent of the boiler output and so the combination of volume and energy content can represent significant heat losses to drain. Alternatively, the blow down water condition can be continuously measured and the blow down throttled to as low a value as possible, while maintaining the water conditions at acceptable limits. This type of a control loop can save 50 per cent of the original blowdown loss. Refer to Boiler Plant Systems, Module 6, for more details.

Sequencing Control

Sequencing control typically involves detectors such as temperature, pressure, level and photoelectric switches combined with the relays, timers and switches to provide a step by step logic system. These systems can interlock consecutive actions so that the second step cannot be initiated without the completion of the first. They can be used to save time, reduce personnel and ensure that safe conditions are maintained. The following examples provide an indication of the available dollar saving opportunities.

1. The normal operation of outdoor lights from a photocell could be combined with a 7-day timer that prevented the photocell from turning on the lights during weekends.
2. Install a master switching system driven by a 7-day timer to turn off all interior lighting at the end of occupied periods.
3. Use 7-day timers to override normal heating or cooling controls during weekends.
4. Add a step-controller to stage resistance elements in electric heating systems. This may result in more effective heat control and electrical demand management.
5. A food processing plant sterilized jars of product in retorts by means of steam-heated hot water. At a certain point in the cycle, the hot water was discharged gradually to a drain and substituted by cold water. The hot water loss to drain was significant, and this loss was eliminated through a sequencing system that temporarily stored the hot water between batches. The sequencing system included a temperature detector to initiate the cooling cycle, timers to achieve the required dwell times for certain conditions, and relay-operated shut-off valves to direct the hot water into and out of storage.
6. Dual-thermostat controls provide automatic setback of night and weekend plant temperatures. They can be incorporated into a simple control system which enables authorized janitorial staff to override the setback settings.
7. Segments of the Food Industry use large volumes of water to clean processing areas. Often this happens every shift. When hot water is regularly used for cleaning there are ways to conserve heat energy. One method is to store the hot water from the second stage of the cleaning cycle, and use it for the beginning of the next phase of cleaning. Effectively, the water is used twice before going to the sewer, but the final washing is always done with clean hot water. An automatic sequencing system controls the operation of a sump pump, valves and a storage tank according to the point in the cycle.
8. There are many examples where product must be heated and then cooled. By automatically sequencing the stages it is possible to direct the cooler fluid through a heat exchanger so that it is heated by the hot fluid that is about to be cooled. Thus, the product that will go through the heating cycle starts to be heated and the product about to go through the cooling cycle is cooled somewhat.

Retrofit Opportunities

Implemented *retrofit opportunities* are Energy Management actions which are *done once and for which the cost is significant*. Automatic control equipment can be applied to most types of equipment and processes so that there is no systematic way of providing retrofit Energy Management Opportunities. This section provides a few examples of how instruments can contribute to the saving of energy and dollars.

Analog Control

Cogeneration is a term used to describe the concept of generating high pressure superheated steam to drive a steam turbine, which in turn drives an electrical generator. Low-pressure exhaust steam from the turbine is used for plant processing or heating systems. This dual use of the steam creates the financial benefit. The efficient operation of this type of facility can involve a sizable analog control system. This includes all of the control loops normally associated with a boiler, the additional requirement of steam temperature control, governor control of the turbine, and the proper operation of the exhaust steam header which serves the plant steam needs.

Programmable Controller

It is not possible to describe all of the typical applications for a programmable control (PC). The following list provides examples from different sectors that will give perspective on the wide use of this form of control.

1. Specialty paper machines must be flexible in terms of modifying the operation to make different qualities of paper as dictated by orders. There would be a different recipe for each grade of paper and these can

be resident in the PC. Thus, the different pulp stocks, chemicals and dyes can be mixed automatically in accordance with the operator selecting the paper grade and the size of the run. The sequencing of the stock from a blending tank to the paper machine would also be PC controlled. Management reports covering raw material and final product quantities can be printed automatically by the system.

2. Programmable controllers are well suited to the control of rubber-mixing machines (Banbury mixers) used in the rubber and plastic manufacturing industries. The controller can provide accurate scale control for the addition of items such as carbon black, oils, waxes, antioxidants and pigments, plus control the component addition times, mixing cycles, ram pressures and batch discharge sequencing. In addition to providing the basis for consistent component additions with the resultant improvement in product quality and increased machine throughput, the controller can produce shift reports on quantities of the various components processed.
3. Precision liquid dye batching is an important function in the textile industry. Flexibility and accuracy are the keys in changing to different dye recipes. This involves a combination of activities during the batching operation: determining quantities; weighing; operating valves; mixing; selecting tanks; operating mixers; accurately establishing the position of movable hoppers; displaying batch status; and generating batch reports. Without this automatic facility the calculations would be time consuming and subject to error.
4. Facility energy management systems can be developed with PC systems. These systems can monitor indoor and outdoor temperatures, process equipment operation, plus heating and cooling unit operation. The PC could control individual or groups of heating or cooling controls, makeup air, illumination and other energy using devices according to facility operation schedules. Energy consumption and demand could be monitored at substations and alarmed if peak demand conditions were being approached.
5. The automotive manufacturing process includes many sequential operations that must be carefully interlocked. For many years, this was accomplished by relays, timers, pushbuttons and lights which were bulky to mount and required individual wiring that might have to be totally revamped after one model year. A PC depends on detectors, such as photoelectric switches, but it can easily duplicate the logic components and allow enhancements as the operation is refined.
6. PCs have been used in many common applications. For example, in a carwash the system can accept the special wax instruction, track the car and activate the pertinent wax application hardware, water sprays and brush action. The accurate positioning of the car can correlate car length to equipment and material use to save dollars. The throughput rate for cars can also be adjusted. The PC readily accepts future enhancements to the carwash operation.
7. Materials handling is another good example of the use of a PC. This typically involves combinations of conveyors, minimum or maximum product load regulation, selection of multiple routes, product loading and discharging, operation display and limited operator intervention capability. All of these functions are easily handled by a PC.

Computer

A computer could be used to control all of the processes described in this module and many other larger and more complicated ones. The financial justification is a complex exercise that considers capital and annual costs and many annual benefit factors. The benefits could include factors such as quality, quantity, efficiency, safety, flexibility, dependability, and better management reporting as an offshoot benefit. This type of analysis requires the participation of an experienced person or team. A few general examples of computer use follow.

1. The Equipment/Systems section described the type of microprocessor systems that are now commonly used to control a complete boiler plant automatically. They provide many features including combustion and feedwater control, sequencing of burner management systems, efficiency calculations, boiler loading for optimum operation, and reporting. These systems are used in Industrial, Commercial and Institutional facilities and are justified on the basis of fuel savings.
2. Computerized weigh scale systems are commonly used for highway truck inspection stations. The computer accepts information from weigh-in-motion and static-scale systems, and provides driver instructions from a message board (while the incoming truck is still in motion). Truck identification data is entered by the operator and automatically combined with the scale information, on the printout sheet along with the date and time.

3. A company decided to build a large sugar-substitute processing plant. The sweetener market was very competitive making processing efficiency very important. The process was reasonably complicated and still changing because of the new technology. A large computer system with complete backup was chosen to control all process loops, to monitor and automatically alarm off-standard process conditions, and to provide operating and management reports.
4. A chemical company installed a waste treatment facility to treat 24 000 m^3 per day of plant effluent before discharging it to a river. The process involved new technology and it was recognized that some original development work would be required to successfully commission the system. Some of the controlled variables would be influenced by several interacting process disturbances. A decision was made to use a small computer system to provide direct digital control (DDC) of the controlled variables. This would allow the interacting variables to be incorporated into control loops. Based on commissioning and operating experience it was possible to change some control strategies by programming. The computer could also provide operating and management reports.
5. A large bulk-mail-handling facility had the task of handling 2 000 tonnes per day of bagged mail, and individual parcels (up to ½ million pieces of mail per day). In one day, the mail had to be received, stored, sorted to hundreds of different destinations, consolidated by destination, stored and then delivered to trucks as they randomly arrived. A large dual-redundant computer system (i.e. computer backed up by an active computer) was selected to control the variable sequencing of 1200 conveyors for the sorting operation. The central control room had several printers to regularly print out normal operating information and alarm conditions. The operator panel and console arrangement included the means of communicating with the computer and many closed circuit television screens. This allowed the centrally-located operator to be aware of the operation throughout the large facility.
6. Electric power demand control can be implemented by using computer systems to stage the load at peak periods. The complete operation must be analysed to establish the main electrical consumers and the conditions that would permit some to be cut back or shutdown during high peak periods. The various combinations of shutdown permissives and the optimizing of plant operation can be easily established by a computer. The computer would then operate the equipment accordingly.
7. Electric utilities and transit systems use Supervisory Control and Data Acquisition (SCADA) systems to monitor power distribution systems. These systems are computer-based and can be programmed to switch power sources as operating problems are experienced.

APPENDICES

Glossary

The Measuring, Metering and Monitoring, Module 15 and Automatic Control, Module 16 are closely related and will often be used together in analyzing energy management opportunities. Thus, the same glossary is used in each module.

Accuracy, measured — The difference between the ideal value and the measured value.

Accuracy, rating — A number or quantity that defines a limit that errors will not exceed when a device is used under specified operating conditions. Accuracy rating includes the combined effects of conformity, hysteresis, dead band and repeatability errors. It is typically expressed in terms of the measured variable, as per cent of span, per cent of upper range value, or per cent of actual output reading.

Air Consumption — The maximum rate at which air is consumed by a device within its operating range during steady-state signal conditions.

Alarm — An audible and/or visual signal that identifies a nonstandard condition.

Analysis, flue gas — The measurement of the constituents of the products of combustion. Normally expressed in % volume of Oxygen (O_2), Carbon Monoxide (CO) or Carbon Dioxide (CO_2)

Annunciator — A complement of hardware used to make operating personnel aware of a nonstandard condition through audible and visual signals.

Audit, diagnostic — Analysis of a potential opportunity to save energy which could involve the assessment of the current process operation, records, the calculation of savings, and estimates of capital and operating costs so that the financial viability could be established.

Audit, walk through — A visual inspection of a facility to observe how energy is used or wasted.

Automatic Controller — A device which operates automatically to regulate a controlled variable.

Automatic-Manual Station — A device which enables an operator to select an automatic or manual signal as the input to a final control element. The automatic signal is normally the output of a controller while the manual signal is the output of a manually operated device.

Calibrate — To establish outputs of a device corresponding to a series of values of the quantity which the device is to measure.

Cathode Ray Tube (CRT) — A display device that permits two way communication between a data logger or computer and a human.

Computer — An electronic device which receives inputs, processes them and produces outputs. It consists of a central processing unit, memory and input/output circuits.

Control Action — This relates to a controller and identifies how the output is affected by the input to the controller.

Control Action, rate (derivative) (D) — Control action in which the output is proportional to the rate of change of the input error signal. It is used to help offset measurement lag problems.

Control Action, reset (integral) (I) — Control action in which the output is proportional to the time integral of the input error signal. It is used to eliminate offset between the set point and the measured variable.

Control Action, proportional — Control action in which the change in controller output is proportional to the change in the input error signal.

Control Action, proportional-plus-rate (derivative) (PD) — Control action in which the output is proportional to a linear combination of the input error signal and the time rate of change of input.

Control Action, proportional-plus-reset (integral) (PI) — Control action in which the output is proportional to a linear combination of the input error signal and the time integral of the input.

Control Action, proportional-plus-reset (integral) plus-rate (derivative) (PID) — Control action in which the output is proportional to a linear combination of the input error signal, the time integral of input and the time rate of change of input.

Control, cascade — Control in which the output of one controller is the set point for another controller

Control Center — An equipment structure, or group of structures, from which the process is measured, controlled and/or monitored.

Control, differential gap — Control in which the output of a controller remains at a maximum or minimum value until the controlled variable crosses a band or gap, causing the output to reverse.

Control, direct digital — Control performed by a digital device which establishes the signal to the final controlling element.

Control, feedback — Control in which a measured variable is compared to its desired value to produce an error signal which is acted upon in such a way as to reduce the magnitude of the error.

Control, feedforward — Control in which information concerning one or more conditions that can disturb the controlled variable is converted, outside of any feedback loop, into corrective action to minimize deviations of the controlled variable.

Control, multielement — The use of more than one process variable to regulate the controlled variable.

Controller, direct connected — A controller which senses the controlled variable instead of receiving a signal from a transmitter.

Controller, direct acting — A controller in which the value of the output signal increases as the value of the input (measured variable) increases.

Controller, program — A controller which automatically holds or changes set point to follow a prescribed program for a process.

Controller, reverse acting — A controller in which the value of the output signal decreases as the value of the input(measured variable) increases.

Controller, self-operated (regulator) — A controller in which all the energy to operate the final controlling element is derived from the controlled system.

Control, optimizing — Control that automatically seeks and maintains the most advantageous value of a specified variable, rather than maintaining it at one set value.

Control, supervisory — Control in which the control loops operate independently subject to intermittent corrective action.

Control System, automatic — A control system which operates without human intervention.

Control Valve — A final control element, through which a fluid passes, which adjusts the flow as directed by a controller.

Data Logger — An electronic data recording device which has the ability to store and manipulate data.

Dead Band — The range through which an input signal may be varied, upon reversal of direction, without initiating an observable change in output signal.

Disturbance — A disturbance acts on a process to drive the controlled variable away from the set point.

Drift — An undesired change in output over a period of time.

Element, final control — A controlling element which directly changes the value of the manipulated variable.

Element, primary — The system element that converts the measured variable energy into a form suitable for measurement.

Element, sensing — The element directly responsive to the value of the measured variable.

Energy — The capacity for doing work; taking a number of forms that may be transformed from one into another, such as thermal (heat), mechanical (work), electrical, and chemical, in customary units, measured in kilowatt-hours (kWh) or megajoules (MJ).

Energy Accounting — The process of accurately gathering all pertinent information on production and energy usage and the subsequent analysis for reporting and control purposes.

Energy Management Opportunities, housekeeping — Activities which should be done on a regular basis and never less than once per year.

Energy Management Opportunities, low cost — Improvements that are implemented once and the cost is not great.

Energy Management Opportunities, retrofit — Improvements that are implemented once where the cost is considered to be significant.

Energy Performance — A measure of the effectiveness of utilizing energy expressed in energy per unit of production.

Energy, waste — Energy which is lost without being fully utilized.

Flowmeter — A device that measures the rate of flow or quantity of a moving fluid in an open or closed conduit.

Hardware — Physical equipment directly involved in performing process measuring and controlling functions.

Heating Value — The gross(Higher Heating Value) energy content of a fuel in MJ.

Indicator Travel — The length of the indicator scale.

Instrumentation — A collection of instruments or their application for the purpose of observation, measurement or control.

Instrument, indicating — A measuring instrument in which the present value of the measured variable is indicated.

Instrument, measuring — A device for ascertaining the magnitude of a quantity or condition.

Instrument, recording — A measuring instrument in which the values of the measured variable are recorded.

Intrinsically Safe Equipment and Wiring — Equipment and wiring which are incapable of releasing sufficient electrical or thermal energy under normal or abnormal conditions to cause ignition of a specific hazardous atmospheric mixture in its most easily ignited concentration.

Linearity — The closeness to which a curve approximates a straight line.

Loop, closed (feedback loop) — A signal path which includes a forward path, a feedback path and a summing point, and forms a closed circuit.

Microcomputer — A single circuit or component computer which uses a microprocessor as its central processing unit and has built-in memory and input/output circuits.

Microprocessor — A microelectric circuit or device which performs the processing function of a computer.

Modulating Control — Any form of control in which the manipulated variables can be set to any position within the control range to maintain the controlled variable at set point.

Monitoring — The act of observing facility conditions is called monitoring and the equipment that assists with this activity are called monitoring devices. In this module monitoring also means analyzing the data obtained through the monitoring process.

Offset — The steady-state deviation between the set point and the controlled variable.

Operating Conditions — Conditions to which a device is subjected, not including the variable measured by the device.

Operative Limits — The range of operating conditions to which a device may be subjected without permanent impairment of operating characteristics.

Overrange Limit — The maximum input that can be applied to a device without causing damage or permanent change in performance.

Pressure, absolute — Any pressure where the base for measurement is full vacuum expressed as kPa(absolute).

Pressure, differential — The difference in pressure between two points.

Pressure, gauge — Any pressure where the base for measurement is atmospheric pressure expressed as kPa(gauge). Note that kPa(gauge) + atmospheric pressure = kPa(absolute).

Pressure, maximum working (MWP) — The maximum total pressure permissible in a device under any circumstances during operation at a specified temperature.

Pressure, operating — The actual pressure at which a device operates under normal conditions.

Pressure, rupture — The pressure, determined by test, at which a device will burst.

Pressure, static — The pressure exerted in all directions by a fluid at rest. For a fluid in motion it is measured in a direction that is at right angle to the flow direction.

Pressure, velocity — The pressure measured in the direction of flow less the static pressure.

Process — Physical or chemical change of matter or conversion of energy.

Process Control — The regulation or manipulation of variables to obtain a product of desired quality in an efficient manner.

Process Measurement — The acquisition of information that establishes the magnitude of process quantities.

Programmable Controller — A solid state device that performs a control function by means of a stored program and feedback from input and output devices.

Proportional Band — The change in the input error signal required to produce a full range change in output due to proportional control action. It is reciprocally related to proportional gain.

Range — The region between the limits of lower and upper range-values.

Range-Value, lower — The lowest value of the measured variable that a device is adjusted to measure.

Range-Value, upper — The highest value of the measured variable that a device is adjusted to measure.

Reliability — The probability that a device will perform its objective adequately, for the period of time specified, under the operating conditions specified.

Repeatability — The closeness of agreement among a number of consecutive measurements of the output for the same value of the input under the same operating conditions, approaching from the same direction, for full range traverses.

Response, dynamic — The behavior of the output of a device as a function of the input with respect to time.

Sampling Period — The time interval between observations in a periodic sampling control system.

Self-regulation — The property of a process or machine which permits attainment of equilibrium, after a disturbance, without the intervention of a controller.

Set Point — An input variable which sets the desired value of the controlled variable.

Signal — The physical variable, which carries information about another variable (which the signal represents).

Signal, analog — A signal representing a variable which may be continuously observed and represented.

Signal, digital — Representation of information by a set of discrete values in accordance with a prescribed law. These values are represented by numbers.

Signal, error — The difference between the set point and the controlled variable.

Signal, output — A signal delivered by a device.

Span — The algebraic difference between the upper and lower range-values.

Span Adjustment — Means provided in an instrument to change the shape of the input-output curve

Standard — A unit of measure established to permit accurate comparisions to be made.

Steady State — The condition where a measured variable or instrument are not changing with time.

Temperature, ambient — The temperature of the medium surrounding a device.

Time, dead — The interval of time between initiation of an input change or stimulus and the start of the resulting observable response.

Transducer — An element or device which receives information in the form of one quantity and converts it to information in the form of the same or another quantity.

Transmitter — A transducer which responds to a measured variable by means of a sensing element, and converts it to a standardized transmission signal which is a function only of the measured variable.

Tune — An expression used to describe the exercise of adjusting controls and observing the process reaction until the operation responds acceptably to process disturbances.

Value, desired — The value of the controlled variable chosen.

Value, ideal — The exact quantity of a measured variable relative to a specific standard of measure.

Variable, controlled — In a control loop, the variable which is sensed to originate a feedback signal.

Variable, manipulated — The process variable which is regulated to maintain the controlled variable at or near set point.

Variable, measured — A quantity, property, or condition which is measured.

Zero Adjustment — Means provided in an instrument to provide a parallel shift of the input-output curve.

COMMON CONVERSIONS

1 barrel (35 Imp gal) = 159.1 litres
(42 US gal)

1 gallon (Imp) = 1.20094 gallon (US)

1 horsepower (boiler) = 9809.6 watts

1 horsepower = 2545 Btu/hour

1 horsepower = 0.746 kilowatts

1 joule = 1 N-m

Kelvin = (°C + 273.15)

1 kilowatt-hour = 3600 kilojoules

1 Newton = 1 kg-m/s^2

1 therm = 10^5 Btu

1 ton (refrigerant) = 12002.84 Btu/hour

1 ton (refrigerant) = 3516.8 watts

1 watt = 1 joule/second

Rankine = (°F + 459.67)

Cubes

1 yd^3 = 27 ft^3

1 ft^3 = 1728 in^3

1 cm^3 = 1000 mm^3

1 m^3 = 10^6 cm^3

1 m^3 = 1000 L

Squares

1 yd^2 = 9 ft^2

1 ft^2 = 144 in^2

1 cm^2 = 100 mm^2

1 m^2 = 10000 cm^2

SI PREFIXES

Prefix	Symbol	Magnitude	Factor
tera	T	1 000 000 000 000	10^{12}
giga	G	1 000 000 000	10^{9}
mega	M	1 000 000	10^{6}
kilo	k	1 000	10^{3}
hecto	h	100	10^{2}
deca	da	10	10^{1}
deci	d	0.1	10^{-1}
centi	c	0.01	10^{-2}
milli	m	0.001	10^{-3}
micro	u	0.000 001	10^{-6}
nano	n	0.000 000 001	10^{-9}
pica	p	0.000 000 000 001	10^{-12}

UNIT CONVERSION TABLES
METRIC TO IMPERIAL

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
amperes/square centimetre	A/cm^2	amperes/square inch	A/in^2	6.452
Celsius	°C	Fahrenheit	°F	(°C × 9/5) + 32
centimetres	cm	inches	in	0.3937
cubic centimetres	cm^3	cubic inches	in^3	0.06102
cubic metres	m^3	cubic foot	ft^3	35.314
grams	g	ounces	oz	0.03527
grams	g	pounds	lb	0.0022
grams/litre	g/L	pounds/cubic foot	lb/ft^3	0.06243
joules	J	Btu	Btu	9.480×10^{-4}
joules	J	foot-pounds	ft-lb	0.7376
joules	J	horsepower-hours	hp-h	3.73×10^{-7}
joules/metre, (Newtons)	J/m, N	pounds	lb	0.2248
kilograms	kg	pounds	lb	2.205
kilograms	kg	tons (long)	ton	9.842×10^{-4}
kilograms	kg	tons (short)	tn	1.102×10^{-3}
kilometres	km	miles (statute)	mi	0.6214
kilopascals	kPa	atmospheres	atm	9.87×10^{-3}
kilopascals	kPa	inches of mercury (@ 32°F)	in Hg	0.2953
kilopascals	kPa	inches of water (@ 4°C)	in H$_2$O	4.0147
kilopascals	kPa	pounds/square inch	psi	0.1450
kilowatts	kW	foot-pounds/second	ft-lb/s	737.6
kilowatts	kW	horsepower	hp	1.341
kilowatt-hours	kWh	Btu	Btu	3413
litres	L	cubic foot	ft^3	0.03531
litres	L	gallons (Imp)	gal (Imp)	0.21998
litres	L	gallons (US)	gal (US)	0.2642
litres/second	L/s	cubic foot/minute	cfm	2.1186
lumen/square metre	lm/m^2	lumen/square foot	lm/ft^2	0.09290
lux, lumen/square metre	lx, lm/m^2	footcandles	fc	0.09290
metres	m	foot	ft	3.281
metres	m	yard	yd	1.09361
parts per million	ppm	grains/gallon (Imp)	gr/gal (Imp)	0.07
parts per million	ppm	grains/gallon (US)	gr/gal (US)	0.05842
permeance (metric)	PERM	permeance (Imp)	perm	0.01748
square centimetres	cm^2	square inches	in^2	0.1550
square metres	m^2	square foot	ft^2	10.764
square metres	m^2	square yards	yd^2	1.196
tonne (metric)	t	pounds	lb	2204.6
watt	W	Btu/hour	Btu/h	3.413
watt	W	lumen	lm	668.45

UNIT CONVERSION TABLES
IMPERIAL TO METRIC

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
ampere/in^2	A/in^2	ampere/cm^2	A/cm^2	0.1550
atmospheres	atm	kilopascals	kPa	101.325
British Thermal Unit	Btu	joules	J	1054.8
Btu	Btu	kilogram-metre	kg-m	107.56
Btu	Btu	kilowatt-hour	kWh	2.928×10^{-4}
Btu/hour	Btu/h	watt	W	0.2931
calorie, gram	cal or g-cal	joules	J	4.186
chain	chain	metre	m	20.11684
cubic foot	ft^3	cubic metre	m^3	0.02832
cubic foot	ft^3	litre	L	28.32
cubic foot/minute	cfm	litre/second	L/s	0.47195
cycle/second	c/s	Hertz	Hz	1.00
Fahrenheit	°F	Celsius	°C	(°F-32)/1.8
foot	ft	metre	m	0.3048
footcandle	fc	lux, lumen/ square metre	lx, lm/m^2	10.764
footlambert	fL	candela/square metre	cd/m^2	3.42626
foot-pounds	ft-lb	joule	J	1.356
foot-pounds	ft-lb	kilogram-metres	kg-m	0.1383
foot-pounds/second	ft-lb/s	kilowatt	kW	1.356×10^{-3}
gallons (Imp)	gal (Imp)	litres	L	4.546
gallons (US)	gal (US)	litres	L	3.785
grains/gallon (Imp)	gr/gal (Imp)	parts per million	ppm	14.286
grains/gallon (US)	gr/gal (US)	parts per million	ppm	17.118
horsepower	hp	watts	W	745.7
horsepower-hours	hp-h	joules	J	2.684×10^{6}
inches	in	centimetres	cm	2.540
inches of Mercury (@ 32°F)	in Hg	kilopascals	kPa	3.386
inches of water (@ 4°C)	in H_2O	kilopascals	kPa	0.2491

UNIT CONVERSION TABLES
IMPERIAL TO METRIC (cont'd)

FROM	SYMBOL	TO	SYMBOL	MULTIPLY BY
lamberts	* L	candela/square metre	cd/m^2	3.183
lumen/square foot	lm/ft^2	lumen/square metre	lm/m^2	10.76
lumen	lm	watt	W	0.001496
miles (statute)	mi	kilometres	km	1.6093
ounces	oz	grams	g	28.35
perm (at 0°C)	perm	kilogram per pascal-second-square metre	kg/Pa-s-m^2 (PERM)	5.721×10^{-11}
perm (at 23°C)	perm	kilogram per pascal-second-square metre	kg/Pa-s-m^2 (PERM)	5.745×10^{-11}
perm-inch (at 0°C)	perm. in.	kilogram per pascal-second-metre	kg/Pa-s-m	1.4532×10^{-12}
perm-inch (at 23°C)	perm. in.	kilogram per pascal-second-metre	kg/Pa-s-m	1.4593×10^{-12}
pint (Imp)	pt	litre	L	0.56826
pounds	lb	grams	g	453.5924
pounds	lb	joules/metre, (Newtons)	J/m, N	4.448
pounds	lb	kilograms	kg	0.4536
pounds	lb	tonne (metric)	t	4.536×10^{-4}
pounds/cubic foot	lb/ft^3	grams/litre	g/L	16.02
pounds/square inch	psi	kilopascals	kPa	6.89476
quarts	qt	litres	L	1.1365
slug	slug	kilograms	kg	14.5939
square foot	ft^2	square metre	m^2	0.09290
square inches	in^2	square centimetres	cm^2	6.452
square yards	yd^2	square metres	m^2	0.83613
tons (long)	ton	kilograms	kg	1016
tons (short)	tn	kilograms	kg	907.185
yards	yd	metres	m	0.9144

* "L" as used in Lighting

The following typical values for conversion factors may be used when actual data are unavailable. The MJ and Btu equivalencies are heats of combustion. Hydrocarbons are shown at the higher heating value, wet basis. Some items listed are typically feedstocks, but are included for completeness and as a reference source. The conversion factors for coal are approximate since the heating value of a specific coal is dependent on the particular mine from which it is obtained.

ENERGY TYPE	METRIC	IMPERIAL
COAL		
— metallurgical	29,000 megajoules/tonne	25.0 × 10^6 Btu/ton
— anthracite	30,000 megajoules/tonne	25.8 × 10^6 Btu/ton
— bituminous	32,100 megajoules/tonne	27.6 × 10^6 Btu/ton
— sub-bituminous	22,100 megajoules/tonne	19.0 × 10^6 Btu/ton
— lignite	16,700 megajoules/tonne	14.4 × 10^6 Btu/ton
COKE		
— metallurgical	30,200 megajoules/tonne	26.0 × 10^6 Btu/ton
— petroleum		
— raw	23,300 megajoules/tonne	20.0 × 10^6 Btu/ton
— calcined	32,600 megajoules/tonne	28.0 × 10^6 Btu/ton
PITCH	37,200 megajoules/tonne	32.0 × 10^6 Btu/ton
CRUDE OIL	38,5 megajoules/litre	5.8 × 10^6 Btu/bbl
No. 2 OIL	38.68 megajoules/litre	5.88 × 10^6 Btu/bbl
		.168 × 10^6 Btu/IG
No. 4 OIL	40.1 megajoules/litre	6.04 × 10^6 Btu/bbl
		.173 × 10^6 Btu/IG
No. 6 OIL (RESID. BUNKER C)		
@ 2.5% sulphur	42.3 megajoules/litre	6.38 × 10^6 Btu/bbl
		.182 × 10^6 Btu/IG
@ 1.0% sulphur	40.5 megajoules/litre	6.11 × 10^6 Btu/bbl
		.174 × 10^6 Btu/IG
@ .5% sulphur	40.2 megajoules/litre	6.05 × 10^6 Btu/bbl
		.173 × 10^6 Btu/IG
KEROSENE	37.68 megajoules/litre	.167 × 10^6 Btu/IG
DIESEL FUEL	38.68 megajoules/litre	.172 × 10^6 Btu/IG
GASOLINE	36.2 megajoules/litre	.156 × 10^6 Btu/IG
NATURAL GAS	37.2 megajoules/m^3	1.00 × 10^6 Btu/MCF
PROPANE	50.3 megajoules/kg	.02165 × 10^6 Btu/lb
	26.6 megajoules/litre	.1145 × 10^6 Btu/IG
ELECTRICITY	3.6 megajoules/kWh	.003413 × 10^6 Btu/kWh

User Guide for Automatic Control Checklist 16-1

As the name implies this is a checklist and not a worksheet for energy and dollar savings calculations. It is intended to direct the first level of analysis in an orderly way. The use of the checklist can be adjusted to suit the specific needs, but the following represents the general intentions. The following numbers correspond to the Checklist numbers.

1. *Process performance*, safety, and energy use were intentionally placed at the beginning of the check-off points since they should identify the control loops with the greatest potential for improvement. Process performance includes the obvious question of whether the process is functioning and not causing problems for operating personnel, but the key issue is the *efficiency* of the operation.
2. *Safety* must always be a prime consideration and automatic controls can be the means of simultaneously satisfying *legislated codes, personnel safety and product safety* requirements.
3. *Energy use* is a mechanism for establishing where the greatest energy saving opportunities may exist. The relative energy use may be initially estimated with more precise measurements later, if justified.
4. *Process capacity* may be expressed in terms of normal and maximum throughputs. Knowledge of this may trigger questions about why maximum capacity is never achieved. This data can also be used to establish the cost per unit of production as a start toward establishing efficiency goals.
5. *Process condition/life* puts into perspective the worth of upgrading the process with automatic controls.
6. *Process quality* can be sufficient justification for adding automatic controls even if they won't save dollars. Without achieving this quality, the product may not be marketable or the working conditions of personnel being served by an HVAC System may not be acceptable.
7. *Number of disturbances* to a process is one of the fundamental requirements of understanding the operation.
8. The *elimination of disturbances* may be the most effective way of improving the process operation. Unacceptable operation may result from a single troublesome disturbance. This process influence could be lessened by different strategies including automating what is causing the disturbance. This eliminates the disturbance.
9. The process may be illogically organized and it should not be assumed that it cannot be altered. *Process modifications* may provide benefits without the use of automatic controls or they may permit automatic controls to realize their performance potential.
10. An assessment of control enhancement potential must begin with knowledge of the *existing loop instruments*.
11. *Instrument follow-up* is intended to draw attention to the possibility of using the existing loop instruments better. The control influence on the process may be enhanced by calibrating the individual instruments or "tuning" the control settings to optimize the loop operation.
12. *Loop optimization* is shown as a separate checking item to prevent an attitude of acceptance because a loop was operated in a certain way for several years. Consideration should be given to optimizing normal operation as well as developing efficient down-time strategies.
13. *Operator training* may be required to get the most out of the process including the automatic control systems.
14. *Assistance from others* may be the key to arriving at the best control solution. This can include other persons within the organization, other organizations operating similar systems and equipment suppliers. The actions of the competition may be crucial to survival.

The objective of all the foregoing activities is to identify actions which will improve the facility operation. The most common objectives are listed below.

- Better product.
- More product.
- Less energy use.
- Lower labor costs.
- Less raw material use.
- Extended equipment life.
- Adaptability to changing market needs.

Automatic Control

Checklist 16-1

Facility ______________ Date ______________
Location ______________ By ______________
Process ______________ Page ______ of ______

Check Off Legend

✓ — O.K.
? — Don't Know
X — Not Good
H — High
M — Medium
L — Low
Y — Yes
N — No
C — Calibrate
T — Tune

Process Loop Name	1. Process Performance (✓, ?, x)	2. Safety (✓, ?, x)	3. Energy Use (H, M, L)	4. Process Capacity	5. Process Condition/Life (✓, ?, x) / Years	6. Process Quality (✓, ?, x)	7. No. of Disturbances	8. Eliminate Disturbances (Y, N)	9. Modify Process (Y, N)	10. Existing Loop Instruments (✓, ?, x)	11. Instrument Follow-up (C, T)	12. Loop Optimization (Y, N)	13. Operator Training (✓, ?, x)	14. Assistance From Others	Comments (Actions, Costs, $ Savings Potential, Cross References)