DESIGN OF A CONTROL SYSTEM FOR A COGENERATION PLANT BOILER

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by
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İZMİR

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We certify that we have read this thesis and that in our opinion it is fully adequate, in scope and in quality, as a thesis for the degree of Master of Science.

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This thesis is prepared as a result of a long time studying and practicing period and many hours of field applications. Every problem faced is tried to be solved, and all knowledge is summarized in this work. My purpose is to let anyone read this thesis have a basic knowledge about cogeneration and waste heat boiler systems.

There are many people shared their knowledge with me. I want to thank my professor Mr. Yavuz SENOL. He let me able to finish this work, and I completed these two years of Master of Science Program in his leadership.

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Ahmet HARTOKA

ABSTRACT

The number of the cogeneration systems increases rapidly day by day, both in our country and in the rest of the world. Especially in our country, because of some unpredictable events in energy sector and the insufficiency of the electricity distribution network, cogeneration plants are helpful solutions.

In a cogeneration system, both steam and electricity can be produced. By using the turbine's flue gas, a boiler called "waste heat recovery boiler" can accomplish this job.

This thesis depends on a real time applied project which controls a waste heat recovery boiler, gives a brief summary of these systems' working principles and advises some solutions for a proper operation.

ÖZET

Gerek dünyada, gerekse ülkemizde kojenerasyon tesislerinin sayısı giderek yükselen bir hızla artmaktadır. Özellikle ülkemizde, enerji şebekesindeki kötü şartlar ve enerji sektörünün içerisinde bulunduğu belirsizlik sebebiyle, kojenerasyon sistemleri faydalı birer çözüm haline gelmektedir.

Bir kojenerasyon sisteminde hem elektrik, hem de buhar üretilebilir. Buhar üretimi, türbinin egzost gazını ısı kaynağı olarak kullanan ve bu yüzden atık ısı kazanları olarak adlandırılan kazanlar tarafından gerçekleştirilmektedir.

Bu çalışma gerçek hayatta çalışan bir atık ısı kazan kontrol sistemine dayanmakta, sistemin tüm bölümleri ile ilgili özet bilgi açıklamakta, ve düzenli bir çalışma için çeşitli öneriler sunmaktadır.

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CHAPTER ONE
INTRODUCTION TO COGENERATION CONCEPT

1. INTRODUCTION

The word cogeneration means producing heat and energy from a unique system at the same time [1]. This unique system, satisfies both the electric and heat requirements of the plant. Cogeneration may take place when both of these two kinds of energy is needed by the plant or producing electricity is economical.

In industry, cogeneration is applicable in systems where mass production is made and big amount of energy and vapor usage takes place. Usage of the cogeneration in the industry, leads to appear spread and small electric producing facilities and decreases the dependence to the main distribution system.

Although the countries in Europe has confidential energy distribution systems, cogeneration systems is being used successfully in every field for years. The usage ratio of cogeneration systems is increasing day by day. Only Zanting Co. has built 1400 cogeneration systems all over Europe, and this shows the priority of such systems in Europe energy sector. The facts that bring this success to cogeneration systems are those efficiency, and economical advantages.

In the generators that use liquid or gaseous fuel, approximately 35% of the burned fuel is converted to electrical energy. The rest 65% of energy is wasted as exhaust and motor heat. Thus, the system that recovers 85% of this 65% waste energy is called cogeneration. By using the waste heat recovery boiler system which is featured in this thesis, the waste energy is used to produce vapor, hot water and etc., for internal need of the plants.

The cost of producing electricity with the cogeneration systems, is approximately 50% cheaper than the traditional methods, so such systems can cover their costs in two or three years.

In cogeneration systems, energy is produced directly where it is used, so we can not talk about line losses. The efficiency in these systems is 85-90%, where this ratio is much lower in national energy plants; 45%.

In cogeneration systems, energy is produced directly where it is used, so we can not talk about line losses. The efficiency in these systems is 85-90%, where this ratio is much lower in national energy plants; 45%.

Cogeneration systems are suitable to operate with LPG, diesel, fuel oil and etc. So we can say these systems are also nature friendly.

1.1 SAVINGS WITH COGENERATION

One of the reasons which make these systems applicable and preferable is the fuel disposal. The waste heat produced can be used to meet local heat requirements. The usage of the waste heat has no effect on the amount of the used fuel, even though savings can be obtained.

In the traditional systems, the electrical energy requirement of the plant is afforded by the electricity purchased externally, and the process and heating requirements are afforded by burning the purchased fuel in burners. To conduct the heat energy to long distances is very hard, so heat energy production has to take place in the facility, in both cogeneration and traditional systems. In coal plants, where the electric energy is purchased, the waste heat is 47 to 60% of the heat obtained from the primary fuel. The plant has to exhaust this heat to operate correctly. In the cogeneration system, maximum recovery from this inconvertible energy can occur and heat for process can be obtained. The hot water or vapor can be used conducting the heat energy. This choice is up to user's need.

Also if the system uses little energy than it produces, the unused electrical energy can be sold and this is another income.

1.2 ELECTRICAL ENERGY PRODUCTION

This systems, which are also called "compound energy plants", can be classified into two sections, to the priority of the production:

1. First electricity, then heat producing (Topping Cycle) is seen more frequently. Firstly, the fuel is converted to electricity, and the rest is used to produce heat.
2. First heat, then electricity producing (Bottoming Cycle). The principle is just the opposite of the previous.

Some of the cogeneration systems include:

- Vapor turbine
- Diesel motors
- Open loop gas turbines
- Open-closed loop gas turbines

1.3 OPERATING PRINCIPLES

The cogeneration systems can be operated in two modes : Motor and turbine principle.

1.3.1 Motor Principle

While the generator ran by a motor produces electrical energy, the motor exhaust gas heat passes through heat converters, and heat energy is obtained in a combined form. The generator converts the mechanical power of the motor to electrical energy, the heat of the motor itself is converted to heat energy.

Motor principle depends on electrical energy more than the heat energy, because the ratio of the produced electrical energy to the heat energy is 1/1,5 (1000 kW electrical energy- 1500 kW heat energy).

Combining two or more cogeneration systems parallel, the general capacity and the reliability of the system can be increased. Because of the big motors do not produced commonly, the spare parts are expensive and hard to find. Therefore parallel working systems are preferred.

1.3.2 Turbine Principle

While the generator ran by a turbine produces electrical energy, the turbine exhaust gas heat passes through heat converters, and heat energy is obtained in a combined form.

Turbine principle depends on the heat energy more than the electrical energy, because the ratio of the produced electrical energy to the heat energy is 1/3 (1000 kW electrical energy- 3000 kW heat energy).

Since the turbine speed is too much (approx. 20000 rev/min), full capacity working and usage of all of the produced energy is needed, otherwise the system becomes irrational.

1.4 RUNNING PRINCIPLES

The electricity production can take place in a cogeneration system in two ways : isolated from the network and synchronized with the network.

1.4.1 Isolated From The Network

In this way of running, the electricity and heat energy produced by the system are completely used for internal requirements. The system is isolated from the distribution network.

1.4.2 Synchronized With The Network

In this way of running, the electricity and heat energy produced by the system again affords the system requirements, and the rest of the energy which is not used is sold to the national or main distributor.

The companies which are disturbed by voltage and frequency changes in the distribution systems, can not protect their computers and computer networks because of the delays up to 10-20 seconds of the generators , have to spend extra money to purchase UPS systems. It will be much better for such companies to pass to a cogeneration system.

1.5 THE WASTE HEAT BOILER IN A COGENERATION SYSTEM

Boilers today are used in power, petrochemical, iron and steel, food and beverage, pulp and paper industries. Steam turbines are used industrially both as a power source and in processing. Boilers are available in two basic designs; fire tube and water tube. Because of thermodynamic considerations, boilers should produce steam at high pressure and temperature to realize a maximum work efficiency.

Traditional steam boilers consist of a furnace where air and fuel are combined and burned to produce combustion gases and a water tube system the contents of which are heated by these gases. The tubes are connected to steam drum where the generated water vapor is withdrawn. If superheated steam is generated, the steam from the drum is passed through the super-heater tubes which are exposed to combustion gases.

A steam boiler outlet may be connected to a header in parallel with other boilers or directly to a single steam user. The boiler may be controlled by pressure or flow depending upon the process requirements. The load on a steam boiler refers to the amount of steam demanded by the steam users.

In this thesis, the control problem of the boilers so called “waste heat recovery boilers” because of the usage of the gas turbine’s hot exhaust gas as the heat source instead of fuel burning itself, is the subject. When the gas turbine burns its fuel to produce electricity, it also produces exhaust gas, approximately at 500 °C. This is a waste gas, but it can be used and recovered. By mounting a boiler after gas turbine’s exhaust, the boiler can use this waste exhaust gas as heat source, produce steam and hot water, and can meet such requirements of the system.

To achieve this job, the boiler and the gas turbine must work sequentially. The boiler need not to work for the gas turbine to work, without steam producing the gas turbine can be able to produce electricity. But it is a reqirement for the gas turbine to work in order to produce steam.

To make this sequential work certain, some interface signals must be provided between the gas turbine control system and the boiler control system. These interface signals and their meanings are defined properly in the following chapters.

According to these signals, the boiler produces steam. There are two more critical controls in boiler dynamics in this system. These are drum level and pressure. Generally drum type boilers are used in cogeneration systems. For these controls, separate controllers are used. These controllers are of Honeywell UDC 3000 series [2].

Some safety interlocks are realized with a PLC. Also PLC is the part in which interface signals from the turbine are evaluated and interface signals to the turbine are produced. Also, some critical temperature values like boiler gas inlet and boiler gas outlet are evaluated in the PLC. PLC is Telemecanique TSX Micro 37 Series with a number of digital and analog input/outputs [3], determined by the system requirements. The PLC functions and explanation are given in detail in the following chapters.

At the end of the project, some alternatives are discussed, in order to provide more efficient working. The goal is to provide more heat and steam with the least number of boiler trips, and the ratio of gas inlet to gas outlet temperatures must be as large as possible. This shows us the maximum of the waste exhaust gas is used.

CHAPTER TWO

THE FUNDAMENTALS OF A PROCESS AUTOMATION SYSTEM

2. INTRODUCTION

Process control is the regulation of an industrial process. In the early days of industrial history, process control was quite simple. Typically, a worker observed a process and turned a valve or made other adjustments by hand to keep everything running properly [4].

Automatic devices have simplified the job of human workers in controlling industrial processes. Today many sophisticated devices are used for process control.

In this chapter, these subjects about process control are covered :

- Basic concepts
- Basic control modes
- Techniques for feedback control
- Combining feedback control loops

2.1 SYMBOLS AND DIAGRAMS

Symbols and diagrams are used in process control to illustrate the application of hardware, type of signals employed, sequence of interconnected components and, to some degree, the hardware specified.

The Instrument Society of America (ISA) publishes standards for symbols, terms and diagrams that are generally recognized throughout industry [5].

2.1.1 Instrument Identification

Each instrument or function to be identified is designated by an alphanumeric code or tag number as shown if Figure 2.1. The loop identification part of the tag number generally is common to all instruments or functions of the loop. A suffix or prefix may be added to complete the identification. Typical identification is shown in Figure 2.1.

TYPICAL TAG NUMBER

TIC 103	Instrument Identification or Tag Number
T 103	Loop Identification
103	Loop Number
TIC	Functional Identification
T	First Letter
IC	Succeeding Letters

EXPANDED TAG NUMBER

10 PAH 5A	Tag Number
10	Optional Prefix
A	Optional Suffix

Figure 2.1. Tag Numbers

Tag numbers identify both the process function or variable and the loop in which it is located. Figure 2.2 indicates how letters and numbers are selected and grouped in order to achieve positive identification. The function or process variable can be readily associated with the measurement made by the hardware. Thus, the FRC shown in Figure 2.2 identifies a flow recorder controller. The complete alphabet is used to make up these names.

First Letter	Succeeding Letters	Loop Number	Suffix
F	RC	102	A
Functional Identification		Loop Identification	

Figure 2.2. Letters and numbers are used for tag numbers

In drawings, tag numbers are placed in circles called balloons. Figure 2.3 shows the various standard balloon arrangements. Note that the functional identification is always in the upper half of the balloon while the loop is in the lower half. A solid line drawn across the center indicates a board-mounted instrument. A balloon with no centerline identifies a local or field mount. A behind the board mount is shown by a dashed line. When two balloons are drawn with their edges touching multiple functions are indicated.

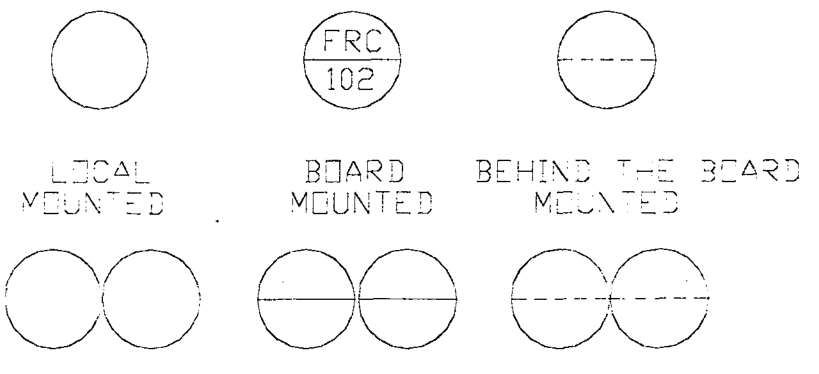


Figure 2.3 Standard balloon symbols

Process control signals used in modern instrumentation are usually of the following types: pneumatic, electronic (electric), capillary, hydraulic, sonic, or indicating radioactivity. Each signal has a different symbol, and all the symbols are given in Figure 2.4.

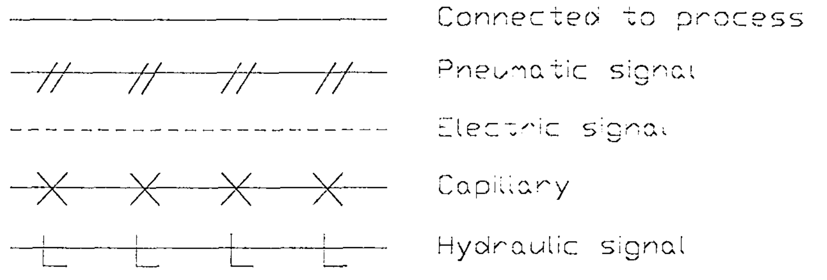


Figure 2.4 Instrument connecting lines

2.1.2 Symbol Recognition

If the meanings of loop connections are wanted to be determined, primary and final devices are to be recognized. Primary devices for flow, level, pressure and temperature are shown in Figures 2.5 through 2.8. Figure 2.9 is devoted to final devices. Other final and primary devices exist in addition to those shown.

2.1.2.1 Flow

Much time and effort has gone into designing standard symbols that resemble the actual operating mechanism. Thus, FE 4 in Figure 2.5 looks like a pitot tube.

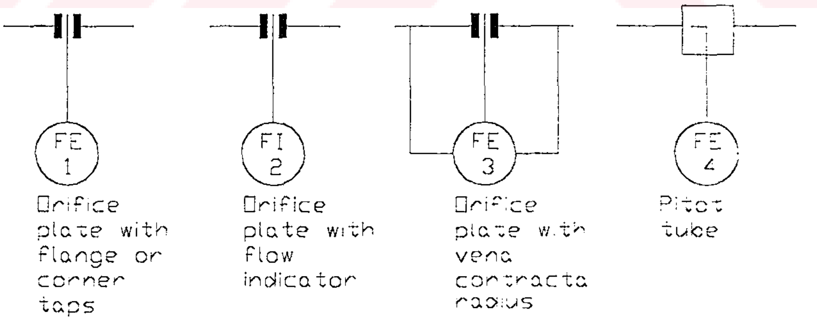


Figure 2.5 Primary elements for flow control

2.1.2.2 Level

Figure 2.6 shows that level symbols and actual installations have much in common. Note that the difference between LT 18 and LT 19. LT 18 has differential taps applied to a closed or pressurized vessel, and LT 19 is piped to an open or atmospheric tank; in addition, the low-pressure side is vented to the atmosphere.

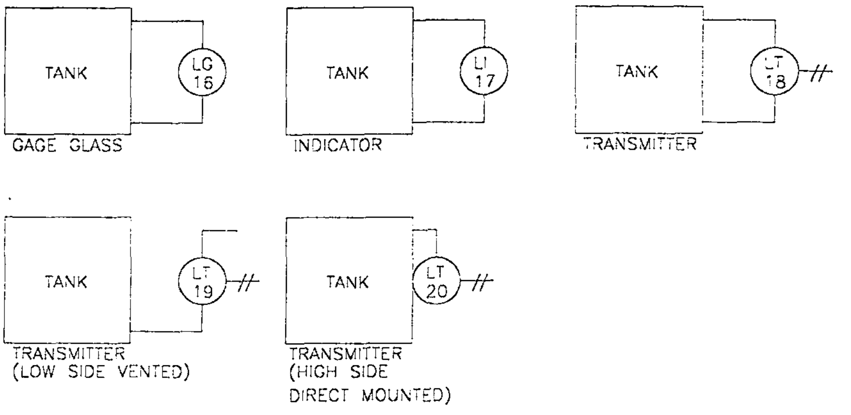


Figure 2.6 Primary elements for level control

2.1.2.3 Pressure

Figure 2.7 shows some applications of pressure measurement common in process instrumentation. A filled capillary system is not required in PI 29, since the gage could not be mounted directly on the chemical seal. In PT 28, the direction of flow is shown where the pressure measurement is taken. In this system, downstream pressure is measured. If the process requirements called for an upstream measurement, the flow arrow would be reversed, or the PT would be placed on the opposite leg of the FT.

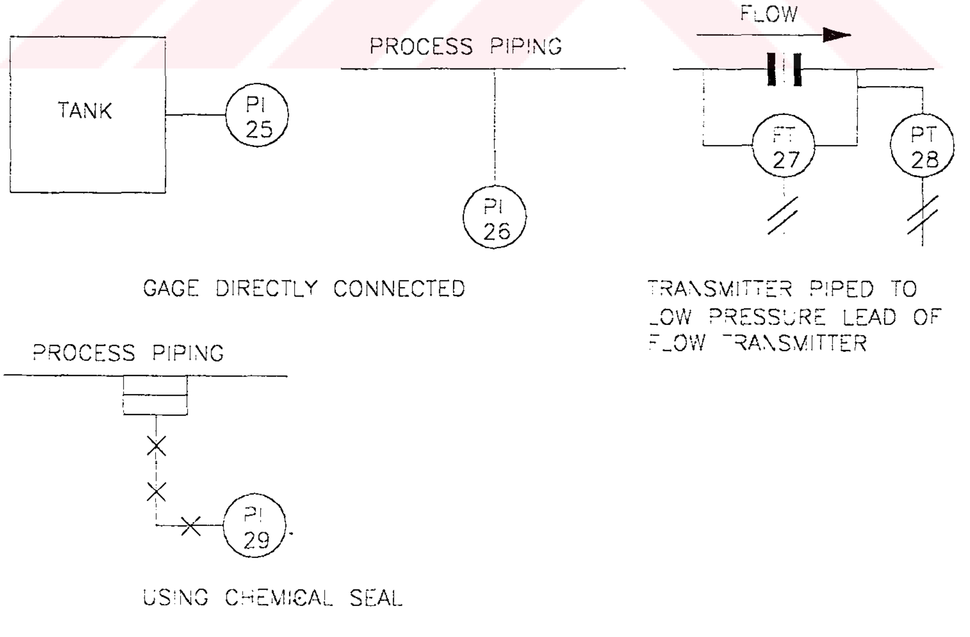


Figure 2.7 Primary elements for pressure control

2.1.2.4 Temperature

In Figure 2.8, test wells are included with the primary elements. For example, primary element TR 31 indicates a temperature recorder that is directly connected to a process pipe by a filled thermal system. A test well is usually installed within 250 to 475 mm of the thermal element. To test installed hardware for accuracy without removing and replacing the primary element, insert a glass stem thermometer, test thermocouple, or resistance bulb into the test well. This procedure is more accurate than one where the primary element is replaced during testing. In the later case, the test well temperature could change during the time required, to remove, test, and replace the primary element and the reading would be inaccurate.

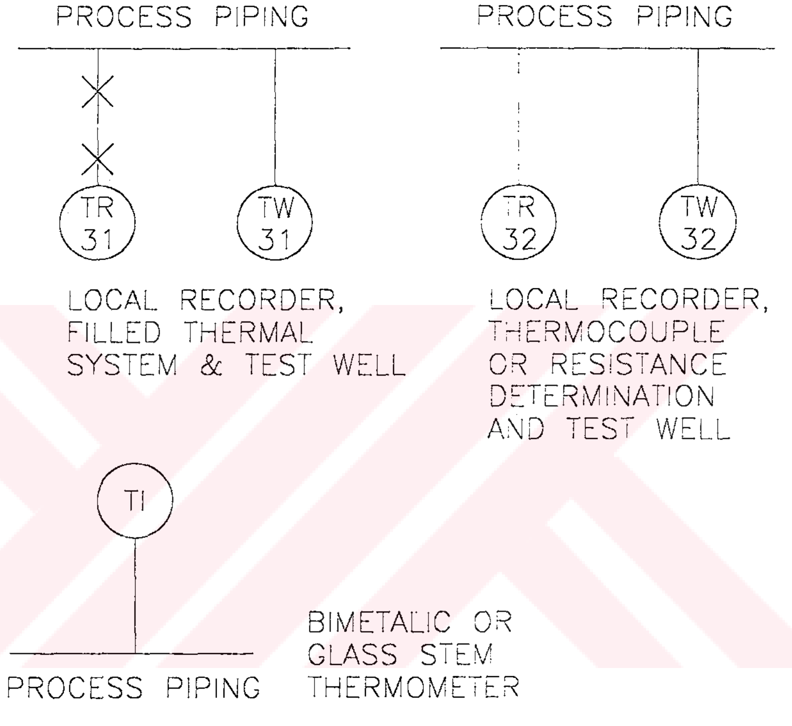


Figure 2.8 Primary elements for temperature control

2.1.2.5 Final Control Elements

Valves, the final devices in the control loop, are shown in Figure 2.9. While valves are the most common final elements, other types are also used. These include damper drives, speed controls, or positioning hardware. Notice that any of the listed actuators can be used with any of the valve bodies shown.

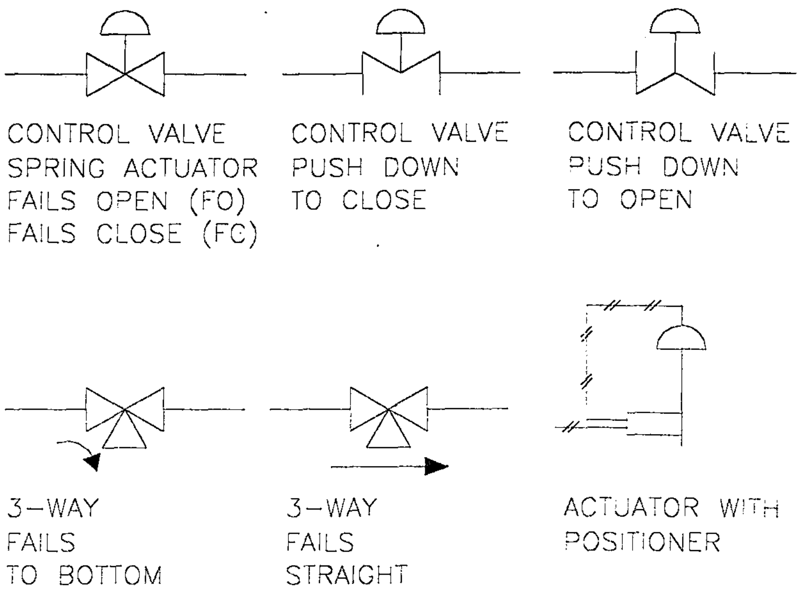


Figure 2.9. Final control elements

2.1.3 Piping and Instrument Drawing

The piping and instrument drawing (P&ID) is the start of any process design. Basically it is a long drawing. It may measure up to 12.2 m in length since the process vessels, pumps and other components are shown in continuous presentation. Single lines in the P&ID represent all the major piping required to operate the process. Thus, the P&ID is a "road map " of the routes taken by the various process fluids. Pumps and pipes are then sized and data is added to the P&ID. A completely accurate P&ID simplifies your decisions on how to control or instrument the process. Not all the instruments shown on a P&ID serve a control function. Pressure gages, temperature indicators or recorders, for example, are simply indicators. All appear on the P&ID in their proper location. The instruments included in a P&ID are those basic to the process and reflect the designer's knowledge of the process operation. They are shown in greater detail in other types of drawings.

The P&ID often is the only document that shows the entire process. It provides a complete guide to both the process operations and the instruments involved. It also permits the instrument mechanic or technician to visualize entire control systems at once, as well as trace the individual circuits. Thus, despite its ungainly size, the P&ID is a valuable tool [4].

2.2 BASIC CONCEPTS, TERMINOLOGY AND TECHNIQUES FOR PROCESS CONTROL

Any study of process control must begin by investigating the concept of a "process". From a production viewpoint, it is generally thought of as a place where materials and energy come together to produce a desired product. From a control viewpoint, the meaning is more specific. A process is identified as having one or more variables associated with it that are important enough for their values to be known and for them to be controlled [4], [6].

The simplest and frequently met process type is that having only one controlled variable, such as the heat exchange process shown in Figure 2.10.a. To maintain the temperature of the product (hot water) in this process , another variable influencing the variable being controlled must be available for manipulation by the control system.

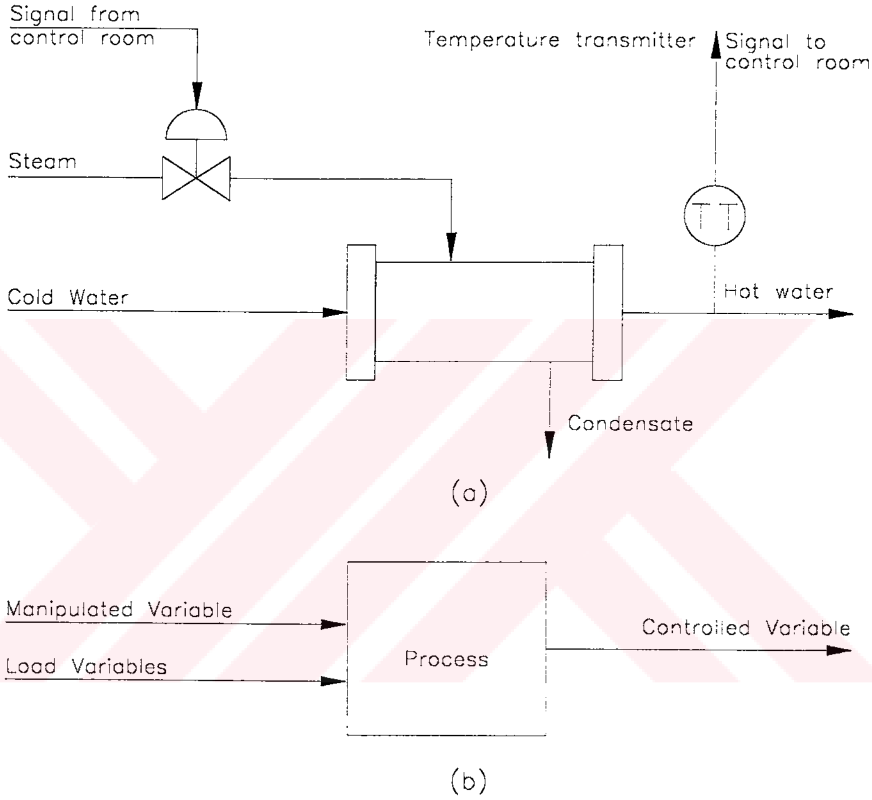


Figure 2.10 Heat exchanger represents a simple process a. Process b. Variables

In this example, the control system manipulates the position of a steam valve. However, the temperature of the water depends not only on the position of this valve but also on the flow rate of the water, its inlet temperature, the enthalpy of the steam, the degree of fouling in the exchanger, and the ambient temperature.

This simple example illustrates controlled, manipulated and load variables- the three categories associated with every process under control (Figure 2.10.b). The parameters that indicate product quality or the operating condition of the process are called controlled variables, such as pressure, level, temperature, pH, specific gravity or density, composition, moisture content, weight and speed , and other variables, depending on the process.

Manipulated variables include valve position, motor speed and blade pitch. Further, one control loop is often manipulated for controlling another variable in more variable is manipulated to control a temperature or level.

All variables affecting a controlled variable, other than the one being manipulated, are defined as loads. Both loads are manipulated variable may influence a controlled variable from either the supply side or demand side of the process. For example, the outlet temperature of a heat exchanger can be controlled by manipulating a steam valve, while tank level can be controlled by manipulating a valve on the outflow from the tank. Often, a controlled variable in one process is a load variable for another.

2.2.1 The Control Problem

The relationship among controlled, manipulated and load variables qualifies the need for process control. The manipulated variable and various load variables may either increase or decrease the controlled variable, depending on the design of the process. Changes in the controlled variable reflect the balance between the loads and the manipulated variable [7].

For the heat exchanger, increases in steam-valve opening, steam enthalpy, inlet temperature and ambient temperature tend to raise the product temperature, while it is lowered by increases in flow rate and exchanger fouling. The temperature responds to the net effect of these influences. If the positive influences are greater than the negative, the temperature will rise. If the reverse is true, the temperature will fall. If all the load variables were to remain constant, the steam valve couldn't be adjusted until the product temperature was constant at the desired value, and would remain there indefinitely.

Process control equipment is needed because these variables do not remain constant. For example, variations in inlet temperature and flow rate both upset product temperature, and require a different steam-valve position in order for water temperature to be maintained at the desired value. The job of the control system is to determine and continuously update this valve position as load conditions change.

Generally, the control problem is to determine the one value of the manipulated variable that establishes a balance among all the influences on the controlled variable and keep the variable steady at the desired value. Other factors as speed of response, shape of the response, and operator interface are also important in designing control systems.

No matter how complicated, every control system solves this same basic problem, and for a given process and load conditions must arrive at the same result.

The control problem can be solved in only two ways: feedback feed forward systems, each of which corresponds to a basic control system design philosophy.

Feedback systems generate the control signal based on the difference between the actual and reference measurement values. For feed forward systems, the control signal is generated from values based on the various load variables as they affect the process.

2.2.2 Feedback Systems

Feedback systems are more common than feed forward ones. The structure of a feedback loop is shown in Figure 2.11 [8]. Here, the value of the controlled variable responds to the net effect of the loads and the manipulated variable. A sensor/transmitter measures the current value of the controlled variable and sends a signal to the feedback controller, where the signal is compared to a reference value. The control function within the controller generates a signal, which positions a valve on the basis of the sign and magnitude of the difference between the measurement and reference or set point values.

In the example for the heat exchanger, a temperature transmitter continuously generates a signal that represents the actual temperature of the hot water. At the controller, this signal is subtracted from an operator set value that represents the desired temperature. If these values are the same, the current position of the steam valve is correct, and the controller will not change its output. However, if the actual value is below the reference value, the controller will change its output in the direction that opens the steam valve and raises the actual temperature. Conversely, if the actual temperature is above the desired one, the controller will change its output in the direction that closes the steam valve, to lower the actual temperature.

Thus, a feedback controller solves the control problem through a trial-and-error procedure. Assume that a change in the load variable upsets the temperature and a new valve position is required. The controller becomes aware of the upset when the imbalance between the loads and manipulated variable begins to change the controlled variable. The controller immediately begins to make corrective changes in its outputs- even as it monitors the effect of these changes on the controlled variable. When the controller sees that its corrections have returned the controlled variable to the desired value, it holds the output steady and continues to observe the controlled variable, and waits for the next upset.

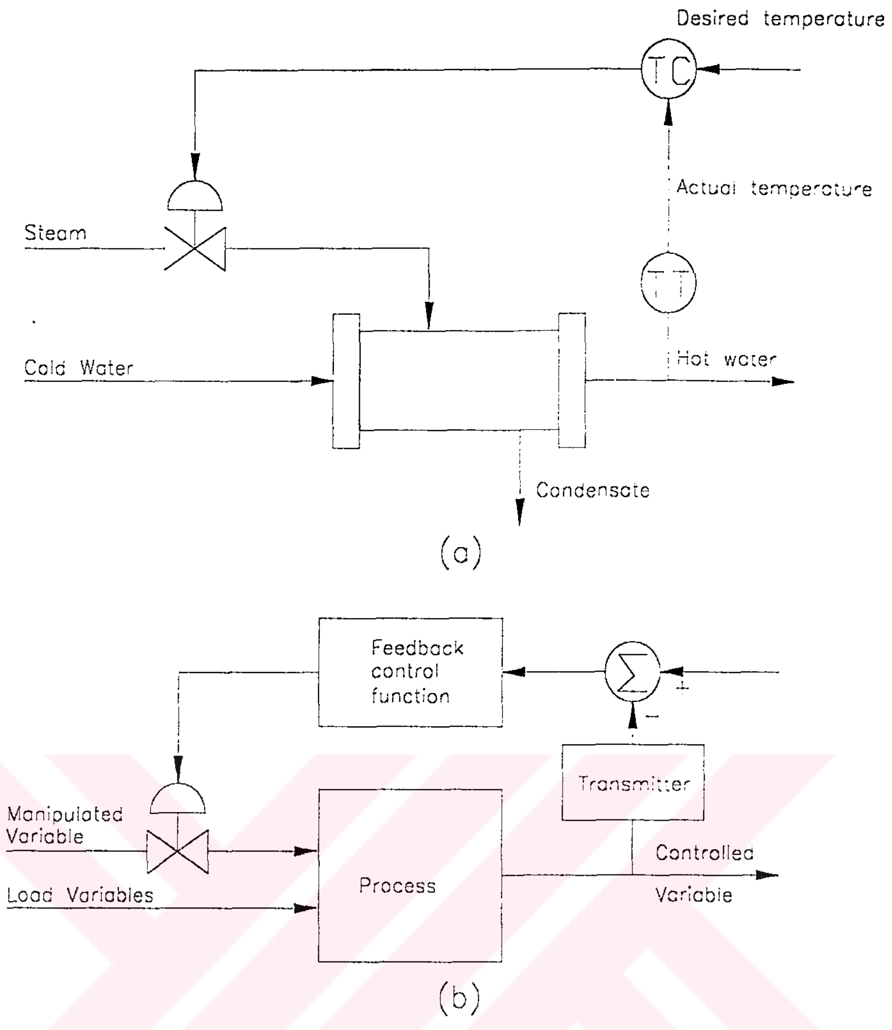


Figure 2.11 Feedback control uses measurement of controlled variable
a. Process and variables
b. Feedback loop

2.2.3 Feed Forward Systems

While feedback control is reactive in nature and responds to the effects of an upset, feed forward schemes respond directly to upsets and, thus, offer improve control.

The block diagram of a feed forward control scheme is shown in Figure 2.12. Transmitters measure the values of the load variables, and a calculation unit computes the correct control signal for the existing load conditions and reference value. In this way, changes in load conditions cause a direct change in the control signal without waiting for the controlled variable to be upset.

In general, this technique is more complicated and more expensive. It requires greater process understanding than trial-and-error feedback. Therefore, feed forward control is usually reserved for default and critical applications.

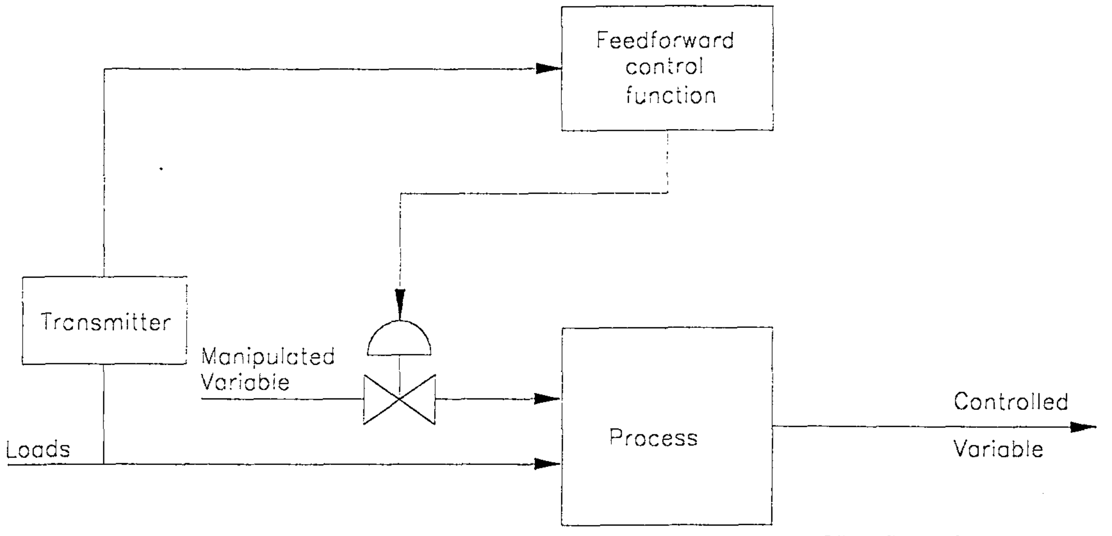


Figure 2.12 Feed forward control uses measurement of load variables

2.2.4 Inside a Feedback Controller

Regardless of the hardware used for implementation, the concept of feedback control remains the same. The first feedback mechanisms were mechanically connected directly to the process and the manipulated variable. When pneumatic and electronic transmission made central control rooms possible, pneumatic and electronic controllers were developed.

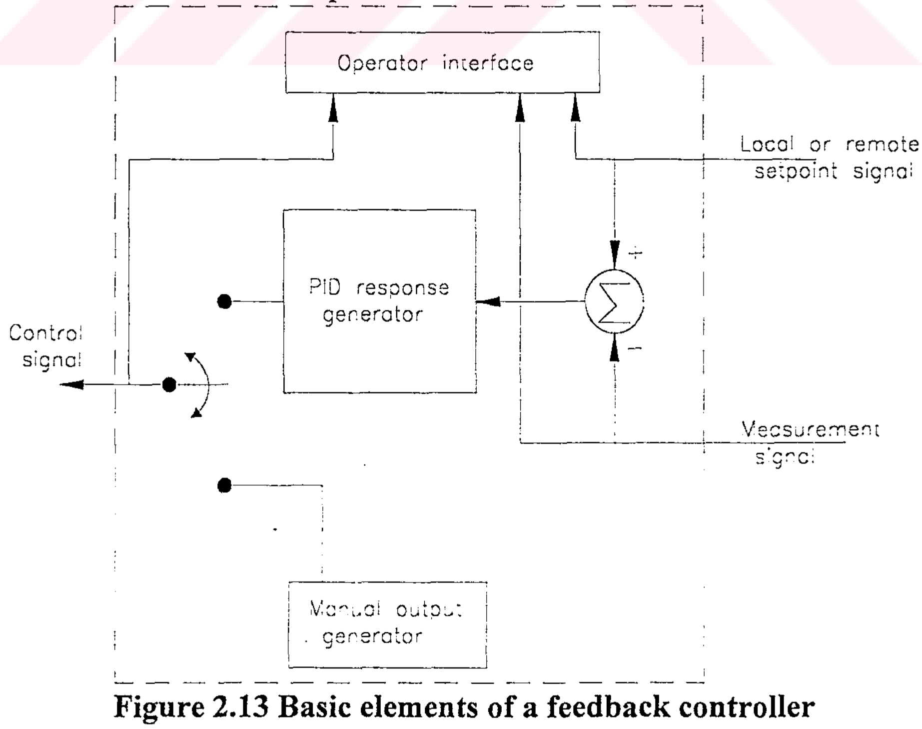


Figure 2.13 Basic elements of a feedback controller

All feedback controllers must have certain common elements (Figure 2.13). The feedback control function always has two inputs and one output. One input will be the measurement signal from the transmitter; the other, the reference value. For feedback controllers, the reference signal is called the set point, which usually represents the desired value of the measurement.

For simple loops, the reference signal may be directly entered by the operator and is called a "local " set point. In complicated schemes, this signal can come from another instrument and is defined as a "remote" set point. Often, the controller can accept both types of set points, and a remote/local switch is available for the operator to select which one the controller will use.

Within the controller, measurement and set point values are compared by subtraction. The difference is called the error, and input to the mechanism, circuit or algorithm that generates the output. Generally, this response contains proportional, integral and derivative (PID) components, although they may not all be present in every controller. Proportional or integral responds to error, while derivative usually responds directly to the measurement. The sum of individual responses forms the automatic control signal.

2.2.5 Startup and Emergencies

For startup and emergency conditions, the controller will also include a manual control signal generator that can be driven by the operator. When the output comes from the PID response generator, the controller is said to be in "automatic". When the output comes from the manual generator, the controller is said to be in "manual".

In simple loops, this signal will directly position a valve, while in more complicated schemes, the signal will be an input to another instrument. Typically the controller will have an associated operator interface. As a minimum, this interface will display the set points, measurement, current output, and the remote/local and automatic/manual status.

Just as all feedback controllers have certain elements in common, so do all feedback control loops share three important concepts: open vs. closed loop, positive vs. negative feedback and oscillation.

2.2.5.1 Open vs. Closed Loop

Figure 2.11 also illustrates the first of these concepts. Once a feedback controller is installed on a process and placed in automatic, a closed loop is created. The controller output affects the measurement, and vice versa. This closed loop creates the possibility of control through feedback.

Should this effect be broken in either direction, the loop is said to be open, and feedback control no longer exists. Several events can open a feedback loop :

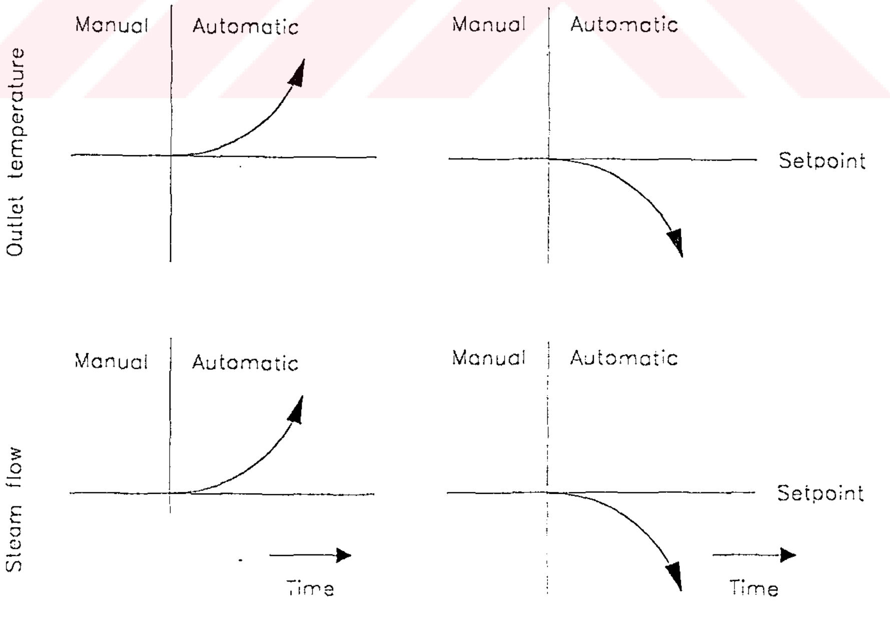
- Placing the controller in manual. This causes the output to remain constant unless changed by the operator even if the measurement changes.
- Failure of the sensor or transmitter. This ends the ability of the controller to observe the controlled variable.
- Saturation of the controller output at 0 or 100% of scale. This ends the ability of controller to influence the process.

When a control loop does not seem to be operating properly, the fist thing to check is whether or not the loop is closed.

2.2.5.2 Positive vs. Negative Feedback

Connecting a controller to a process, as shown in Figure 2.11, creates a closed feedback loop. However, feedback can be either positive or negative, and the difference is crucial to the loop's performance.

Every feedback controller will have a means of changing the controller action, which defines the direction of the controller response to change in the measurement. Increase-increase (or direct) action causes the controller to increase its output in response to an increasing measurement. Increase-decrease (or reverse) action causes the controller to decrease its output when the measurement increases. Choosing the wrong action will make control impossible.



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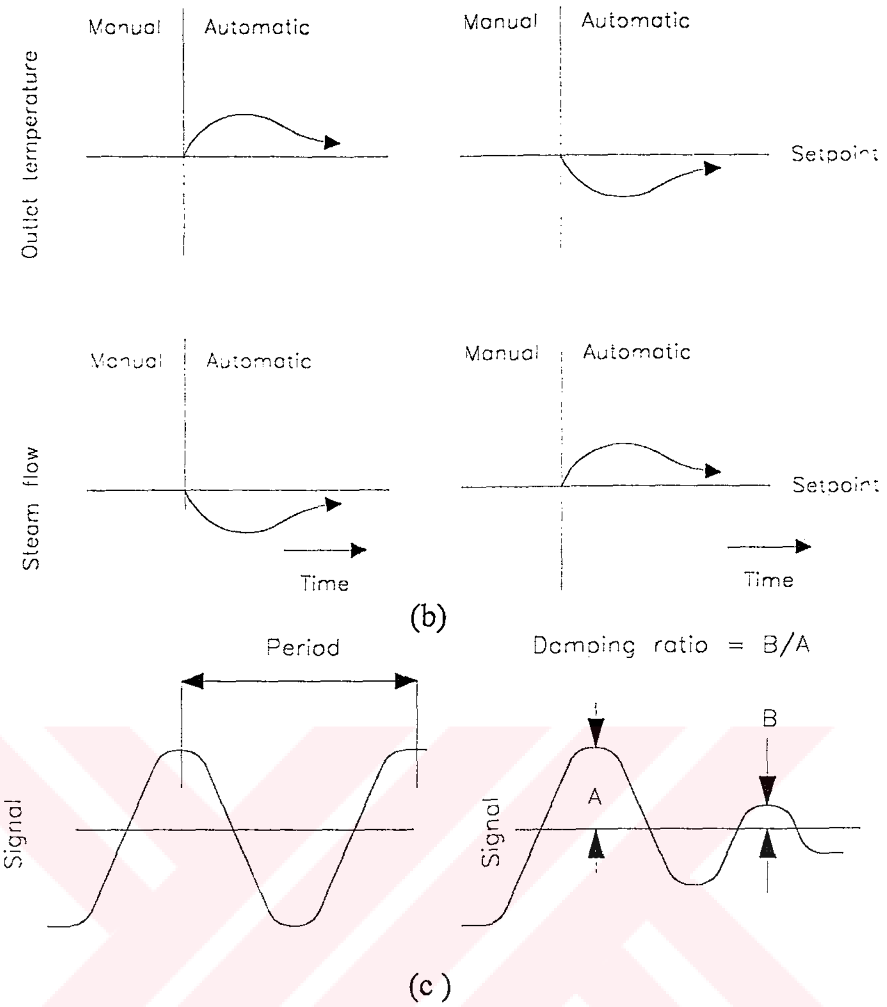


Figure 2.14 Control actions affect performance of a closed feedback loop
a. Positive feedback causes instability
b. Negative feedback causes stability
c. Oscillating signals

Figure 2.14.a. shows a possible record of an output temperature control loop installed on the heat exchanger of Figure 2.11. The steam valve is set air-to-open (i.e. fail closed). This means that an increasing signal will open the valve to increase steam flow. The controller action is set to increase-increase, which is incorrect.

The measurement may be brought to the set point under manual control, but as soon as the controller is placed in automatic, the loop becomes unstable. Any small disturbance that increases the temperature will also cause an increase in the controller output. This opens the valve, causing the temperature to increase further and the valve to continue opening. The result is a runaway temperature. If a small disturbance caused the temperature to drop, the controller would close the valve, and the temperature would fall even more. In turn, this would cause the valve to close even more.

In both cases, the response of the controller has reinforced the change in measurement. This is negative feedback.

For a feedback loop to be successful, it must have negative feedback. The controller must change its output in the direction that opposes the changes in measurement. Fig 2.14b shows the same loop, except the controller has been set to increase-decrease action. The controller then responds to increases in temperature by closing the valve. A decrease in the temperature causes the controller to open the valve. These responses tend to drive the measurement back toward the set point. Selecting the proper control action is as fundamental as making sure the loop is truly closed.

The correct choice for feedback will depend on the application. For example, if tank level is controlled by manipulating an air-to-open valve on the outflow, increase-increase action will be needed. Moving the same control valve to the inflow requires increase-decrease action. Reversing the action of the valve to air-to-close (i.e. fail open) can reverse the required control action.

2.2.5.3 Oscillation

While negative feedback is necessary for control, it also leads to oscillation within the loop. At the temperature control loop in Figure 2.11, when the measurement begins to move away from the set point, the controller begins to change its output. Because of the lags within the process, the outlet temperature does not respond immediately. In fact, it continues to move away from the set point. The controller then continues to change its output until the measurement turns around and begins to return to the set point.

When the measurement reverses itself, so will the controller output, but the effect of this reversal will also be delayed. Later, the measurement may reverse a second time and cause another reversal in the controller output. In turn, this causes another reversal in the measurement and so on. The result is oscillation in both the measurement and the controller output.

Thus, the combination of the negative feedback and lags in the process means that the oscillation is natural response of feedback control loop to an upset. The characteristics of this oscillation are the primary means for evaluating the performance of the control loop. Specifically, an instrument engineer will be interested in the period and the damping ratio of the cycle.

Fig 2.14.c shows a typical oscillation. The period of this cycle may be measured as the time (usually in minutes) between two analogous points, such as between two positive or negative peaks. Figure 2.14.c also shows another oscillation that is steadily decaying a constant signal. The damping ratio measures the rate of decay.

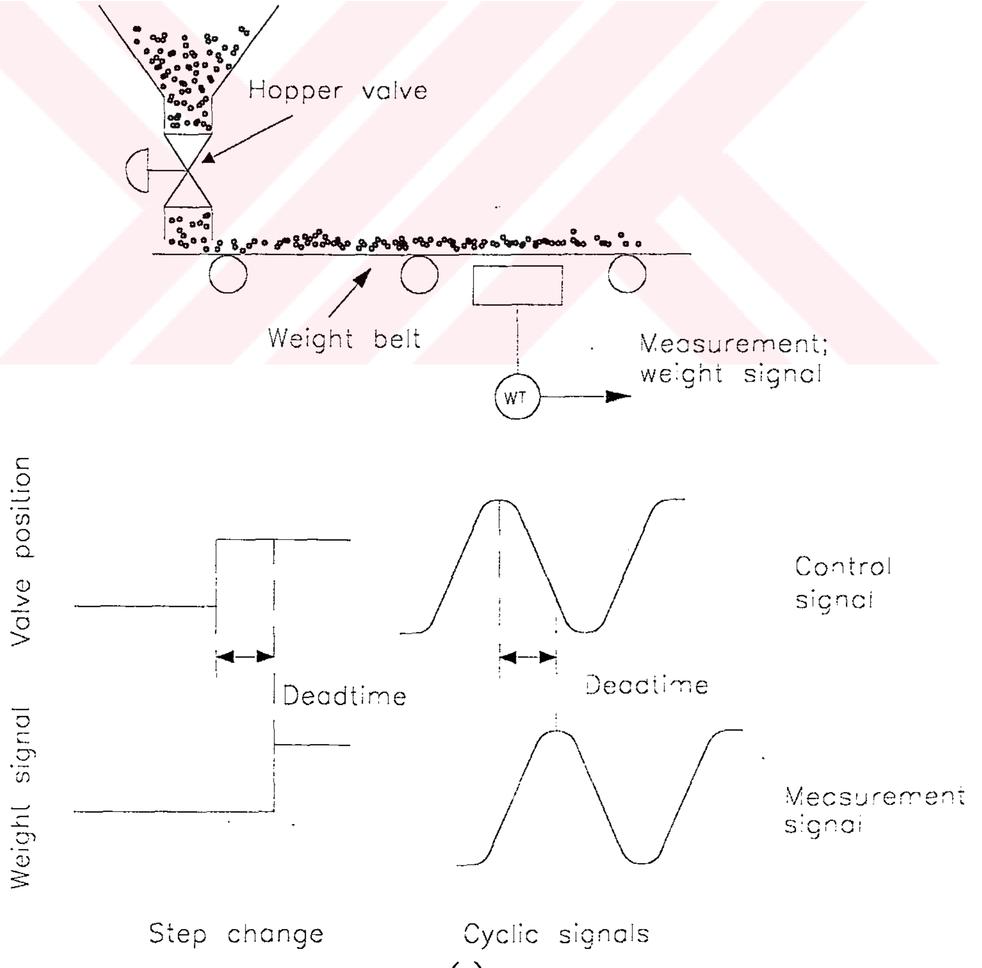
The exact characteristics of the oscillation in a particular loop will mainly depend on the adjustments to the proportional, integral and derivative responses within the controller. Incorrect adjustments can make this period too long or too short. Even worse, they can make the cycle grow larger instead of smaller.

2.2.6 Process Characteristics

The existence of lags in the process has fundamental effect on the performance of the feedback loop. Without understanding the causes and characteristics of these lags, it is impossible to evaluate which control modes will be required, or whether feedback control will be successful in any particular application. Basically, lags may be considered in two categories ; dead time and capacity.

2.2.6.1 Dead Time

A process with pure dead time response is shown in Figure 2.15a. A hopper valve deposits material on a moving belt. A weight transmitter measures the amount of the material.



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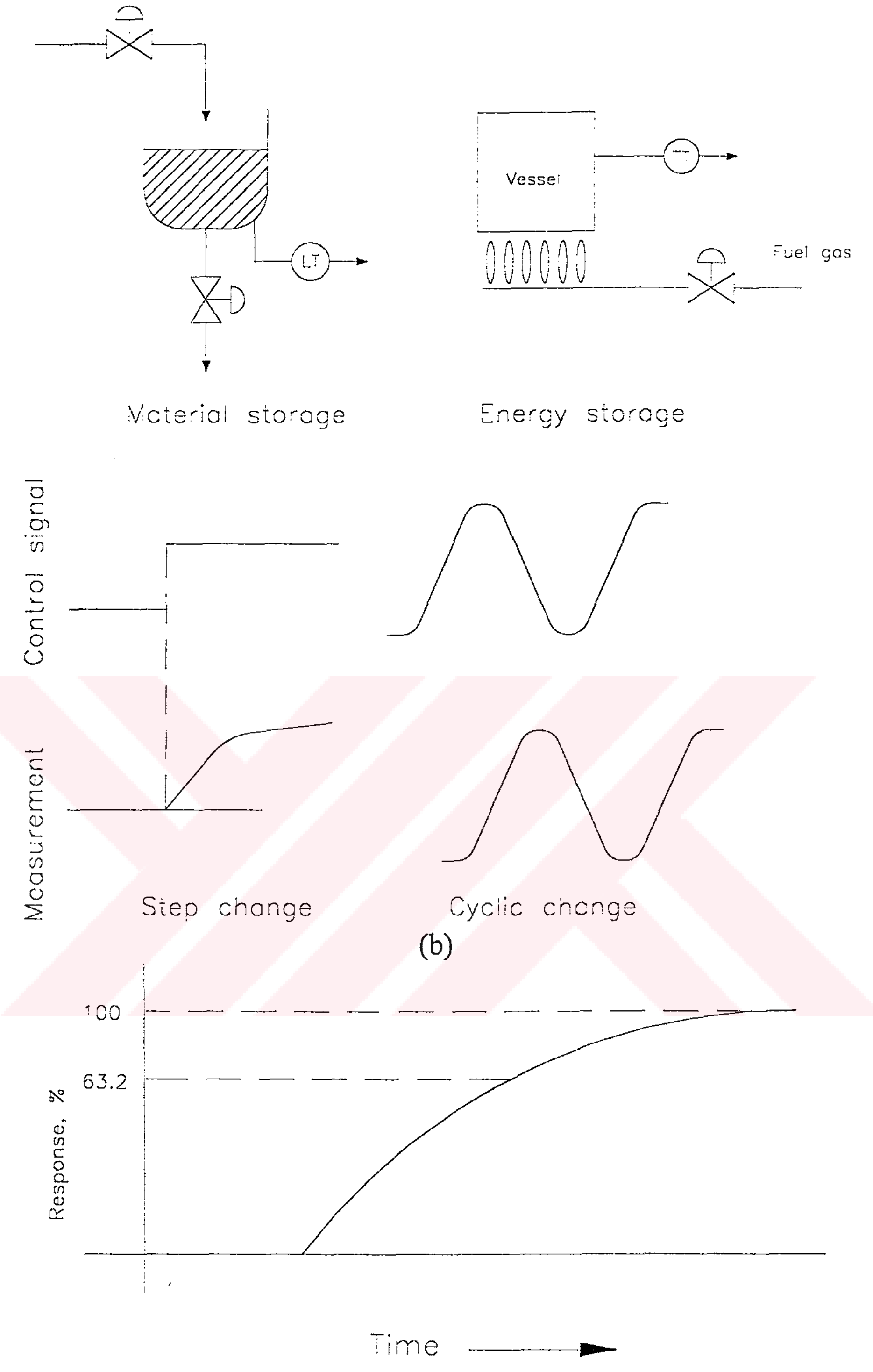


(c)

Figure 2.15 Process characteristics affect type of control mode and feedback
a. Dead time delays
b. Storage capacities
c. Time constant

As shown in Figure 2.15a, a step change in control signal will immediately begin to deposit more material on the belt. This step change will appear in the measurement after a delay (dead time) that corresponds to the time necessary for the material to travel from the hopper to the sensor.

In general, dead time is defined as the time delay between a change in the control signal and the beginning of its effect on the measurement. The shape of the change in the control signal is not relevant. Figure 2.15a also shows an oscillating control signal delayed by the same time interval.

Because dead time is often caused by the time required to move the material from one point to another, it may be referred to as transport lag or distance/velocity lag. The actual size depends on the distance traveled and the velocity of the material.

Delay in the process response can be created in other ways. The performance of the mixers has a large influence on the dead time in loops monitoring composition, such as pH, density, or oxidation-reduction potential. The sampling operation of a chromatic analyzer will also create delay in the perceived measurement. And, significantly, a combination of a number of capacity-lag elements will also create dead time.

From a control point of view, what is important is the length of the delay. Dead time represents an interval during which the controller has no information about the effect of a control action already taken.

Dead time does not slow down the rate at which the measurement can change. Except for the delay, the measurement changes at the same rate as does the control signal. Still, the longer the delay, the more difficult it will be to control. As will be shown, the amount of dead time in the process has a strong effect on the controller adjustments and on performance that can be expected from the loop.

Because dead time interferes with good control, attempts should be made to reduce this delay by properly locating transmitters, specifying sufficient mixing, designing proper tankage, and minimizing transmission lags.

2.2.6.2 Capacity and Its Effects

Pure dead time processes are rare, and virtually every control loop will include, and will be dominated by capacity elements.

A capacity element is that part of the process system where material or energy will accumulate. The tank shown in Figure 2.15b represents a single capacity (material storage). Flow into the tank is manipulated to affect the level; flow out of the tank is the load variable. Initially, the level remains constant because inflow and outflow are equal.

Let us assume that the valve and flow respond instantly to changes in control signal. When a step change occurs in the control signal, the difference between inflow and outflow will immediately cause an increase in the level. However, as level increases, the gradually increasing pressure across the drain valve raises the outflow. This tends to bring the two flows back into the balance, with the net result that level rises more rapidly at first, then more slowly, and finally stops as the flows become equal.

The other vessel shown in Figure 2.15b also represents a single capacity (energy storage). Temperature responds to the accumulation of energy in a process just as level responds to the accumulation of the material. The response of the temperature to a step change in heat input will be the same as the response of the level to a step change in flow input.

The responses of these capacity elements differ from that of the dead time element in two significant ways :

1. No delay occurs before the measurement begins to change (i.e. no dead time is associated with a single capacity element).
2. The capacity inhibits the rate at which the measurement can change.

Because level is a measure of the liquid stored in the tank, and because the rate of accumulation (positive or negative) responds to the difference between inflow and outflow, level can not change instantly even if the control signal does. The bigger the tank in comparison with the flows, the slower the level will change. Therefore, the capacity element in the process tends to attenuate disturbances. This makes control easier, whereas dead time makes control more difficult.

The size of a capacity is measured by its time constant. Figure 2.15c shows, in more detail, the level response of Figure 2.15b. Since the two flows (in and out) approach equality asymptotically, they never quite become equal-at least in theory. The level never stops changing, and therefore, the response can not be measured by the time to completion.

Instead, the response is quantified by a time constant that is defined as the time required to complete 63.2% of the total response. (This number is not arbitrary. It has significance in terms of the differential equations that model the process) As a first approximation, the time constant of a capacity element will be roughly equal to its residence time, which is defined as the volume divided by the throughput (in consistent units).

Figure 2.15b also shows the response of a capacity element to a cycling control signal. If the signal cycles the inflow, the outflow will approach the average value of the inflow. The level will rise while the inflow is greater than the outflow; and it will fall while the inflow is less than the outflow. In short, for a cycling input, the measurement signal from a capacity element will also cycle at the same period.

The variation in the measurement signal, in comparison with the variation in the control signal, depends strongly on the period. If the control signal cycles very rapidly (with a short period), the swing in the level will be very small. Conversely, if the same variation in the control signal occurs at a much longer period, the swing in the level will be much greater.

The purpose of every control loop is to find the one value for the control signal that holds the measurement at the set point for the existing load conditions. A feedback or feed forward approach may be used.

2.3 FEEDBACK CONTROL MODES

Understanding the individual modes in a controller is essential to successfully apply feedback control. These modes involve : on-off, proportional only, integral and derivative actions. Each possible combination represents a tradeoff between cost and performance.

A feedback controller must be connected in a closed loop, and appropriate control action selected, to establish negative feedback. Given these essentials, the controller can solve the control problem by a trial and error search for the output that establishes a balance among all the influences on the controlled variable.

Selecting the proper control action establishes negative feedback by defining the direction of the controller response. The next objective is to determine the magnitude of this response.

2.3.1 Control Modes

A controller in a feedback loop is in a difficult position. Unpredictable forces can influence the measurement it is trying to control. Even worse, the dynamic characteristics of the rest of the loop will delay and distort the output variations used by the controller to reduce error.

In this environment, it is misleading to believe that control is imposed on the process. Instead, the relationship between the controller and the process is interactive. Here, the size, shape and rate of the variations in the controller's output are crucial as the controller restores the measurement to the set point value following an upset.

A control mode is a particular controller response to a change in the measurement or error. The four basic responses are :

- On-off (two position)
- Proportional
- Integral
- Derivative

Variations on these basic responses exist among manufacturers of control instrumentation. Sometimes, these responses are identified by different names, or are quantified in different units. The derivative response may be generated in several ways; and varying degrees of interaction are possible among the proportional, integral and derivative modes.

For specific situations, many special features have been added to improve control, such as external integral feedback, batch switches, tracking, and output biasing. In the future, the flexibility inherent in digital feedback algorithms will increase the specialization and variety of feedback controllers. Nevertheless, control systems will still be built on the foundation provided by the basic responses.

A controller is a non thinking device- its responses are built in. It is up to the designer to select those appropriate to the application. Specifying the wrong combination of control modes leads to poor system performance, increases the complexity of the tuning problem, and may add unnecessary cost.

2.3.1.1 On-Off Control

On-off or two position response is the simplest form of feedback control loop. Figure 2.16 shows the performance of this loop for a process in which liquid is being heated.

An on-off control function has only two possible outputs (on, 100%; or off, 0%), and only considers the sign of the error. In the example, the controller closes the fuel valve when the measurement rises above the set point (Figure 2.16b). Because of dead time and/or lags in the process, the temperature continues to rise before reversing and moving toward the set point. When the temperature falls below the set point, the controller opens the fuel valve. Dead time and/or lags in the process again create a delay before the temperature begins to rise. As it crosses the set point, the controller again shuts off fuel flow, and the cycle repeats.

Cycling is the normal condition for a loop under on-off control. The limitation arises because with only two possible outputs the controller is unable to solve the control problem exactly. The output is either too high or too low to establish a balance among all the influences on vessel temperature. A 100% output supplies too much heat, causing the temperature to rise. A 0% output supplies too little heat, allowing the temperature to fall. Negative feedback causes cycling between two conditions.

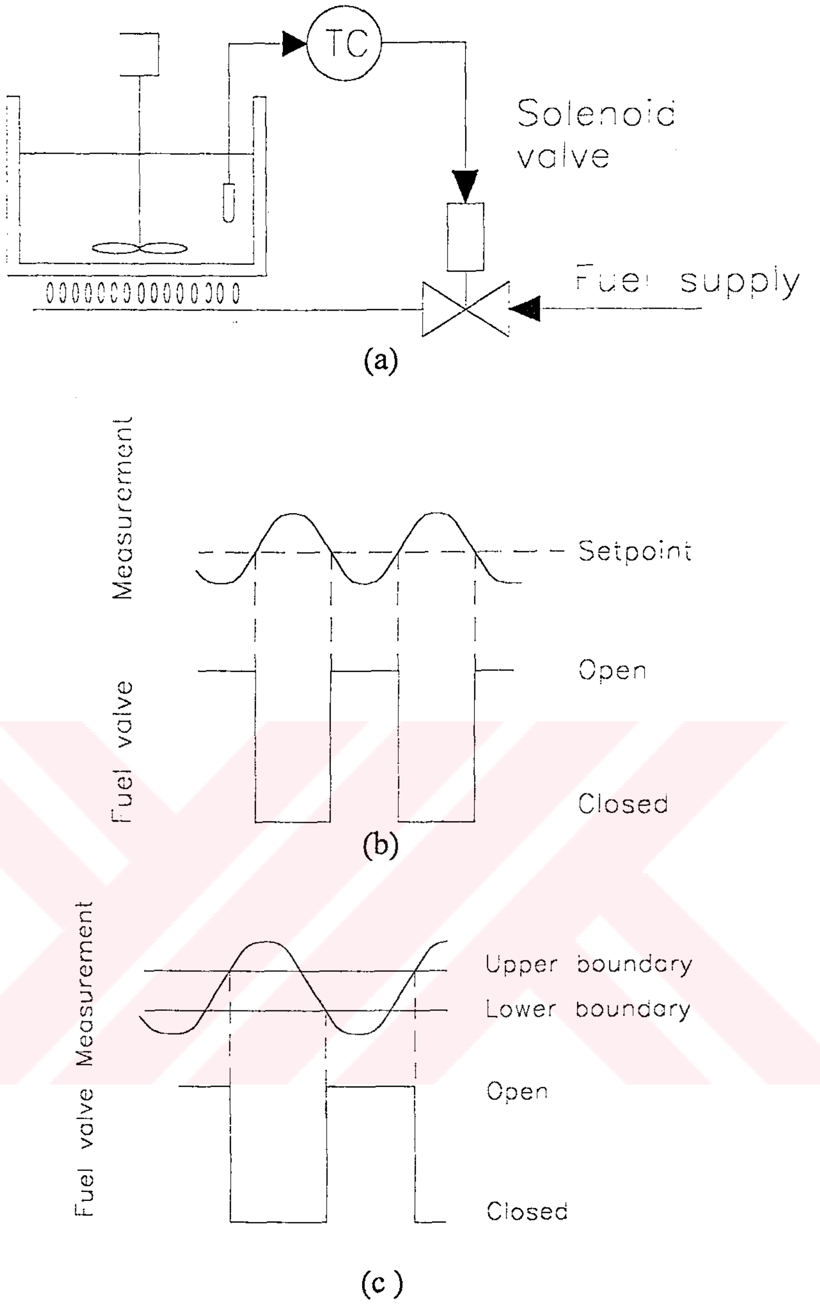


Figure 2.16 On-off response is the simplest type of feedback control
a. Process
b. Two-position control
c. Gap-action control

The principal disadvantage of on-off control is constant cycling; the principal advantage is low cost. Because of its simplicity, on-off control will be the least expensive approach to feedback control. It does not even require a controller, the same function can be created with alarms, contacts, digital outputs, and relays.

Acceptability of on-off control depends on the characteristics of the cycle in the measurement. If the amplitude of the swing is too large, unacceptable variations in product quality, or upsets to other process units, may occur. If the period of the cycle is too short, the wear on the valve and/or upsets to the fuel distribution system (Figure 2.16a) may be unacceptable.

The period of the cycle depends on how long it takes for the measurement to turn around after a change in the valve position. Thus, the period is directly proportional to dead time, τ_{DT} . If the dead time were reduced to zero, the measurement would instantly reverse itself with each change in controller output. Since the output reverses each time the measurement crosses the set point, both the period and the amplitude would be reduced to zero. Control would be very good, but the valve wear would be excessive and unacceptable.

Amplitude of the cycle depends on how much the measurement changes before it reverses. In turn, this depends on the length of the period and the rate at which the measurement changes. Since capacity inhibits measurement change, the amplitude is inversely proportional to the time constant τ_1 of the process.

On-off control should be applied to those situations where three conditions are present:

1. Precise control must not be required, because the measurement will constantly cycle.
2. Dead time must be moderate to prevent excessive valve wear of too short a period.
3. The ratio τ_{DT} / τ_1 must be small to prevent too large an amplitude in the measurement cycle.

When these conditions apply, the simplicity and economy of on-off control offer significant advantages.

A variation of on-off control that reduces wear on the final operator, and that may be described as differential gap or gap action control, is shown in Fig1.c. Instead of changing the output in both directions at a single point, the control function may take action only at specified high and low limits. A long as the measurement remains within the gap, the controller holds the last output state. As Figure1.c illustrates, the effect of this variation is to extend the period, and to increase the amplitude.

Often, the size of the gap will be adjustable and need not be symmetrical, hence some acceptable compromise can be achieved. Typically, an on-off controller will have a very small gap designed into its mechanism.

As was discussed in previous chapters, feedback control requires a closed loop. The closed response is to a change in the set point or in the measurement caused by a load upset. The simplicity of the on-off function allows it to be represented in terms of closed loop response. However, the interaction between the controller and the process in this configuration obscures the properties of the proportional, integral and derivative control modes.

process in this configuration obscures the properties of the proportional, integral and derivative control modes.

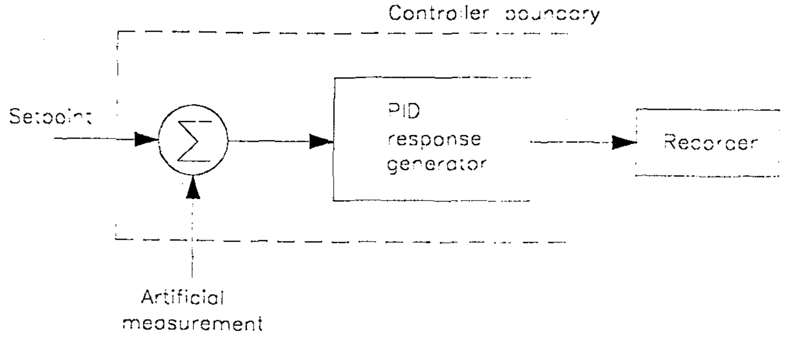


Figure 2.17 Isolating the controller allows study of its open loop response

A controller is isolated from a process in order to study its open loop responses (Figure 2.17). Here, the controller receives an artificial measurement and a set point. The difference between these values generates an error signal, ant the controller output is merely recorded. In this configuration, the effect of a change in the controller's output does not appear at the measurement point where it would cause further changes in the output. Any desired measurement or set point change may be applied, and the controller's response observed on the recorder.

An on-off control function can not solve the control problem, because it has only two possible outputs. For example, the response of an on-off controller to the smallest error is to drive its output to one extreme. To solve the control problem, the controller must also be able to generate any output between the extremes. Proportional, integral and derivative modes have this capability, but each is based on a different concept oh how the controller should response to an error.

2.3.1.2 Proportional Control

Proportional control is based on the principle that the size of the controller response should be proportional to the size of the error. To achieve this, proportional control ties the change in output to the change in error, with both values being usually expressed as percent of range.

Figure 2.19 is a graphical representation of proportional action. Regardless of how proportional action is created (pneumatic, electronic or digital), this effect may be imagined as a double ended pointer, pivoted in the middle, (for proportional band = 100%) and moving along an error scale and an output scale. Changes in either the measurement or the set point create changes in the error, which drives the left hand end of the pointer. The right hand indicates the corresponding output. As shown in Figure 2.19, the output scale describes increase-decrease (I/D) action. Changing to increase-increase action simply reverses the output scale.

change. With the pivot in the middle, a 100% change in the measurement (from 50% below the set point to 50% above it) will cause the output to change from 0 to 100%. Moving the pivot to the left can reduce the measurement change required for a 100% output change to 50%, i.e. from 25% below to 25% above the set point. In the same way, moving the pivot to the right will increase the percent change in error required for full valve travel.

The proportional band, PB, is defined as the percent change in measurement (at a constant set point) required to cause 100% output change. Gain, G, is defined as the ratio of the output change to error change. Both quantify the same thing- the sensitivity of the controller to changes in the error, and each can be expressed in terms of the other :

$$G = 100\% / PB \qquad \text{Equation 2.1}$$

This relationship can also be expressed in the form of a matched scale :

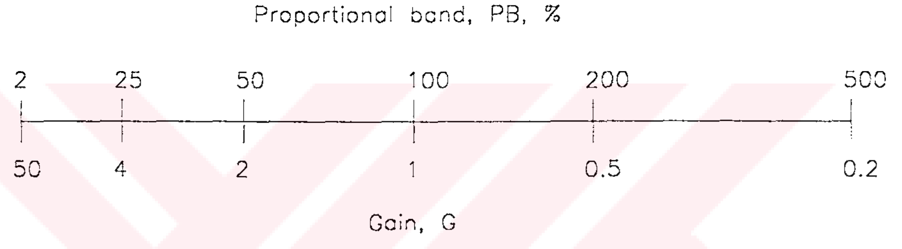


Figure 2.18 The relationship between gain and proportional band

Figure 2.19 also illustrates the concept of the proportional bias. Regardless of the value of the proportional band, the output will be 50% when the input error is zero (measurement at the set point). This bias on the output gives the controller a value around which it can vary its output to reduce error. As the error increases (or becomes negative), the output changes from 50%, according to the value of the proportional band. Normally, the bias in a proportional controller is adjusted at the instrument factory but some manufacturers make this adjustment available to the operator.

Figure 2.19 also illustrates two properties of proportional action that have the most influence in a closed loop. Proportional action is both immediate and specific.

1. The linkage between the error ant the output, represented by the pointer, means that the output change occurs simultaneously with error change. No delays occur in the proportional response.
2. Each value of the error for a given proportional band generates a unique value of the output. The proportional response is incapable of any other combination. This one to one relationship between the error and the output places severe limitations on the closed loop performance on the proportional-only control, as will be described shortly.

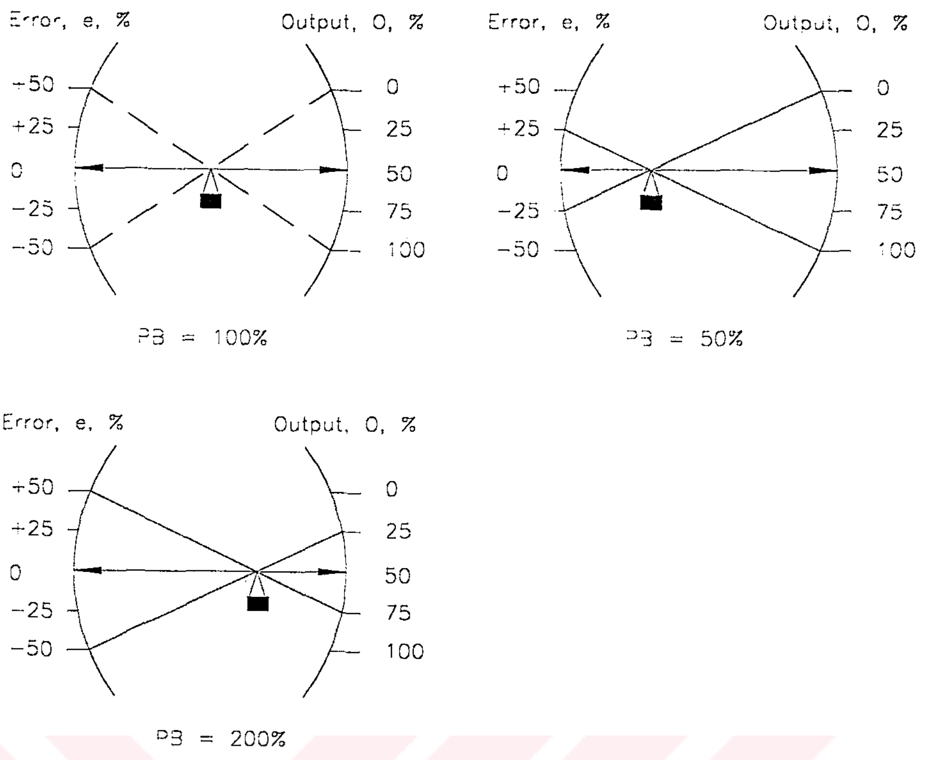


Figure 2.19 Proportional action relates change in output to change in error

Figure 2.20 presents another graphical representation of proportional action. Each value of the proportional band defines a specific relationship between error, e, and output, O, which may be expressed as :

$O = e(100) / PB + 50\%$ Equation 2.2

where O is output, %; e is error, %; and PB is proportional band, %.

For example, assume that set point is at 60% of scale, measurement at 40% at scale, and that proportional band equals 50%. Then for increase-decrease action :

$O_{ID} = (60\text{-}40)(100/50) + 50 = 90\%$ Equation 2.3

here O_{ID} is the output for increase-decrease action.

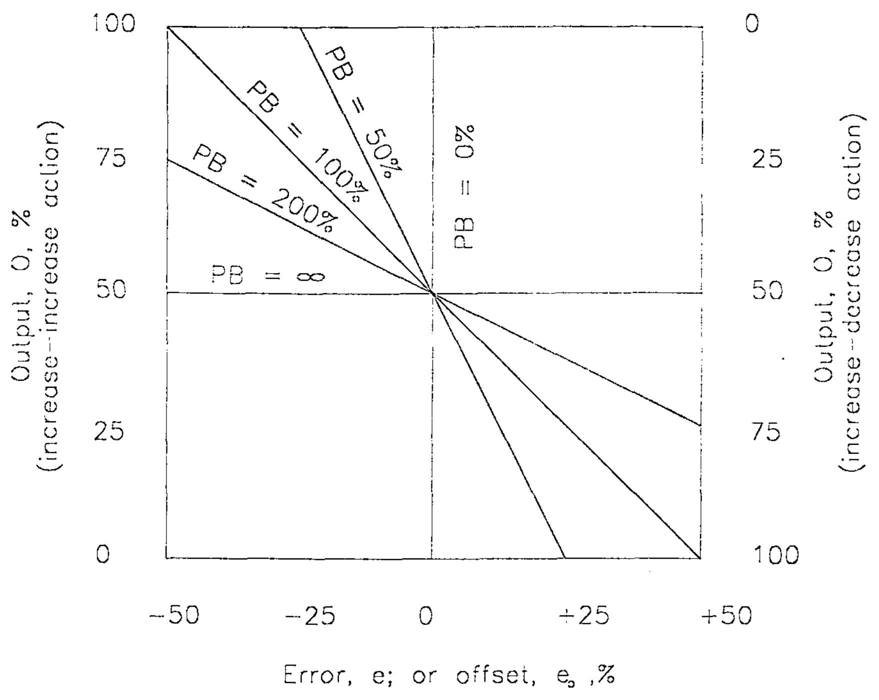


Figure 2.20 Relationships between error and output for various proportional bands and action

Increase-increase action is achieved by reversing the calculation of the error within the controller. Then;

$$O_{II} = (40-60)(100/50) + 50 = 10\%$$

The straight line relationship between error and output identifies a proportional-only controller as a linear or constant gain device. In this representation, the specific character of proportional action means that the coordinates of error and output must identify a point on the given proportional band line, and the operating point for the controller can only move along this line.

As the proportional band is decreased, proportional action is concentrated into a narrower band around the set point. From a gain point of view, the same change in error causes larger changes in output. In the limit, the proportional band equal zero (gain equals infinity), and the smallest error causes the output to go full scale. On-off control, then, becomes a limiting case of proportional-only control. At the other extreme, when the proportional band equals infinity (gain equals zero), the controller simply does not respond to changes in the error.

A level process under proportional-only control is shown in Figure5a, where the outflow is the load on the process. To control the level, the controller must balance the outflow by manipulating the inflow. This requires increase-decrease action. Both flows vary from 0 to 100%, the set point of the controller is 50%, and the proportional band equals 100%.

As a starting point, assume that the load equals 50% and that the level is at the set point. Then, the controller output will also be 50%, inflow will equal outflow, and level will remain constant.

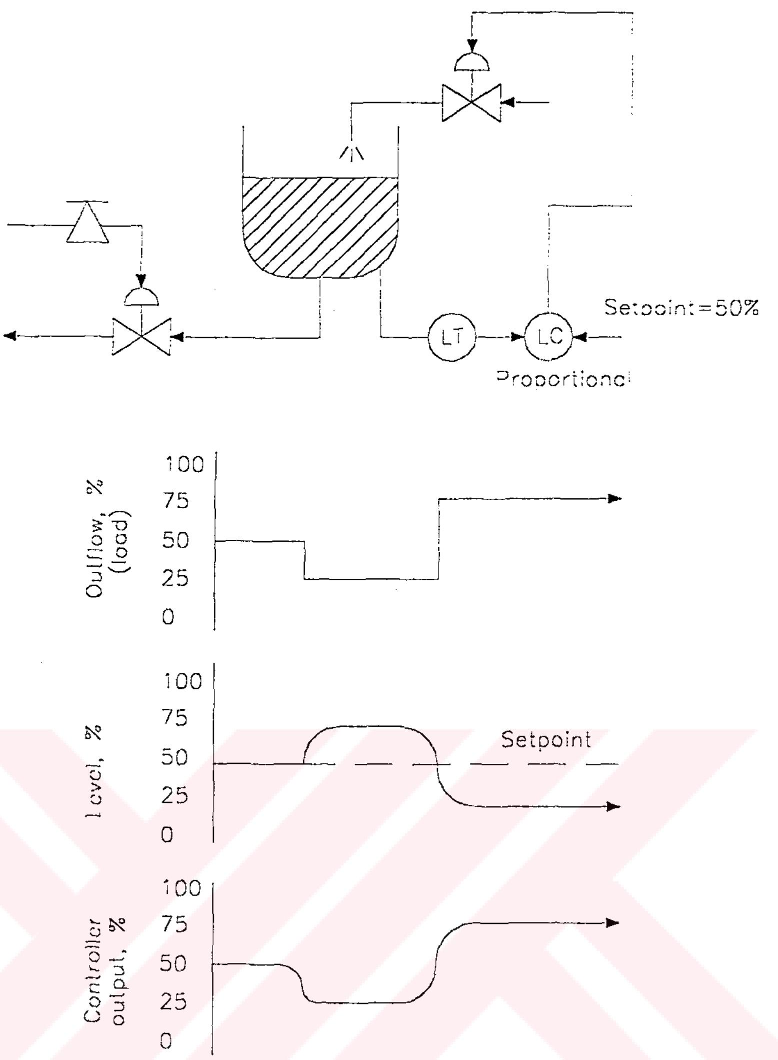
Next, assume an upset in the form of load decrease to 25%, i.e., outflow is reduced. Since the outflow is less than the inflow initially, level will begin to rise, and the error will begin to go negative. By referring to the 100% PB line in Figure 2.19, it will be seen that the controller output (for increase-decrease action) will simultaneously begin to decrease as the operating point moves toward the upper left hand corner of the chart. This action gradually restricts inflow until it equals 25% when level has risen to 75% (Figure 2.21a). Then, inflow equals outflow, and the level will remain constant.

The controller can not return the measurement to set point. When the proportional band equals 100%, the output equals 25%, but only when the error is -25%. Therefore, a steady state deviation is required to balance the load on the process. In the same manner, if the load increases to 75%, level will fall until 25% below set point, where the 75% output from the controller again balances the load on the process.

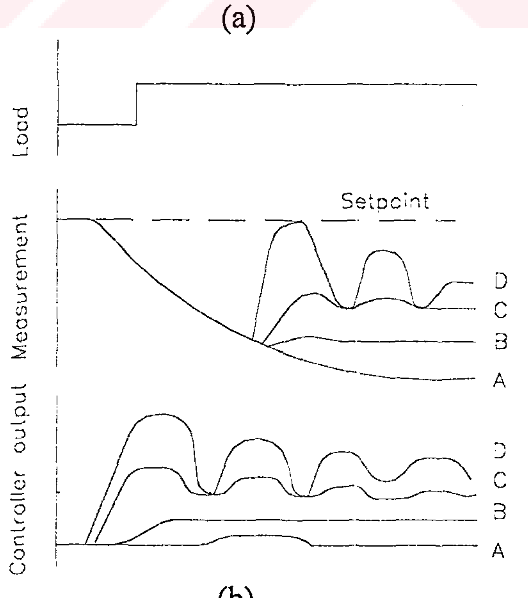
This steady state deviation from set point is called "offset". It arises because the bias, B (output when the measurement equals set point), is fixed. If the loading conditions require an output different from the bias, some steady state error must be present. Each variation in the load will require a different output and a different offset. The amount of offset, e_0 is a function of the required output and the proportional band, according to the following equation describing a proportional-only controller :

$$O = e(100/PB) + B \qquad \text{Equation 2.4}$$
$$e_0 = (PB/100)(O-B) \qquad \text{Equation 2.5}$$

Thus, the purpose of an adjustable bias becomes clear. By changing the bias on the proportional response to equal the required output, the measurement can be returned to the set point. This adjustment is often called "manual reset".



(a)



(b)

Figure 2.21 Level process under proportional-only control
a. Offset varies with load
b. Effects of narrowing the proportional band

Assuming the bias remains fixed at 50%, the offset for a required output is also seen to vary with the proportional band. Referring to Figure4, if the load conditions require a 75% output and the proportional band is 200%, offset will be 50%. Reducing the proportional band to 50% reduces the required offset to 12 ½ %. However, reducing the proportional band also increases the gain of the controller and reduces the damping in the closed loop response.

Figure 2.21b shows the effect of narrowing the proportional band on the closed loop response to a load upset:

- Case A-The controller does not respond. The measurement falls to a new steady state value.
- Case B-The proportional response is too weak, leading to excessive offset.
- Case C-The proportional band is correct. The response of the controller is just strong enough to cause quarter wave damping.
- Case D-The proportional band is too narrow. The overreaction causes excessive swing in the measurement, which takes too long to even out.

If the proportional band is reduced too much, the gain in the controller will become high enough to make the open loop gain greater than 1. Instead of decaying, the cycle for both the measurement and the controller output will grow until the valve cycles between its limits, as in on-off control.

For every process under proportional only control, one particular proportional band (i.e. gain) creates the desired closed loop response. The exact value will depend on the other elements in the loop, each having individual gains. In general, where process gains are low because of small τDT / τl ratio, the required proportional band will also be low. Once tuned, however, offset will vary with the load on the process, as in Figure 2.21a.

Proportional control is a major improvement over on-off control because its ability to stabilize the loop. Its main disadvantage is the inevitable offset. Where the loads are fairly constant and the required proportional band is narrow, offset will not be a problem. The set point is then no longer the desired measurement value but simply a reference for proportional action.

2.3.1.3 Integral Action

Integral action may be combined with proportional action to eliminate offset where it is unacceptable. Like proportional action, integral action also responds to the error. However, integral action is based on the principle that the response should be proportional to both the size and duration of the error.

The open loop response in Figure 2.22a shows how integral action is related to the error. Initially, while the error equals zero, the output remains constant at a value that depends on the history of the error. Errors in the measurement will produce the following :

- Point A-A constant error appears. The integral responds by driving the output at a constant rate, proportional to the size of the error, as long as the error remains constant.
- Point B-The size of the error increases. The integral responds by driving the output at a faster rate.
- Point C-The sign of the error changes. The integral responds by driving the output in the opposite direction.
- Point D-The error returns to zero. The integral action stops at the existing output value.
- Point E-The error increases at a constant rate. The integral responds by driving the output at an increasing rate.
- Point F-The error returns to zero. The integral action ceases at that output.

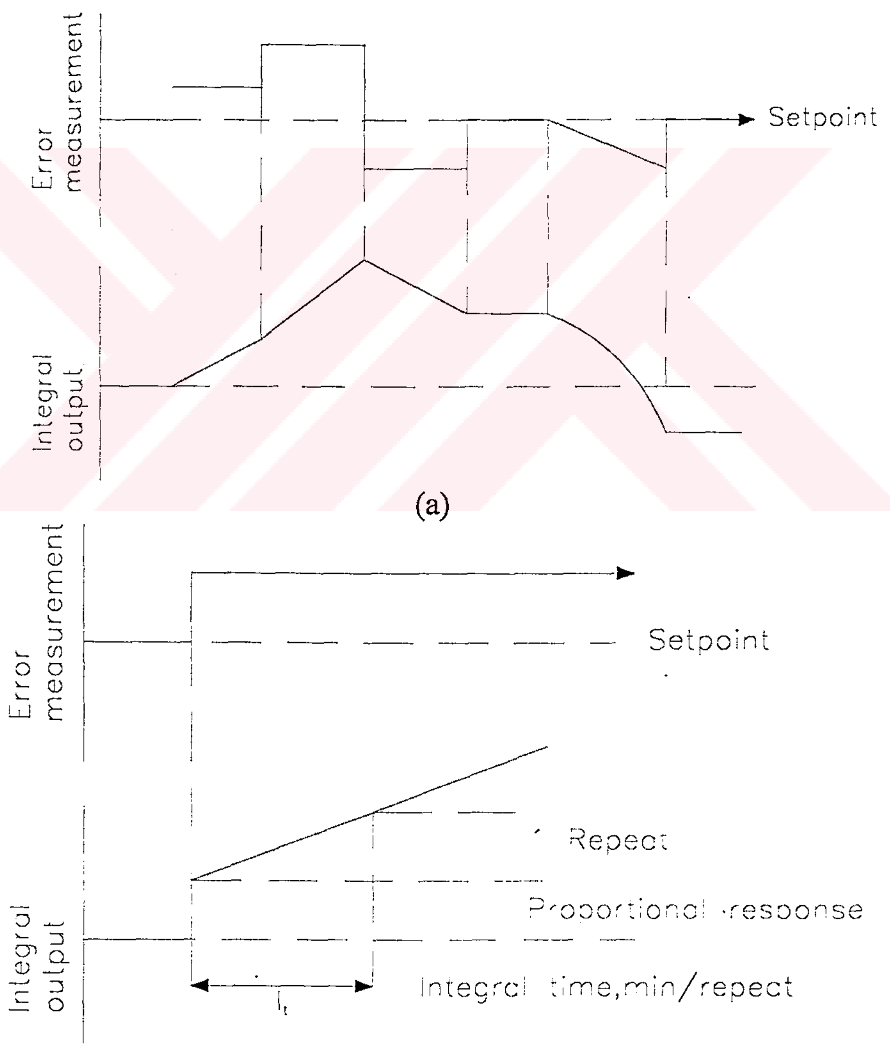


Figure 2.22 Integral action improves the control response
a. Integral action responds to sign, size and duration of error
b. Integral time determines rate of response

These responses illustrate the most significant property of integral action. Whereas proportional action ties the output to the measurement through the error, integral action can achieve any output value-stopping only when the error is zero. This is the property that enables integral action to eliminate offset. Integral action is only satisfies when the measurement has returned to the set point. As long as an error exists, integral action will drive the output in the direction that reduces error.

The open loop response in Figure 2.22b shows how proportional and integral actions are combined in a controller. Initially, the output is constant because the error is zero. When a step change in the error appears, a simultaneous step change occurs in the output because of the proportional action. The size of this response depends on the proportional band. At the same time, the integral action begins to drive the output, as shown in Figure 2.22a.

For a constant error, the adjustment to integral action changes the rate at which the output is driven. This rate is quantified in terms of the time required for the change in the output (due to integral action) to equal or repeat the response caused by proportional action.

Some instrument manufacturers use dimensional units of minutes/repeat, referred to as integral time. Others use units of repeats/minute, referred to as integral gain. Each is simply the inverse of the other, as shown in the chart :

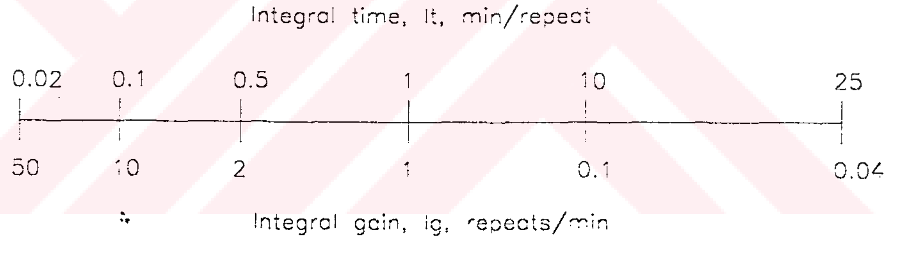


Figure 2.23 The relationship between integral time and gain

Increasing the integral time, or lowering the integral gain, reduces the strength of the integral action.

The combination of proportional plus integral action can also be expressed in equation form :

$$O = (\frac{100}{PB}) e_o + (\frac{100}{PB})(\frac{1}{I_t}) \int e_o dt \qquad \text{Equation 2.6}$$

When Equation 2.6 is compared to Equation 2.4, which describes a proportional-only controller, the only difference is in the bias term. When proportional-only control is limited by a fixed bias, integral action uses the in of the error to adjust the bias, stopping when the error equals zero.

The integral action eliminates offset, following a load upset. Initially, at 50% load, a 50% output holds the measurement at the set point. In the steady state, this is also the value of the variable bias, since the error equals zero. The controller has a 40% proportional band. The 50% bias indicates that the 40% variation in measurement over which proportional action will occur is centered around the set point. When the measurement begins to fall, following a load increase, proportional and integral actions return the measurement to the set point via a quarter amplitude damped response.

The contribution of integral is to increase the bias term as a function of the error. When the response is complete, the bias term has increased to 75%, and the proportional term has returned to zero. The 75% bias means that the proportional band has shifted so that the range of proportional action extends from 10% below to 30% above the set point. Thus, integral action continuously performs the manual reset function, described earlier.

The ability of integral action to eliminate offset is very advantageous, and integral action is almost always specified for feedback control . However, this action has a significant disadvantage: to create its gradual response, a capacity-like lag is built into the controller. This causes a phase lag across the controller and lengths the period of oscillation of the loop, as a function of the relative contribution of proportional and integral actions.

Typically, the period of oscillation for a loop under a properly tuned proportional plus integral controller will be 50% longer than if the controller was proportional-only. For relatively fast loops, such as flow control, this will not be significant. However, for slower loops, extension of the period can be a serious limitation. For loops where the exact value of the measurement is not critical (as in level control), the shorter period of a proportional-only controller can be advantage.

Like proportional action, integral action increases the gain of the controller. Too much of either can cause the loop to cycle. In general, integral time should be proportional to how fast the process responds to the control action. If the time is too short, it will drive the final operator to its limit before the measurement is able to respond. Then, the measurement does not respond, it will overshoot the set point.- causing the integral to drive the operator to its opposite limit.

Applications in which sustained errors are likely (batch processes or those having large set point changes) can lead to integral (or reset) windup. Although the integral time may be correct for normal control in such situations, the output may saturate during the sustained error,. and lead to evershoot when the measurement finally approaches the set point.

In these applications, a "switch" may be added to the integral circuit (whether electronic or pneumatic) of the controller. This switch has become known as a "batch switch" because the windup problem is primarily associated with discontinuous or batch processes. Newer controllers and control algorithms are designed to avoid the integral saturation or windup problem.

2.3.1.4 Adding Derivative Action

Proportional and integral actions share one serious limitation. A significant error must be present before either of these modes generates a strong response.

Derivative action is based on the principle that the controller should also respond to the rate at which the measurement is changing - even though the actual error is still small.

The open loop response in Figure 2.24a shows how derivative response is related to measurement. (The rate of change may be computed as an amount of change divided by the time over which the change takes place.) For example, in Figure2.24a:

- Point A-A step change appears. Because the change takes place in zero time, its rate is infinite, and derivative action responds with an output spike. The response direction will be determined by the controller action. Figure 2.24a shows the response for increase-increase action. Since the measurement is steady after the step change, the derivative contribution immediately returns to zero.
- Point B-A second, negative step appears. The derivative contribution responds with a negative spike.
- Point C-The measurement begins increasing at a constant rate. Derivative responds with a constant, positive contribution that is proportional to the rate of change.
- Point D-The change in the rate of measurement undergoes an increase. The derivative contribution increases proportionately.
- Point E-The measurement stops changing. The derivative contribution returns to zero.

The derivative response is unrelated to the absolute value of the measurement. Whenever the measurement stops changing, the derivative contribution returns to zero. When it starts to change, derivative action opposes that change whether the measurement is moving away from or toward the set point.

The open-loop response in Figure 2.24b shows how proportional and derivative actions are combined in a controller. When the measurement starts to change, derivative action generates an immediate response proportional to its rate of change. As the measurement continues to change, the output changes because of the proportional action. Because of derivative action, the output immediately reaches a value that it would not have reached until sometime later.

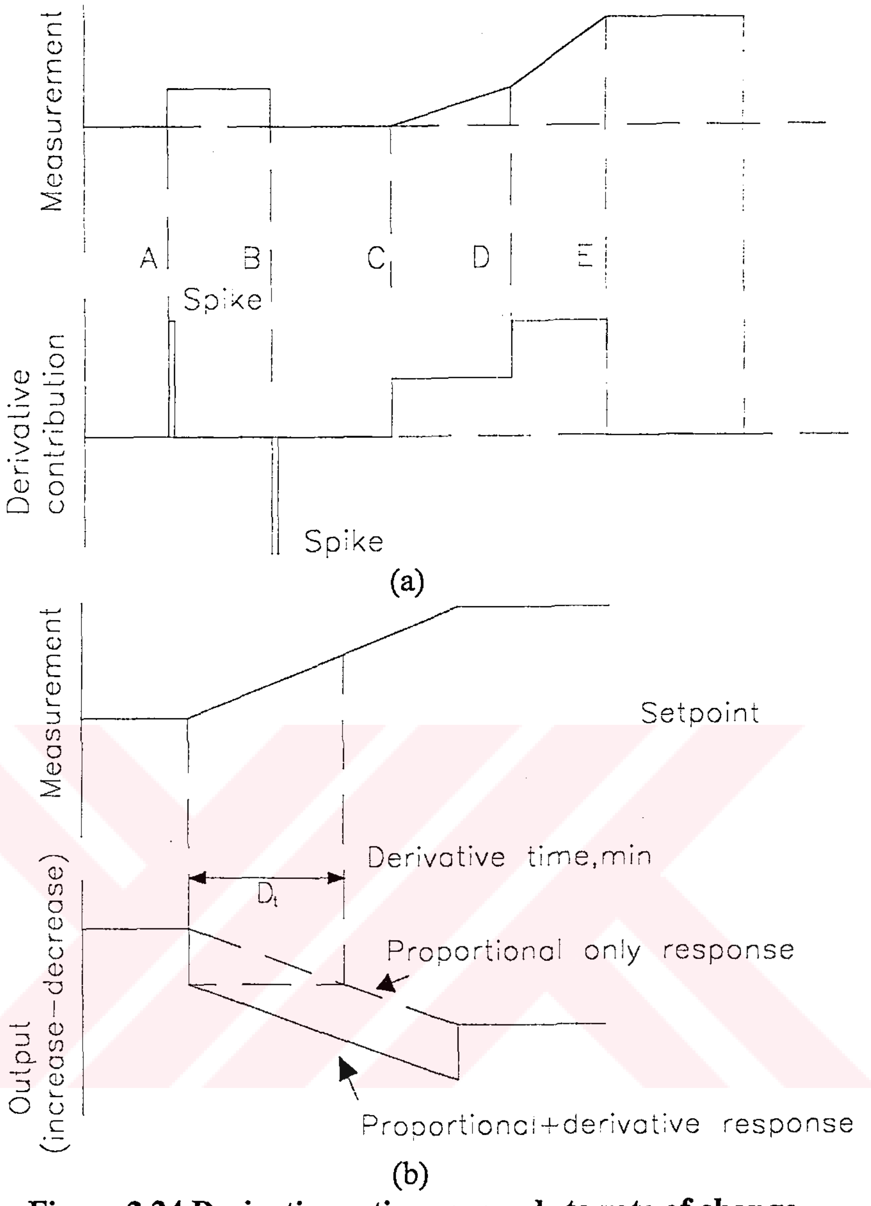


Figure 2.24 Derivative action responds to rate of change
a. Open loop response
b. Proportional response is advanced

In effect, the proportional response has been advanced in time. The size of this advance is the derivative time, D_t, min. Derivative action is sometimes erroneously referred to as "anticipating" action. (Note: the controller can only respond to a real error, and can not anticipate the arrival of an error.) Increasing the derivative time will generate a larger derivative response that will appear as a larger time difference between the two responses in Figure 2.24b.

Following the techniques for proportional and integral actions, earlier controllers applied derivative action to the error. However, this causes the derivative action to respond to both measurement and set point changes. Since set point changes are usually made stepwise, this approach "bumped" the process with large output spikes, as shown in Figure 2.24a.

Almost universally today, controllers are designed that the derivative-response generator looks only at the measurement signal. Initially, only the proportional and integral actions respond the changes in the set point.

When derivative action is combined with proportional and integral actions the total response is given by :

$$O = \frac{100}{PB}\left[e_o + \frac{1}{I_t}\int e_o dt - D_t\left(\frac{dc}{dt}\right) \right] \quad \text{Equation 2.7}$$

where c, a controlled variable, represents the measurement signal.

This equation describes an ideal, non- interacting controller. In most three mode controllers, some interaction occurs among the control modes, so that changing any one of the adjustments has some effect on all the responses.

Incorporating derivative action can significantly improve control for processes having large lags. Derivative action is the opposite of the integral action. To generate the derivative response, the dynamic inverse of the lag (i.e. a lead) is built into the controller. Although derivative action also increases the gain of the controller, its lead characteristics can effectively cancel a lag elsewhere in the control loop, and therefore shorten the period of oscillation. This can more than cancel the increase in the period caused by integral action, even though offset is still eliminated.

The main disadvantage of derivative action is sensitivity to the noise. Because it reacts to the rate of measurement change, even very low amplitude noise can cause large variations in the controller output. In effect, the derivative tries to control the noise; an impossible task.

Since noisy measurements are usually responsive measurements, the reduction in the period offered by derivative action will be a significant benefit. Hence, the derivative action should not be applied to noisy loops. Controlled variables that are slow enough to benefit from derivative action (i.e. temperature) are usually not noisy. One exception is the output of sampling analyzers such as chromatographs. This signal, which changes stepwise, must be filtered before it is applied to a controller having derivative action.

CHAPTER THREE

DESCRIPTION OF THE GAS TURBINE-BOILER INTERFACE SIGNALS

3. INTRODUCTION

From the Gas Turbine (GT)'s point of view the boiler is considered a so called "intelligent black box", which means a self-contained unit that executes it's task (steam production) independently and automatically.

Nevertheless, a few handshake signals are necessary to synchronize the operation of the boiler and the turbine.

In the following, these three different basic operation modes shall be taken into consideration.

- Start-up
- Operation
- Emergency shut down or stop

3.1 THE BACK PRESSURE PROBLEM

One of the most important prerequisites for the safe operation of the turbine is the undisturbed exit of the exhausted gasses. In case that the exhaust gas flow is hindered, upon exceeding a defined limit, the back pressure sensing device installed in the exhaust track of the turbine immediately initiates an emergency stop. Nevertheless if the back pressure for some reason reaches a very high value it will cause serious damage to the turbine.

In order to avoid this the boiler/bypass flaps must be operated and controlled in such a way that the simultaneous closure of both flaps can not occur under no circumstances (one flap must be open at all times). In the following this will be referred to as the "safe position" of the flaps which means

safe position = by-pass flap opened / boiler flap closed

Even in case of no power supply from the mains the boiler control system must be able to move the flaps into the safe position (e.g. by means of an emergency power supply).

3.2 THE BOILER CONTROL SYSTEM

The boiler may be controlled by either hard wired logic or by a PLC. In case that a PLC or alike device is used its proper operation must be supervised by an external, fail safe watchdog circuit. If the watch dog detects a malfunction or the failure of the PLC it must initiate the emergency stop procedure.

3.2.1 Start Procedure (GT and Boiler)

The simultaneous start up of both of the GT and the boiler must not be possible as long as

- the flaps are not in the safe position
- one of the two units is in the emergency stop state (GT emergency stop / Boiler emergency stop signals)

The followings are the steps of the GT start with the boiler

- the GT and the boiler start procedures are initiated manually
- the GT starts accelerating and purging
- the GT purge cycle signal indicates that the boiler shall start it's purging procedure
- the boiler control system indicates the completion of the purge procedure by means of the Boiler purge time elapsed signal. At this point the flaps must be in safe position again
- even though the GT purge time setting is higher than the boiler purge time (approximately 10 sec. i.e. the boiler generally completes the purging procedure faster than the GT) the GT does not ignite before both purging procedures have been finished.
- the falling edge of the GT standstill signal indicates that the turbine is accelerating and can be used as trigger to reset the Boiler purge time elapsed signal.
- after the GT has reached rated speed and the generator circuit breaker has been closed the GT on-load signal indicates that the GT is supplying electrical energy and that the boiler may start to operate .

Figure 3.1 is the timing diagram of the GT start procedure with the boiler.

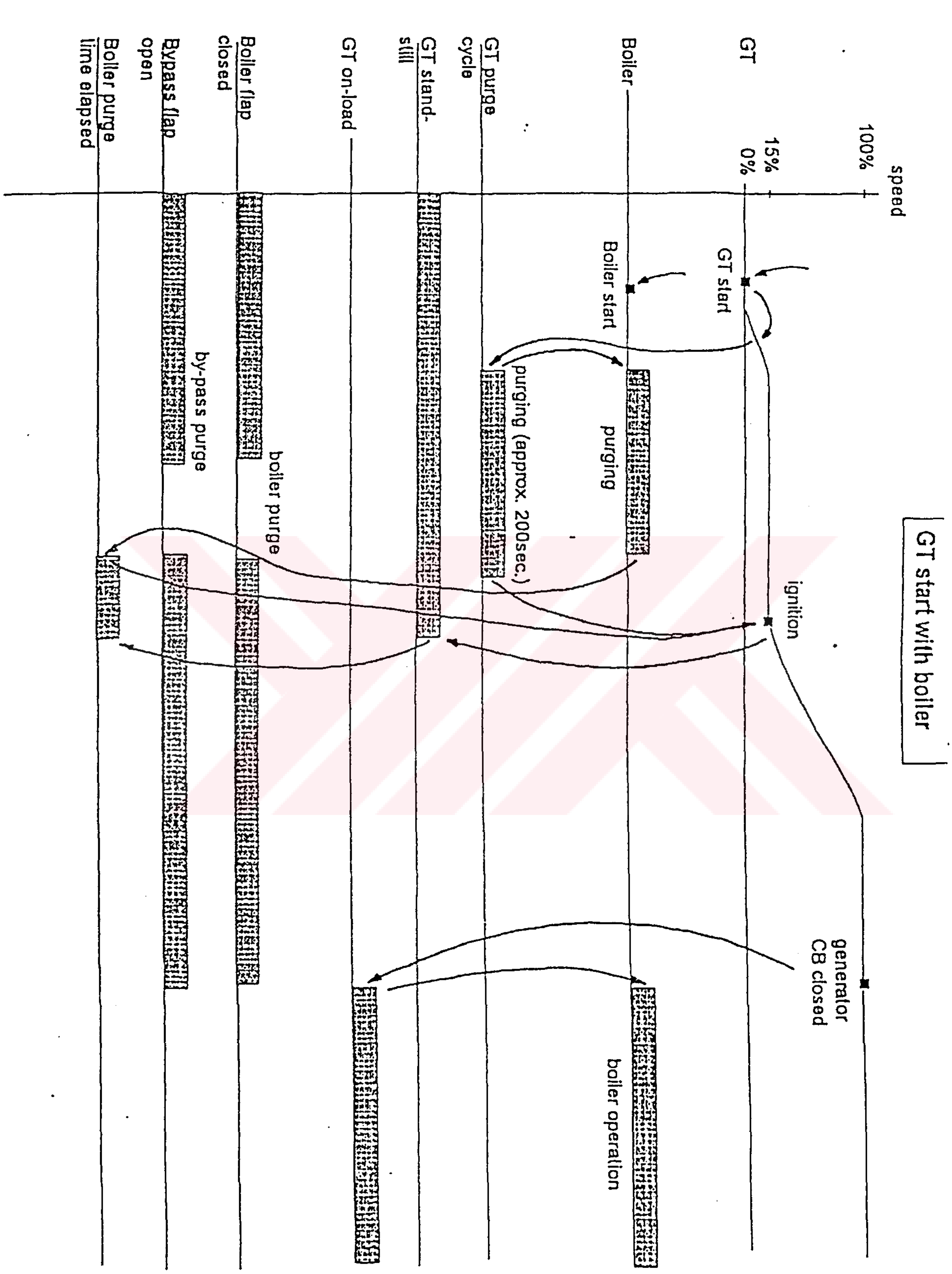


Figure 3.1 GT start with boiler timing diagrams

3.2.2 Start Procedure (GT only)

Even though the start-up of the boiler may not be possible for some reason the GT can be operated to supply electricity.
Nevertheless, the start up of the GT must not be possible as long as

- the flaps are not in the safe position
- one of the two units is in the emergency stop state

The followings are the steps of the GT start without boiler (Refer to Figure 3.2)

- The GT start procedure is initiated manually
- The GT starts acceleration and purging
- The *GT purge cycle* signal indicates that the boiler shall start it's purging procedure
- The boiler control system in response sets the *Boiler purge time elapsed* signal immediately even though the purging procedure is not executed (flaps remain in safe position)
- Since the *Boiler purge time elapsed* signal is already set upon completion of the GT 's purging procedure the GT ignites immediately
- The falling edge of the *GT standstill* signal indicates that the turbine is accelerating and can be used to trigger to reset the *Boiler purge time elapsed* signal
- After the GT has reached rated speed and the generator circuit breaker has been closed the GT on-load signal indicates that the GT is supplying electrical energy.

3.2.3 Start Procedure (Delayed Boiler Start Up)

In case that the GT only has been started-up (as described in previous section) the boiler can be put into operation while the GT is already running on-load under certain conditions. These prerequisites must be defined by the boiler supplier and may vary according to the type of boiler.

Nevertheless, we assume that the GT power output and thus the exhaust gas temperature shall be lowered to a certain limit.
The followings are the steps of delayed boiler start-up

- The GT' s power output shall be reduced manually in order to lower the exhaust gas temperature below a certain limit which shall be defined by the boiler manufacturer
- The boiler start procedure is initiated manually
- The boiler shall execute the common purging routine
- After the completion of the boiler purging procedure the GT' s power output can be raised to the rated value again.

Figure 3.3 shows the timing diagrams of delayed boiler start-up.

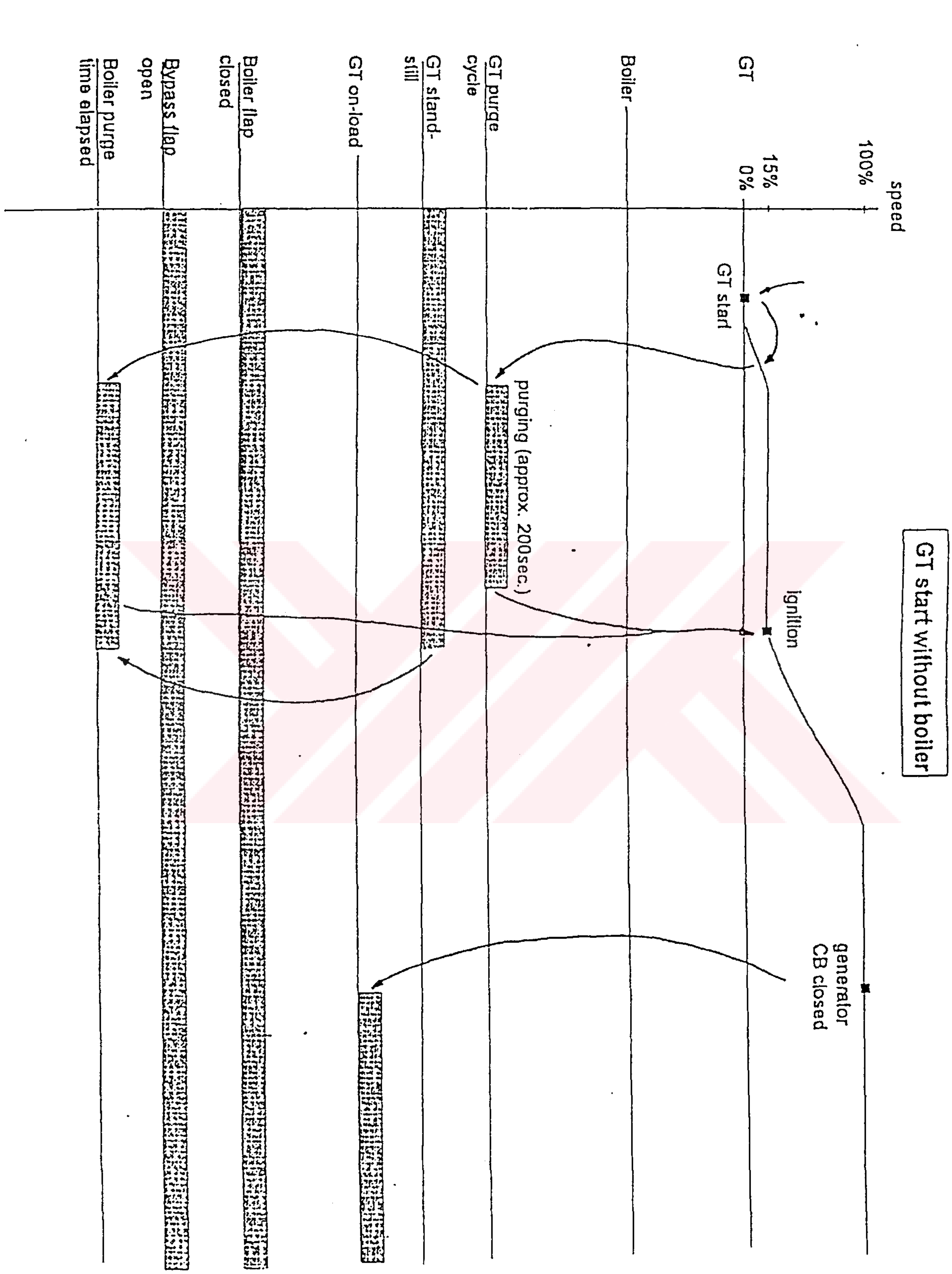


Figure 3.2 GT start procedure without boiler

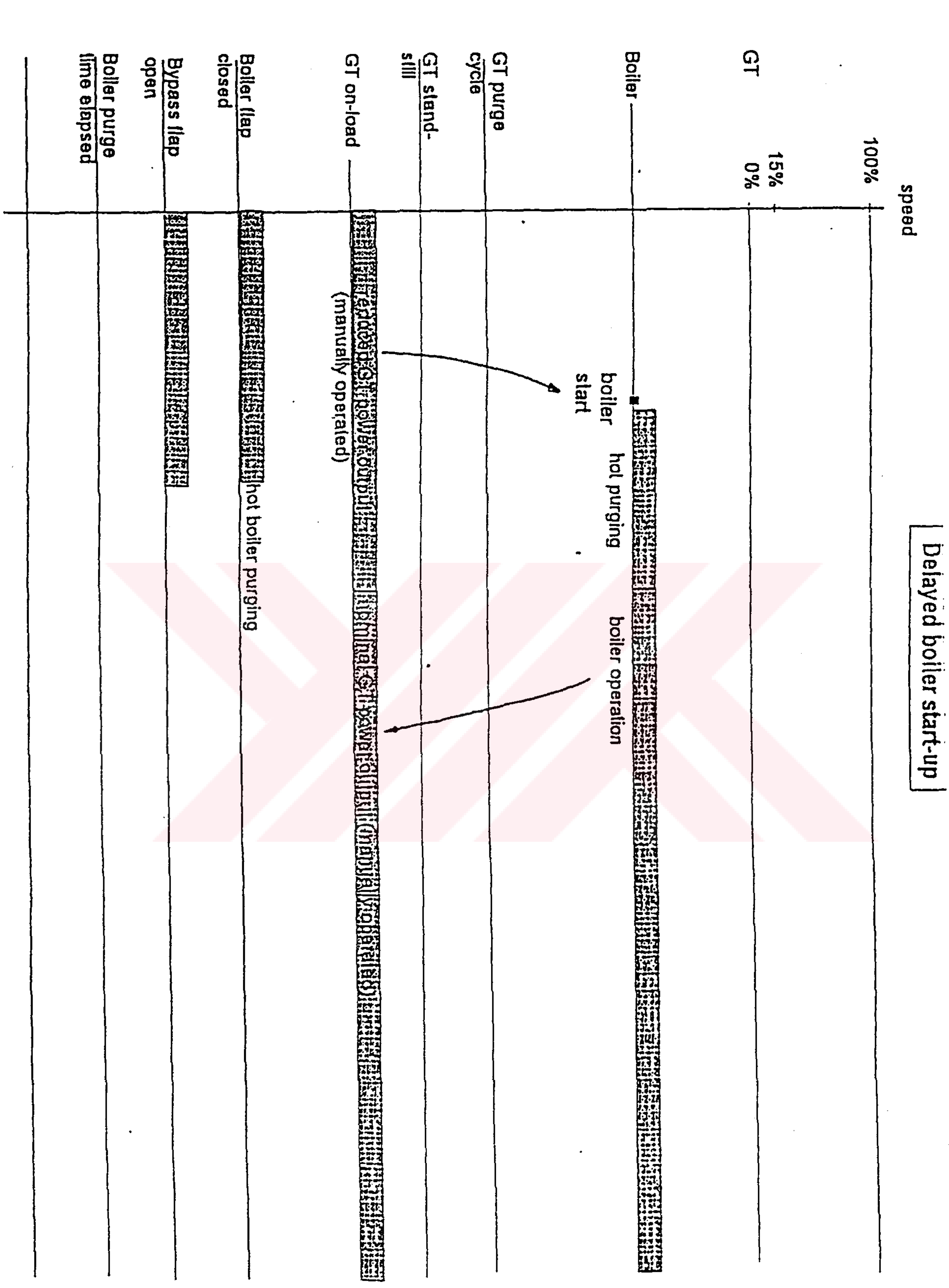


Figure 3.3 Delayed boiler start up procedure

3.2.4 GT Emergency Stop

The GT emergency stop can be initiated by several sources. At the beginning of the emergency stop procedure the GT is immediately separated from the grid (generator CB opened)

The followings are the steps of the GT emergency stop

- The GT emergency stop signal indicates the GT emergency stop procedure is executed
- Since no exhaust gas is available any longer a continuation of boiler operation seems useless. The boiler control system shall stop operation automatically and move the flaps into the safe position
- The rising edge of the GT standstill signal indicates that the turbine has decelerated and the speed is equal or lower 15% rated speed.

Refer to Figure 3.4 for GT emergency stop procedure

3.2.5 GT Stop

The GT stop procedure differs from the GT emergency stop procedure slightly since it takes longer time to reach standstill

The followings are the steps of GT stop

- The GT stop procedure is initiated manually
- The *GT stop* signal indicates that the common stop procedure is executed
- Upon the opening of the generator CB the *GT on load* signal is reset which indicates that the boiler shall stop operation automatically and move the flaps into the safe position
- The rising edge of the *GT standstill* signal indicates that the turbine has decelerated and the speed is equal or lower 15% rated speed. The *GT stop* signal is reset.

Refer to Figure 3.5 for GT stop.

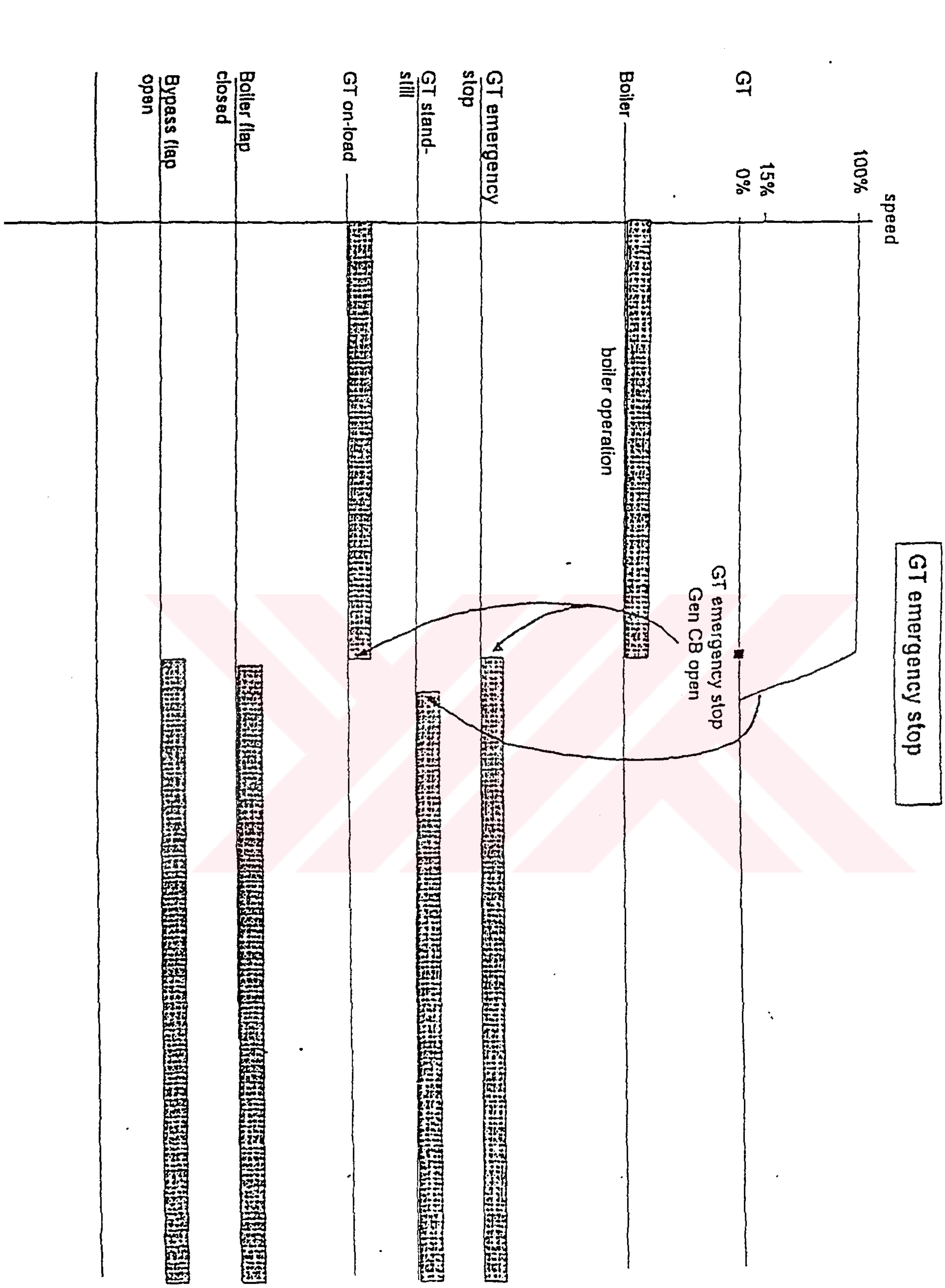


Figure 3.4 Signals in case of GT emergency stop

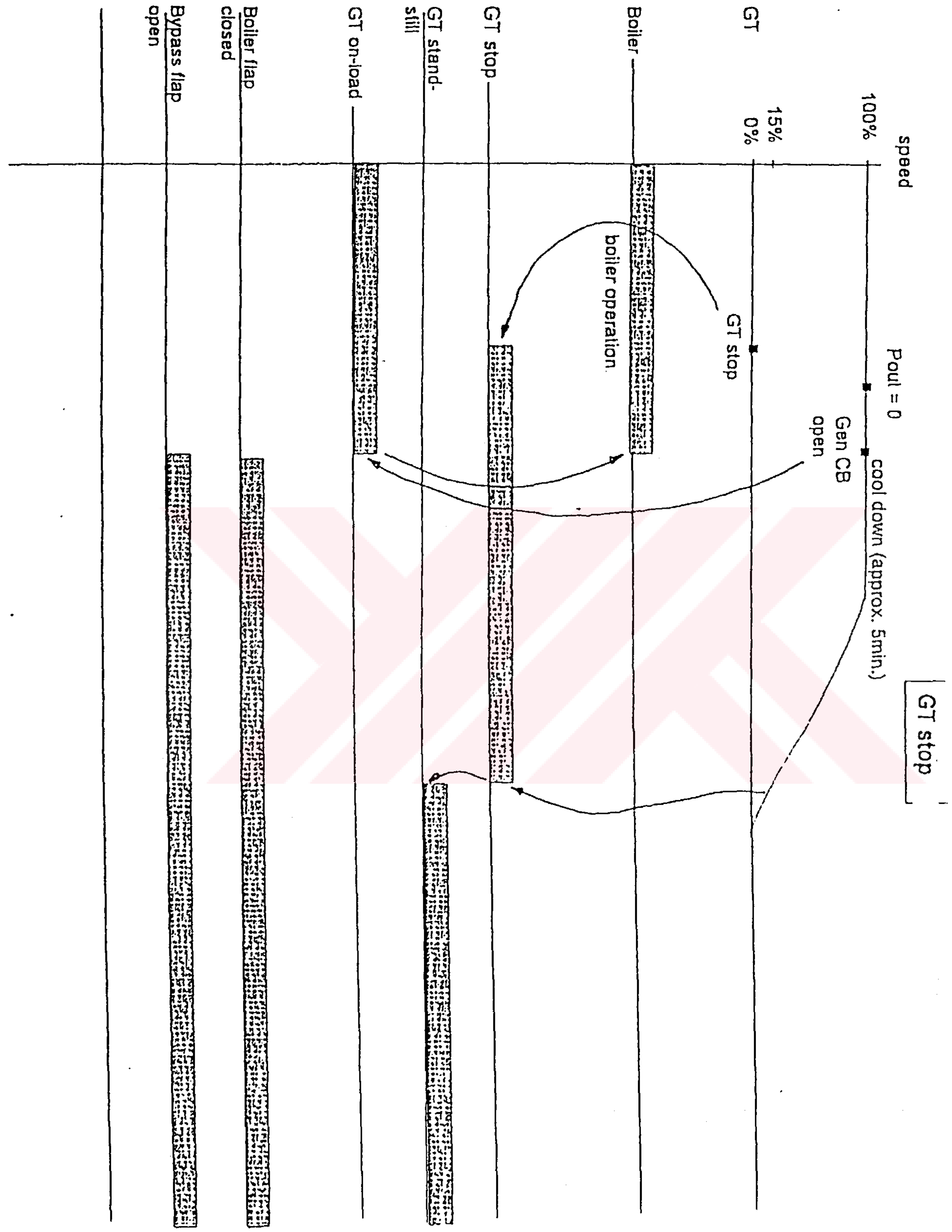


Figure 3.5 Signals in case of GT stop

3.2.6 Boiler Emergency Stop

The boiler emergency stop procedure may be initiated by several sources, such as:

- flaps can not be moved into the safe position.
- too high pressure
- too low water level
- disturbed or broken damper flaps
- released thermo relays
- emergency push buttons

A boiler emergency stop always initiates a GT emergency stop and must therefore be generated by a separate, fail safe hardware device.

The followings are the steps of boiler emergency stop

- The *boiler emergency stop* signal indicates the emergency stop procedure and initiates the GT emergency stop routine
- Upon the opening of the generator CB the *GT on-load* signal is reset
- The boiler control system must move the flaps into the safe position
- The rising edge of the *GT standstill* signal indicates that the turbine has decelerated and the speed is equal or lower 15% rated speed

3.2.7 Boiler Alarm/Failure

The boiler alarm/failure signal indicates that a problem within the boiler unit occured that the boiler failed to operated correctly. This signal is used for indication only and does not stop the turbine operation.

Nevertheless, since a boiler failure might lead a dangerous situation for the GT the boiler control system must move the flaps into the safe position.

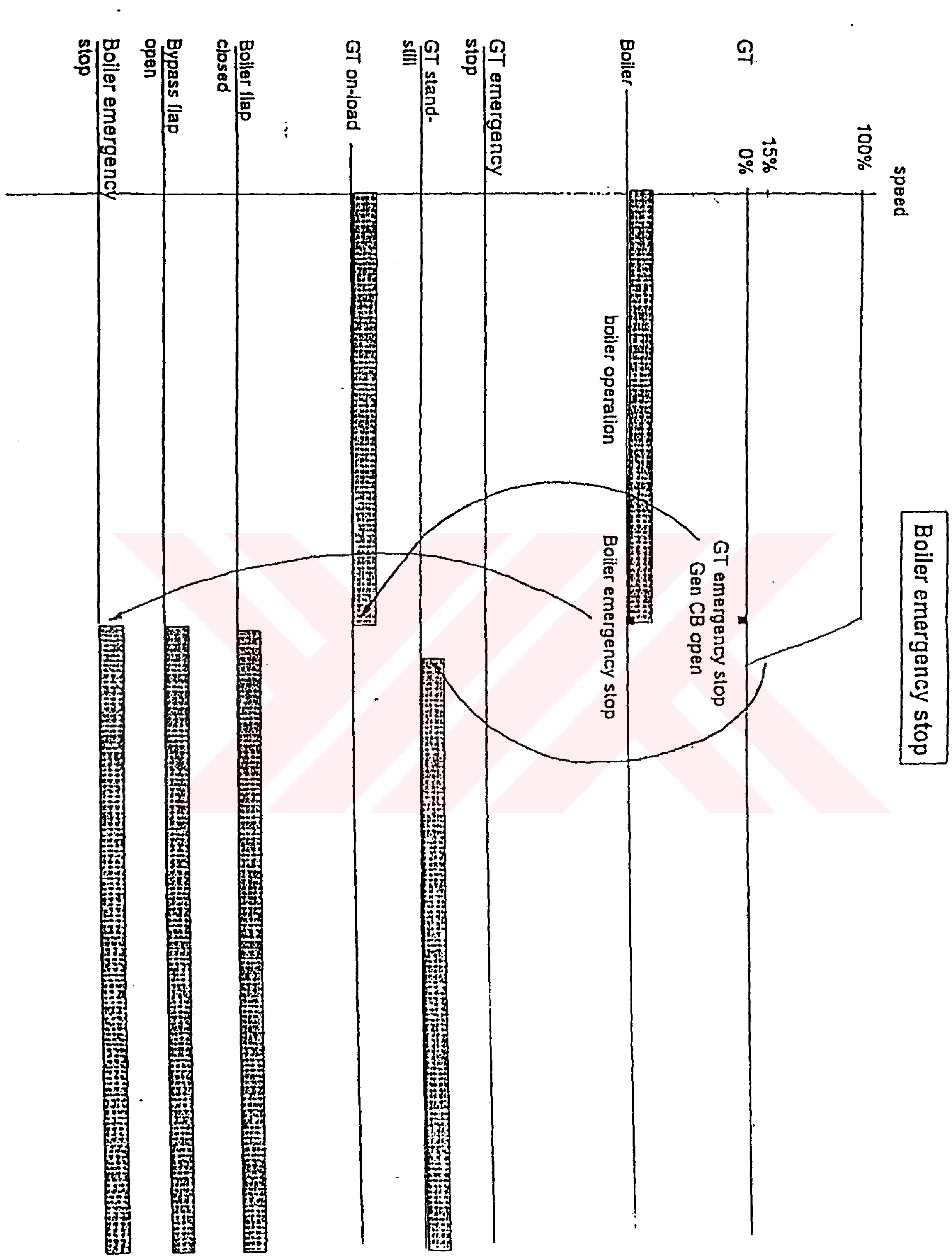


Figure 3.6 Signals in case of a boiler emergency stop

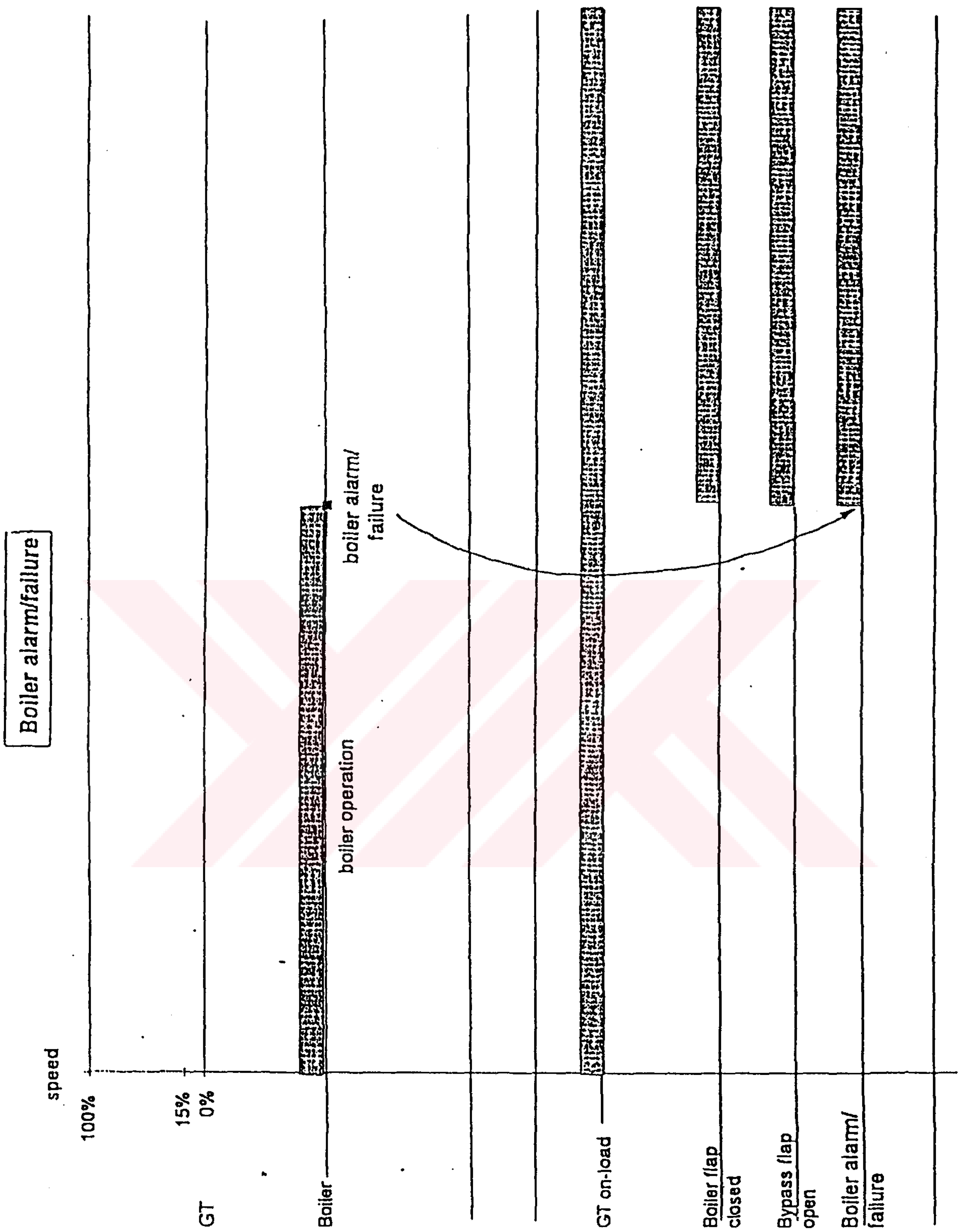


Figure 3.7 Boiler alarm/failure

3.3 GT TO BOILER CONTROL SYSTEM INTERFACE SIGNALS

The following table covers the signals sent to the boiler control system as described in the previous sections.

Table 3.1 GT to boiler control signals

Signal designation	Function	Logic	Boiler action	Signal type
GT purge cycle	Indicates that the GT is in purging mode and that the boiler shall start it's purging procedure	closed: GT in purging mode	The boiler executes the purging procedure (if started previously)	Indication
GT standstill	Indicates the GT speed is equal or lower 15% rated speed GT is not burning fuel	closed: speed equal or lower 15% rated speed	Resets the Boiler purge time elapsed signal	Indication
GT on-load	Indicates that the generator CB is closed (generator supplying electrical energy)	closed: CB is closed	The boiler may operate	Indication
GT emergency stop	Indicates that the GT operation is stopping due to an emergency situation	open : GT operation stopped	Boiler shall stop operation	Indication
GT stop	Indicates that the GT starts execution of the common stop procedure	open : GT stops operation	Boiler shall stop operation	Indication
GT available	Indicates the GT is ready for start-up	closed : GT ready for start-up	Boiler may be started	Indication
GT at rated speed	Indicates that the GT is running at rated speed	closed : GT running at rated speed		Indication
GT alarm		open : alarm	Used for boilers with additional burner	Indication

All signals are of digital type

3.4 BOILER TO GT CONTROL SYSTEM INTERFACE SIGNALS

The following table covers the signals sent to the GT control system as described in the previous sections.

Table 3.2 Boiler to GT interface signals

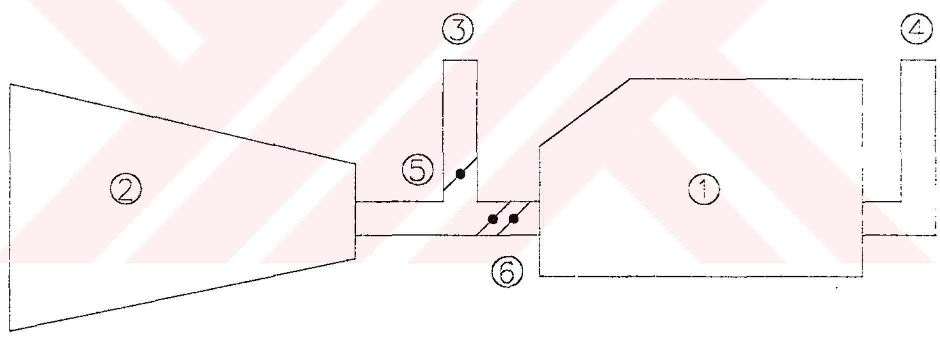
Signal designation	Function	Logic	GT action	Signal type
Boiler flap closed	Indicates that the boiler flap is in closed position	closed : boiler flap closed	Indication of boiler flap position	Indication
By pass flap open	Indicates that the by pass flap is in open position	closed : by pass flap is open	Indication of bypass flap position	Indication
Boiler purge time elapsed	Indicates that the boiler has completed the purging procedure	closed : purge time elapsed	GT may ignite	Indication
Boiler emergency stop	Indicates that the boiler operation is stopped due to an emergency situation	open : boiler operation stopped	GT emergency stop is initiated	Safety chain
Boiler alarm/failure	Indicates that an alarm situation or the failure of the boiler has happened.	open : boiler alarm / failure	Indication	Indication

CHAPTER FOUR

THE SYSTEM DESIGN OF A WASTE HEAT RECOVERY BOILER

4. INTRODUCTION

The main concept of a waste heat recovery boiler (WHRB) is that, the boiler uses the exhaust gas of the gas turbine as a heat source. That's why it is called waste heat recovery boiler. Gas turbine uses LPG, natural gas, naphtha, diesel or fuel oil as fuel, and produces electricity. During this procedure, the gas turbine breeds high amount of exhaust gas at high temperature, approximately at 500°C. Unless recovered by the boiler, this gas is wasted.



1 – Waste heat recovery boiler
2 – Gas turbine
3 – By-pass stack
4 – Boiler stack
5 – By-pass flap
6 – Boiler flaps

Figure 4.1 A fundamental schematic of a cogeneration system

Connecting the turbine outlet to a boiler as shown in Figure 4.1, the boiler can use the exhaust gas as a heat source, and can produce steam and hot water. The turbine's outlet gas at 500 °C, becomes 150-200 °C at the boiler's outlet.

From the boiler's point of view, there are six important subjects in a cogeneration system. These six subjects and their locations on the system are shown in Figure 4.1.

1. The boiler itself
2. The gas turbine
3. By pass stack
4. Boiler stack
5. By pass flap
6. Boiler flaps

There are two stacks on the boiler, one of which is by pass, and the other one is boiler stack. By pass stack is used to transfer the hot exhaust gas from the turbine to open air when the boiler is out of order or off line. Boiler stack is the one from which warmed and used exhaust gas goes out, when the boiler is on line.

To provide the sequential working of the system, some interface signals are used between the gas turbine control and boiler control. These signals are described in detail in Chapter 3.

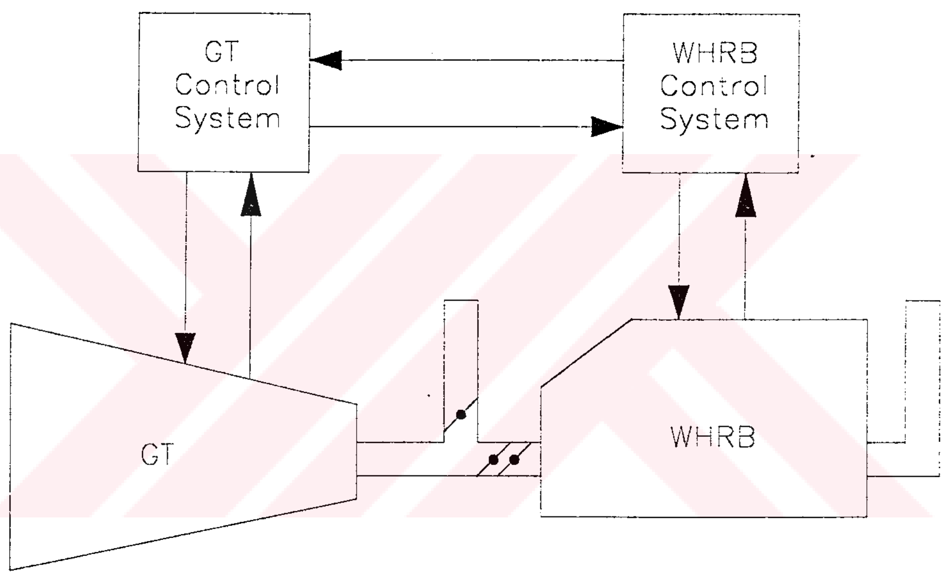


Figure 4.2 Two control systems work interactively

There are some interlocks to provide the boiler safety. These are the pressure, level of the boiler, emergency shut down of the turbine and so. If this safety chain is not obtained, the boiler must not work.

The two critical controls are the level and the pressure control of the boiler. These are realized with two separate controllers.

PLC system collects all the inputs and produces the outputs. Some of these inputs are, failure, and running signals of the motors, some temperature values, the safety chain, and so. To monitor some temperature values, resistance thermometers or thermocouples are used. These signals have the temperature information from test wells.

The full perspective of the control system can be viewed in the P&ID given in Appendix-A.

In this work, the aim is to prepare a control system for a WHRB which is 12 bars. The maximum steam flow allowed from the boiler is 11100 kg/h. The GT has a power of 4,5-5 MW and the flue gas from the turbine is 486 °C. As general there is one element level control.

4.1 SCENARIO OF THE SYSTEM

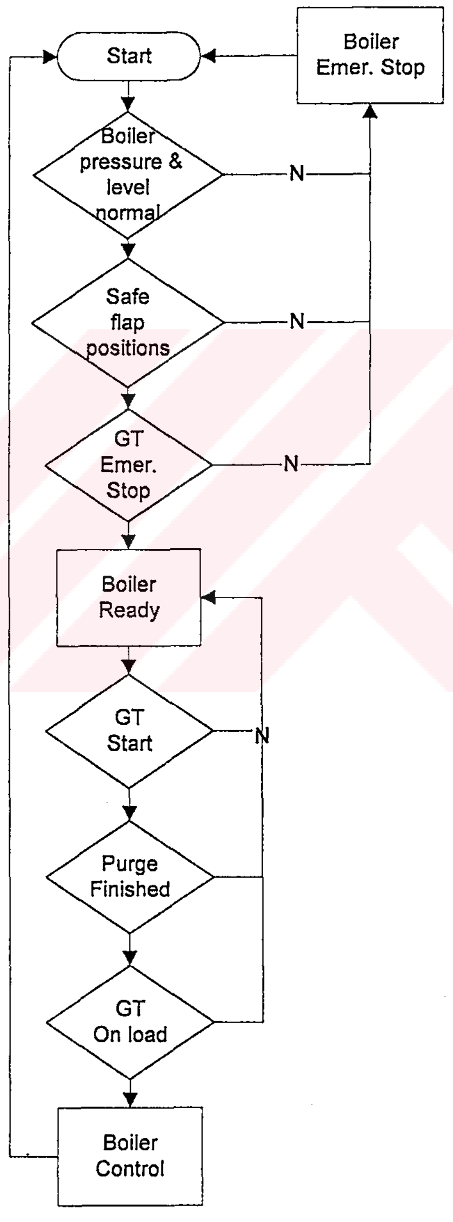


Figure 4.3 The flowchart of the system

As seen from Figure 4.3, until the boiler start command, boiler pressure, boiler level, turbine emergency shut down and the safe flap positions must be provided. Otherwise, the boiler cannot start.

After starting the boiler, boiler waits until the boiler purge signal from the turbine control system. Purge is an operation which cleans the collected gases from the stacks. In these systems, first boiler, then by pass purge is accomplished. Purge signal comes from the turbine when its generator is running, but no fuel is burned. This means, the generator turns and there is an air flow into the boiler, not a waste exhaust gas. This air circulation cleans the harmful gas gathering.

To provide a boiler purge, after the "Purge start" signal comes from the turbine, boiler flap starts to open. After it is fully open, the bypass flap starts to open. Never, and never both flaps must be closed. After the bypass flap is closed and the boiler flap is opened, some time is waited, and boiler stack is cleaned. After a certain time, then bypass flap starts to open. After it is fully opened, boiler flap is closed, and by pass purge is realized.

After purge time exceeds, "Purge finished" signal is sent to turbine control system. This signal is also a permission for the turbine to be ignited. After all these turned out, the system is running and the run-time controls are to be performed.

4.2 THE STACKS AND THE FLAPS

The boiler has two stacks- or chimneys, one called the bypass stack, and the other one named the boiler stack. These stacks include flaps inside, which are opened or closed due to pressure control and steam production.

These stacks and their flap positions are one of the most critical parameters in the waste heat recovery system. The default position of the bypass flap is open, and default position of the boiler flaps are closed, to provide the turbine work without the boiler. The boiler flap consists of two separate flaps to prevent any leakage of gases into the boiler. A fan called *seal air fan,* is placed on the system to blow air between these two flaps when they are closed.

In most of the systems, the boiler flap is controlled on-off, and the bypass flap is controlled proportionally. The bypass flap is controlled with the drum pressure controller, and the boiler flap is controlled from the PLC according to interface signals from the turbine.

The flaps are turned with pneumatic or electrical actuators. Any error of these actuators is very critic, because a stuck flap can damage the boiler. This condition must also stop the gas turbine, because if the flaps cannot be moved into the safe position, the turbine and the boiler can be both lost (the back pressure problem).

4.3 SAFETY INTERLOCKS

There are a few signals and conditions that must be provided in order to commission the boiler properly. These signals are called safety interlocks or safety conditions, where a combination if these is called the "safety chain". Safety chain is the most significant condition in the boiler control, and if this chain is lost because of any signals, the boiler needs to emergency stop.

4.3.1 Drum Pressure

A pressure switch turns an electric circuit on or off at a preset pressure. This pressure is called the set point of the switch. The switch usually is a micro switch or a mercury switch. A Bourdon tube, a diaphragm, or a bellows can actuate the switch.

The contacts in a pressure switch may be normally open or normally closed when the pressure is below the set point. For example, the contacts in a normally open switch remain open until the pressure rises above the set point. Then the sensing element makes the contacts snap to the closed position. The contacts open again when the pressure falls below the set point. The contacts in a normally closed switch remain closed until the pressure rises above the set point. Then the contacts snap open and remain open until the pressure drops below the set point again.

Most switches contain two sets of contacts - one normally open and the other normally closed. Thus, the switch will work regardless of which type of contacts is needed in a particular installation.

A pressure switch has a deadband. That is, the pressure must fall below the set point before the switch resets to its normal position. The amount of deadband is the difference in pressure between the set point and the reset point.

The important use of pressure switch in waste heat recovery boiler is in limiting pressure. The pressure of the steam of the drum must not exceed an upper limit. If it is so, the boiler can be damaged, and this may cost much.

In our system, two pressure switches are used to provide safety. These pressure switches are connected in series, and normally closed contacts are used. In case, if any of them becomes open because of the high pressure limit is exceeded, the boiler becomes out of order, bypass flap is opened and boiler flap is closed in order not to take gas into the boiler but let the gas get out to open air from the bypass stack.

4.3.2 Drum Level

A level measurement can be made with a level switch. This switch can sense upper or lower limits it is set to.

In this system, low level of the boiler is very important. The water travels a long way in the boiler with the pipes. If drum - or boiler level is too low, that means the water in the system is not enough, the boiler may be damaged because the pipes are burned.

To prevent this event, drum level is another element in the safety chain. If the "Level Low-Low" switch is on, it means the system is unsafe and boiler fails. By pass flap opens and boiler flap closes. Boiler is then off-line, and turbine goes on producing electricity. The exhaust gas no longer enters the boiler, and it is set free from the bypass flap.

4.3.3 Turbine Emergency Shut Down

If an emergency occurs in the turbine working conditions, this signal from turbine control systems comes to boiler control system. This signal is also a boiler fail, because when the turbine emergency shuts down, the boiler can no longer work, and this fails the boiler. This signal is described in previous sections.

When all these three conditions are all right, then the boiler is ready to start. By means of pushing a push button, which is called the "Reset", the boiler is now ready, and "BOILER READY" message appears on the screen. If any of these three conditions is lost, the boiler can not be started until they become normal, and boiler is reset again.

4.4 FLAP POSITIONS

Except the safety chain, there are some variable to be tested or controlled. These are given in the following chapters.

The flap positions are to be followed in order to control the boiler. These positions are learned from limit switches, which are mounted on the flaps and the stacks.

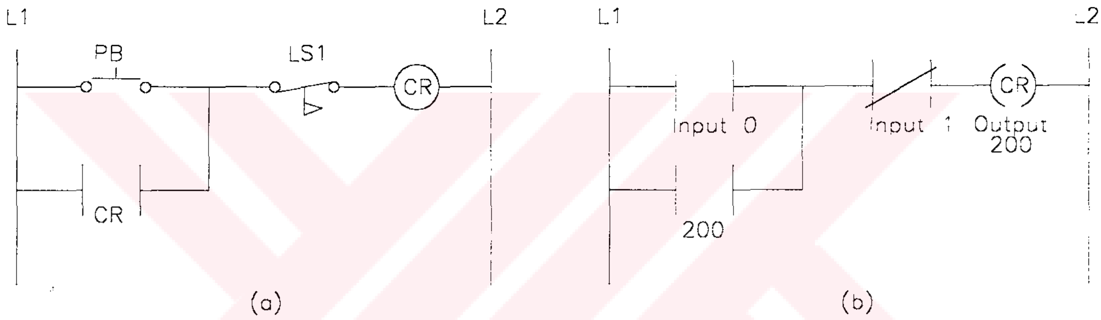
When the flap moves as much as it can, it presses the switch showing the position. This is an opening or closing contact, and this signal is sent to the PLC system. After the boiler is reset, "start" button must be pressed in order to turn on the boiler. "By pass flap open" and "Boiler flap is closed" is one of the conditions of boiler start. These flaps must be in positions so called "safe positions".

4.5 THE BOILER CONTROL SYSTEM WITH PLC

Programmable logic controllers are used in industry where intelligent and/or automatic control processes are needed. Compared to relay logic systems, PLCs are easy to install, operate and maintain. PLCs reduce the costs usually associated with control system implementation, modification, the stocking of spare parts, and troubleshooting [9].

PLCs are intelligent control systems designed to perform sequential industrial processes. The minimum configuration of a PLC system consists of three parts: the central processing unit (CPU), the input/output (I/O) section, and the programming device.

The two most common programming languages are the ladder diagram (LAD) format and the statement list (STL) format (commonly called the Boolean language). The LAD format is commonly used and easy to understand. The program can be organized in a linear or straight line form, which is ideal for most of the control applications. Figure 4.4a shows a relay circuit diagram. Figure 4.4b is the equivalent ladder diagram, and Figure 4.4c is the equivalent statement list program of this circuit in the controller. The addressing format varies for different models and manufacturers.



Address	Instruction word	Data
CLR		
0	LOAD	
1	OR	0
2	AND-NOT	200
3	OUT	1
4	END	200

(c)

Figure 4.4 A hard-wired circuit and its correspondent PLC applications

In this project, a Telemecanique TSX 37 Micro series PLC was used in order to accomplish the control of the boiler [3]. PL7 Micro software is the programming software for TSX 37 PLCs operating under Windows.

This programming language offers ;

• A graphic language, Ladder language for reproducing relay diagrams, and is especially suitable for combinational processing and offers basic graphic elements, that is contacts and coils. Numeric calculations can be written within operation blocks. Ladder language is preferred in the project, because of its advantages in both debugging, understanding and writing the program.

• A Boolean language, Instruction List language, which is in the form of STL described above, is a "machine language" for writing logical and numerical processing operations.

These language includes predefined function blocks (timers, counters, etc.), which can be supplemented by dedicated applications, (analog, communication, counter, etc.) and specific functions (time management, character strings, etc.).

4.5.1 Addressable Objects

Input/output bits - These bits are the "logical images" of the electrical state of the I/O. They are stored in the data memory and are updated on each scan of the task in which they are configured.

Internal bits - Internal bits %M0 to %M255 are used to store intermediate states during execution of the program.

System bits - System bits %S0 to %S127 monitor correct operation of the PLC as well as progression of the application program.

4.5.2 Addressing I/O Module Objects

Addressing of the main word and bit objects in I/O modules is defined by the following characters:

%	**I or Q**	**X,W or D**	**x**	.	**I**
Symbol	**Type of object**	**Format**	**Position**		**Channel No**
	I = Input	**X** = Boolean	**x** =		**I** = 0 to 127
	Q = Output	**W** = Word	position in		or MOD
		D = Double word	the rack		

• **Type of object:** The physical inputs and outputs of modules exchange this information implicitly on each scan of the task to which they are attached.

• **Format (Size):** For objects in the Boolean format, the X can be omitted. Other types byte, word and double word is described in the following sections.

• **Channel position and number:** The base modularity of the TSX 37 is ½ format. The positions for each type of TSX37 PLC (base and extension) are shown in the Figure 4.5.

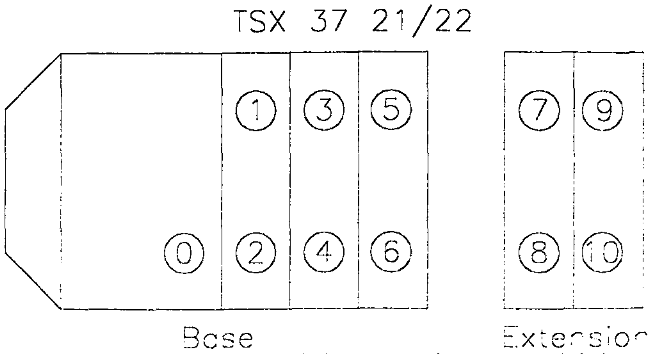


Figure 4.5 Slot numbers of a Telemecanique TSX 37 series PLC

Standard format modules are addressed as two superposed ½ format modules. For example, a 64 I/O module is viewed as two ½ format modules: a 32 input ½ module located in position 5 and a 32 output ½ module located in slot 6.

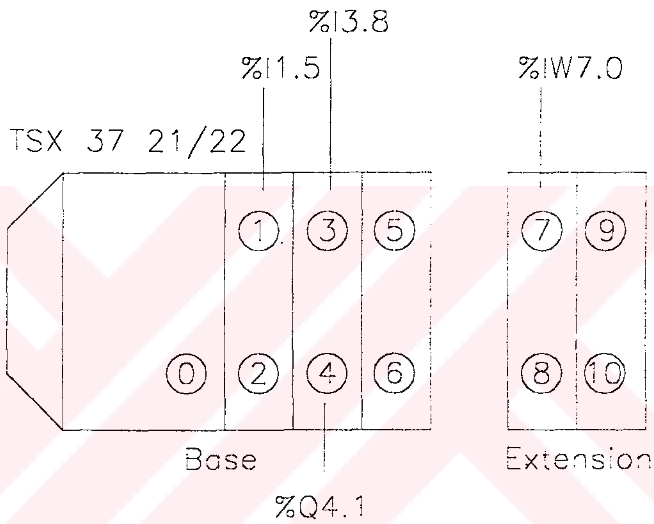


Figure 4.6 Channel addressing

Some addressing examples are shown in Figure 4.6.

4.5.3 Addressing Words

Addressing words different from I/O modules in PL7 language is done in the following way:

%	**M, K or S**	**B, W, D or F**	**I**
Symbol	**Type of object**	**Format**	**Number**
	M = internal	**B** = byte	
	K = constant	**W** = word	
	S = system	**D** = double word	
		F = floating point	

• **Type of object**

M : Internal words which store values during execution of the program. They are stored in the data zone within a single memory zone.

K : Constant words which store constant values or alphanumeric messages. Their content can only be written or modified by the terminal. They are stored in the same place as the program. They can therefore use the EPROM memory as their support.

S : System words. These words provide information of the system and operations on the application.

• **Format**

Object words can be addressed by PL7 software in four different formats:

B byte: this format is used exclusively for operations on character strings

W single length: these 16 bit words can contain an algebraic value between 32,767 and -32,768

D double length: these 32 bit words can contain an algebraic value between 2,147,483,647 and - 2,147,483,648. These words are stored in the memory on two continuous single length words.

F floating point: the floating point format used is that of the IEEE standard. Words are 32 bits long, which corresponds to single length floating point numbers.1285.28 or 12.8528E2 are two examples for floating point values.

4.5.4 The Explanation Of The Program

The inputs to the PLC in the control system is listed in the Table 4.1 below:

Table 4.1 PLC Inputs

Input No	Input Definition	Internal Flag
% I 1.0	Boiler emergency shut down	% M79
% I 1.1	Drum pressure very high	% M51
% I 1.2	Drum level very low / A	% M52
% I 1.3	Drum level very low / B	% M53
% I 1.4	Turbine emergency shut down	% M54
% I 1.5	Turbine normal stop	% M55
% I 1.6	Boiler start	% M56
% I 1.7	Boiler stop	% M57
% I 1.8	By pass flap opened	% M58
% I 1.9	By pass flap closed	% M59
% I 1.10	Boiler flap opened	% M60
% I 1.11	Boiler flap closed	% M61
% I 1.12	Purge start	% M62

Table 4.1 (continued)

% I 1.13	Turbine on load	% M63
% I 1.14	By pass flap close	% M64
% I 1.15	By pass flap open	% M65
% I 3.0	Boiler flap close	% M66
% I 3.1	Boiler flap open	% M67
% I 3.2	By pass flap fault	% M68
% I 3.3	Boiler flap fault	% M69
% I 3.4	Boiler ready	% M70
% I 3.5	Boiler pressure high pressure alarm	% M71
% I 3.6	Boiler level low level alarm	% M72
% I 3.7	Feed water pump 1 failure	% M73
% I 3.8	Feed water pump 1 running	% M74
% I 3.9	Feed water pump 1 failure	% M75
% I 3.10	Feed water pump 1 running	% M76
% I 3.11	Seal air fan failure	% M77
% I 4.0	Seal air fan running	% M78
% I 4.2	Boiler water conductivity maximum	% M80
% I 4.3	Boiler water conductivity minimum	% M81

4.5.4.1 Boiler Start

The boiler start condition is: (Boiler ready) AND (No by pass flap fault) AND (No boiler by pass fault).

If all these conditions are obtained, pushing a "BOILER START" button will start the boiler until any of these conditions are destroyed or a "BOILER STOP" button is pushed. "Boiler ready" signals are a summary of safety interlocks. This is also called the safety chain. Any break in the chain, for example a low level alarm or a high pressure alarm occurs, the boiler will also get out of "Boiler Start" condition.

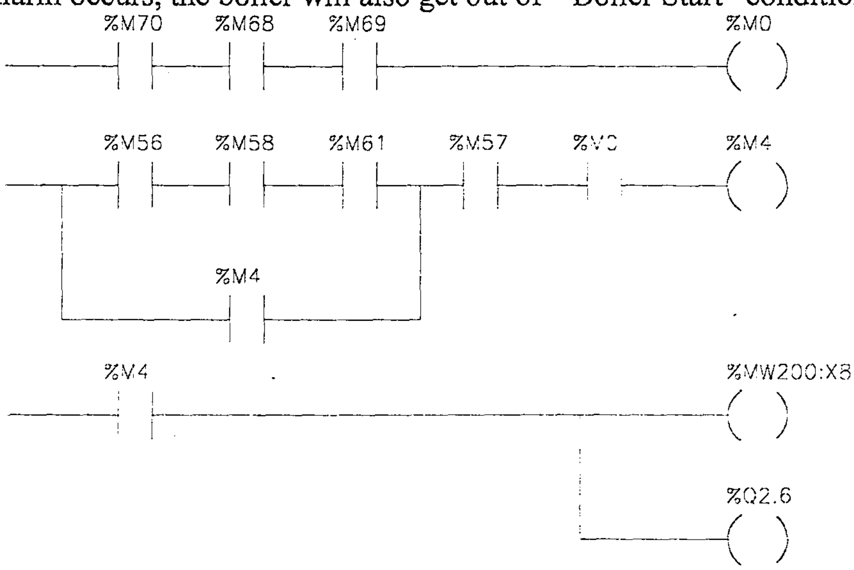


Figure 4.7 Boiler start

4.5.4.2 Ignition Start

Ignition start is a signal produced in the boiler control system and enables the turbine to ignite.

In the operation with boiler and turbine sequentially, if;

- Boiler purge is completed and
- By pass flap is open and
- Boiler flap is closed or in the operation mode without boiler, if by pass purge is completed and boiler is not started, the system send the "Ignition Start" signal to the turbine control system. This signal is cleared with only a "Purge start" signal coming from the turbine control system.

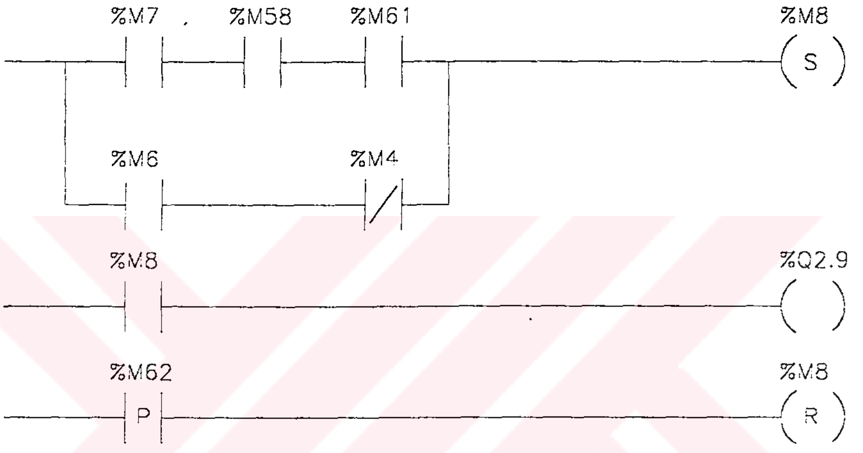


Figure 4.8 Ignition start

4.5.4.3 Turbine On Load

This signal is taken into PLC as input, in order to monitor the condition from the screen and to control the boiler flap.

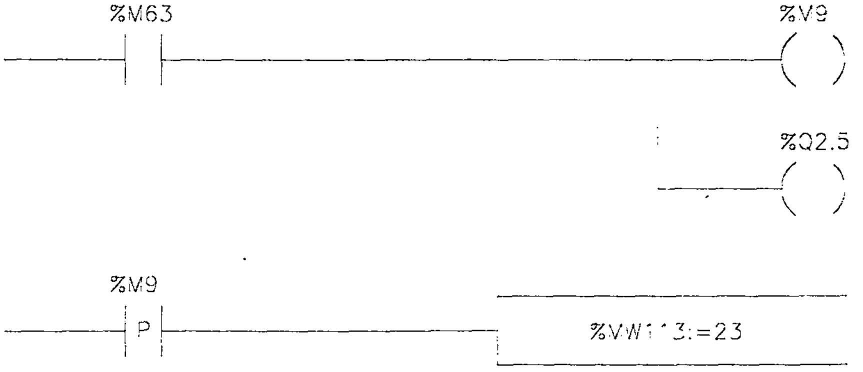


Figure 4.9 Turbine on load

4.5.4.4 Turbine Running Start

During the turbine operation, two things are important :

1.If the boiler is not working, the by pass flap must be open
2.If the boiler is working, the boiler flap must be open

If at least one of these conditions does not appear, this means a critical error, and both the turbine and the boiler must to be stopped. This part of the program achieves this job.

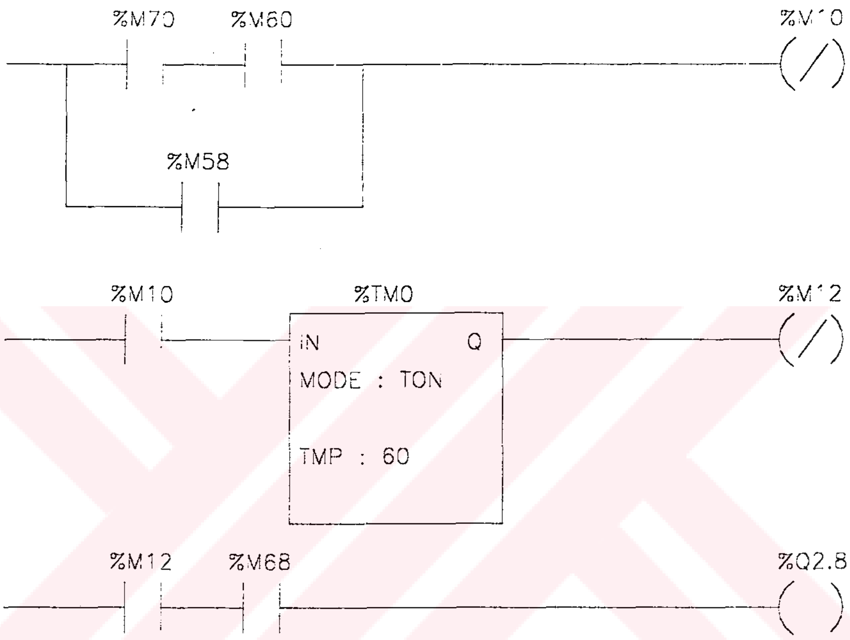


Figure 4.10 Turbine running start

4.5.4.5 By Pass Flap Open

If the boiler is off-line, or the boiler safety chain is not obtained, the by pass flap must be in its default position, open. Additionally, just if the turbine is off-line, using a manual switch, by pass flap can change position, which is test purposed (Figure 4.11)

4.5.4.6 By Pass Flap Close

If by pass purge cycle is completed and boiler flap is opened, by pass flap can be closed. Another alternative to close this flap is when the turbine is off-line, with a manual switch (Figure 4.12).

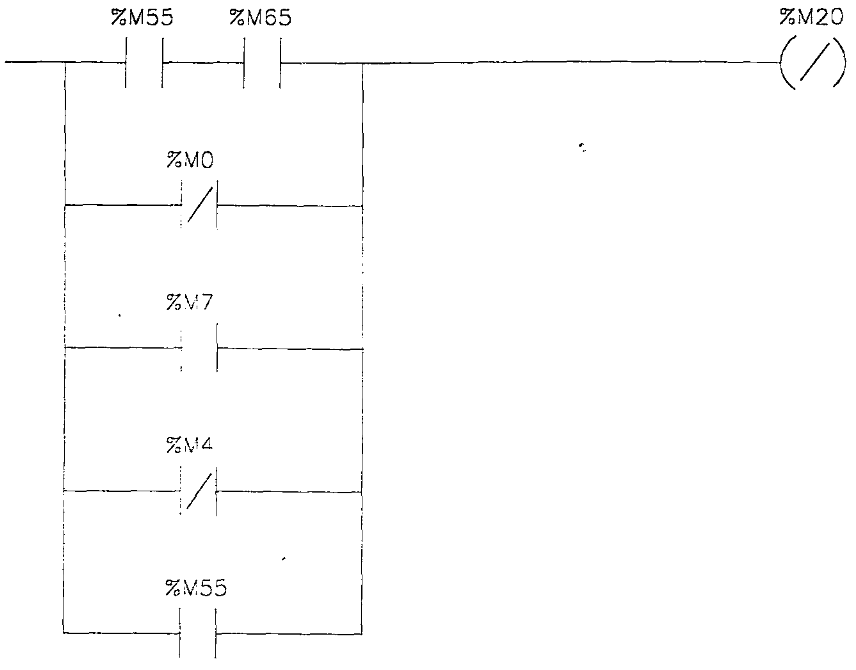


Figure 4.11 By pass flap open

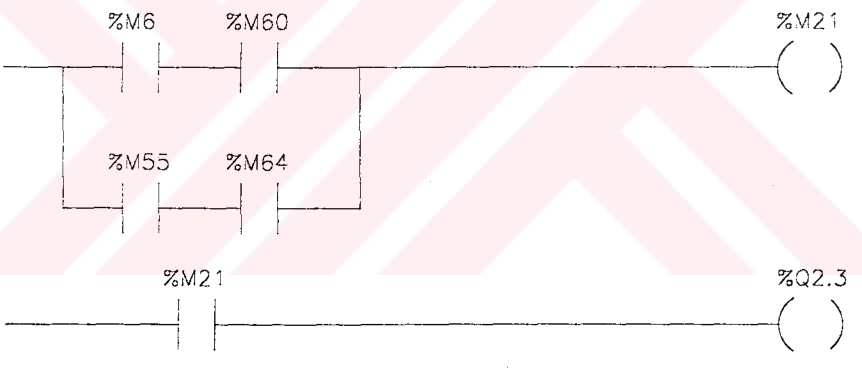


Figure 4.12 By pass flap close

4.5.4.7 Boiler Flap Open

If boiler purge cycle is completed or

1.Turbine is on load,
2.Boiler is safe and
3.No flap faults occur

the boiler flap can be opened. Also with an external switch, if the turbine is off-line, this operation can be accomplished.

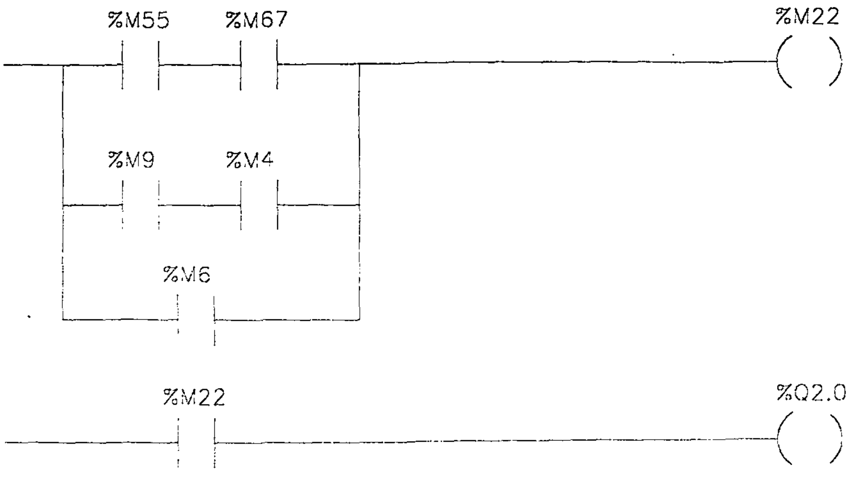


Figure 4.13 Boiler flap open

4.5.4.8 Boiler Flap Close

Boiler flap can be closed under the following conditions :

1. If the boiler purge cycle is completed, or
2. If the boiler is not started, or
3. Boiler is not safe and by pass flap is open,

Again, boiler flap can be closed with an external manual switch if the turbine is off-line.

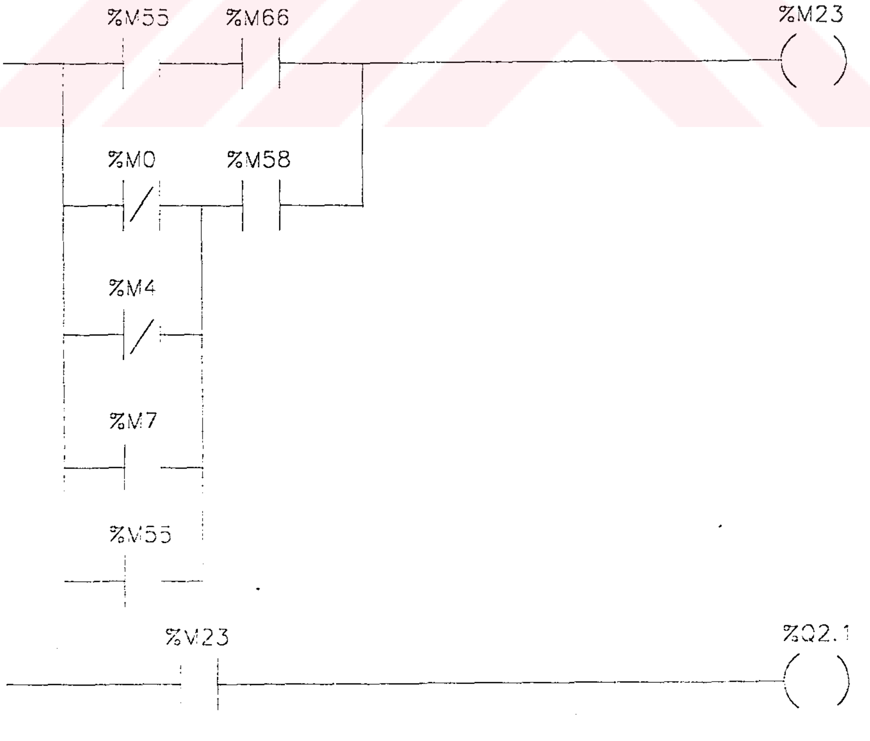


Figure 4.14 Boiler flap close

The most important thing about these flaps is that, at least on of them must be 100% open to improve safety.

4.5.4.9 By Pass Purge

By pass purge is accomplished when "Purge Start" signal comes from the turbine control system and if the turbine is not on load during this signal. This prevents accidental flap movements during on-load operation. By pass purge lasts approximately 30 seconds.

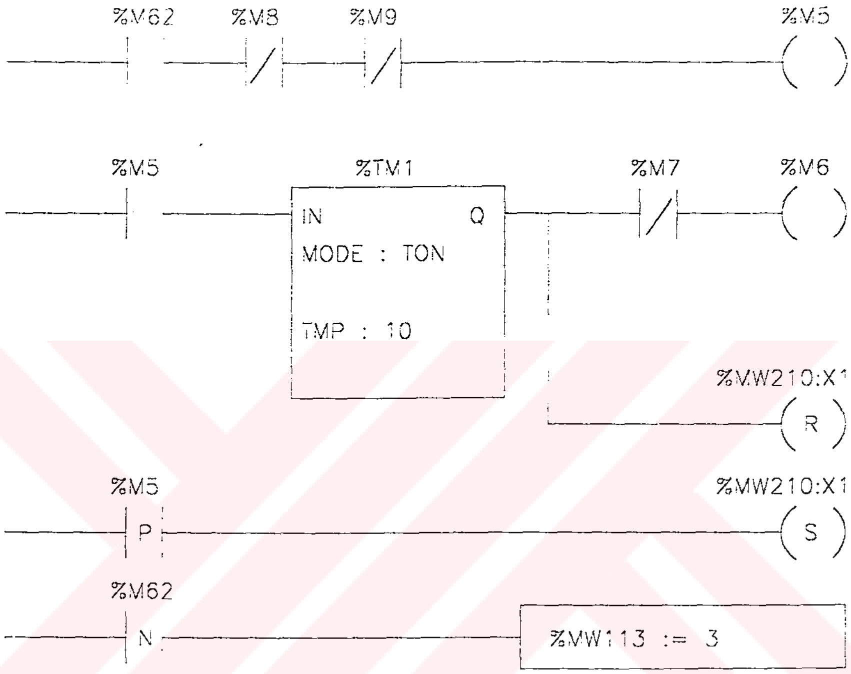


Figure 4.15 By pass purge

4.5.4.10 Boiler Purge

For the boiler purge to be realized, there are some conditions. All of these conditions must be available. These conditions are:

1. "Purge Start" signal from the turbine control is available and by pass flap is closed
2. By pass purge cycle is completed
3. The boiler is started
4. The boiler flap is closed.

The length of this section varies, it is approximately 90 seconds.

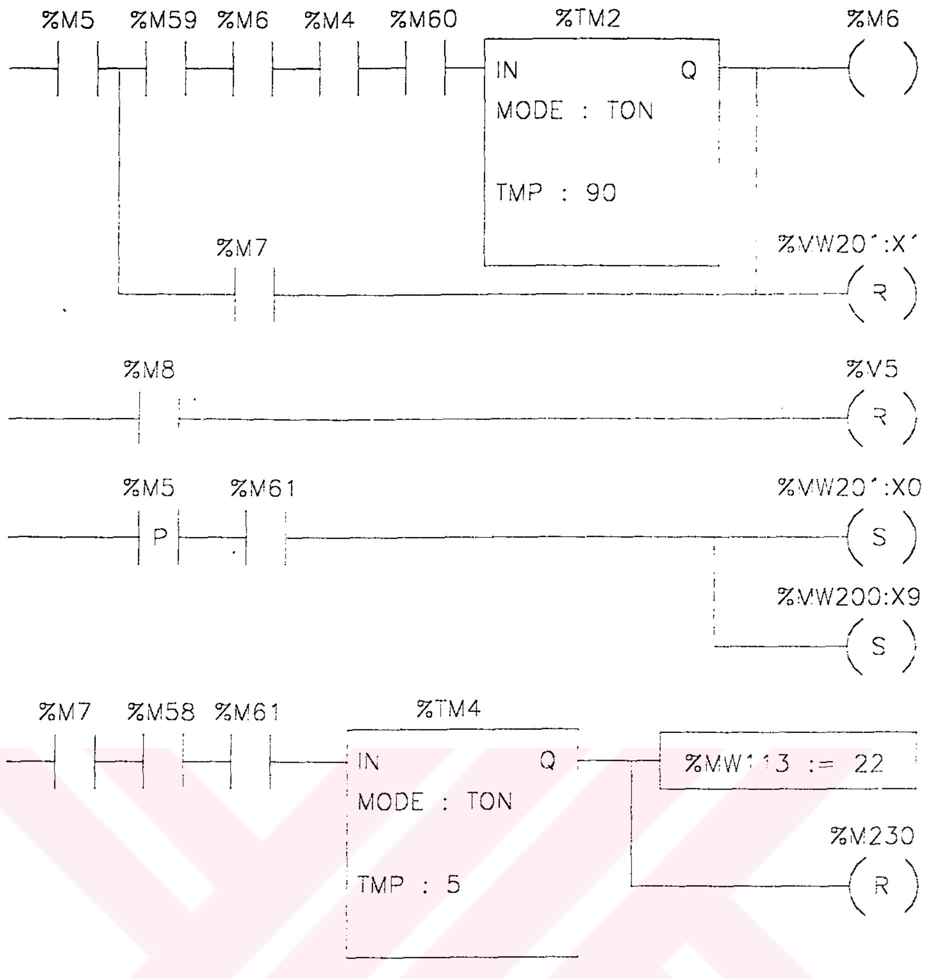


Figure 4.16 Boiler Purge

4.6 SEPARATE CONTROL LOOPS

As told before, there are two critical controls on the boiler control system, which are realized by two separate controllers but not with the PLC. The reason that these controls need controllers is the wish to control some parameters with the controllers easier than the PLC. Honeywell UDC 3000 series controller are used within this project.

4.6.1 Drum Level Control

A continuous equilibrium of the drum water must be provided. The fundamental principle of the control is very easy: an analog signal obtained from the level transmitter is taken into the controller, and compared with the set point signal of the controller, and the controller reacts according to the difference between these two values.

Some important things to be cared are shrink and the swell in the drum. If the used steam decreases, the shrink occurs. Although it is not real, the transmitter perceives a decreasing level. Also, if the used steam increases, the swell occurs. The transmitter can perceive an increasing level, but in fact this is not a real increase.

Drum level controls are very important because boiler loads are being varied to meet rather than operating at full capacity and wasting fuel and steam. The effects of pressure surges and steam flow on the drum level dictate the use of complex controls on this important parameters.

The steam drum is an integral part of a boiler (Figure 4.17).

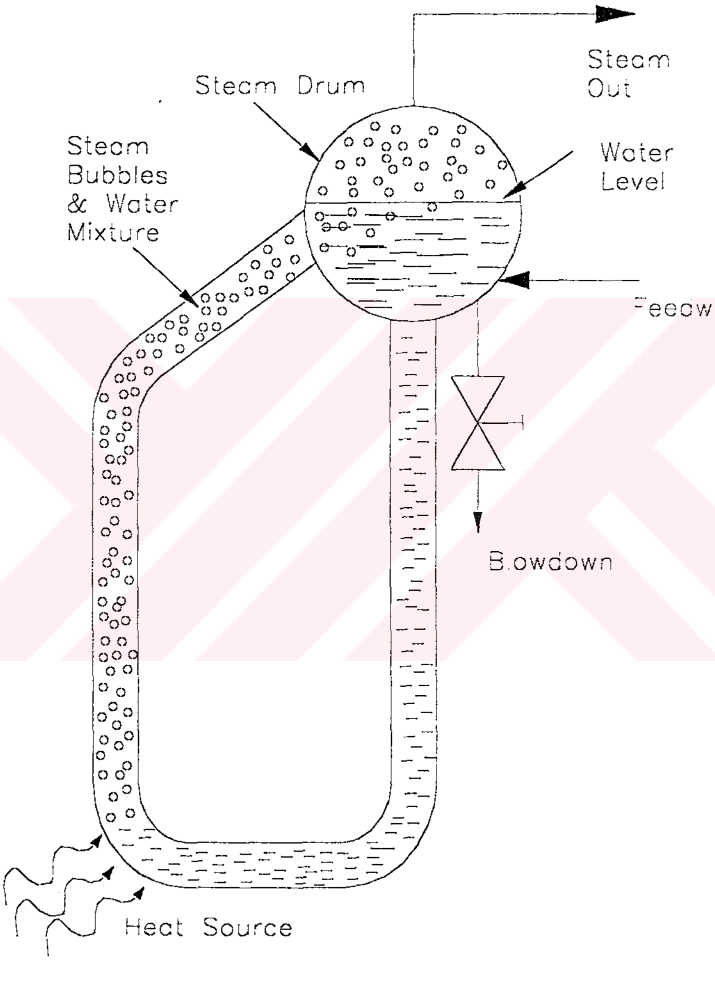


Figure 4.17 Boiler drum and water system

This vessel's primary function is to provide a surface area and volume near the top of the boiler where separation of steam from water can occur. It also provides a location for chemical water treatment, addition of feed water, re-circulation water, and blow down (see section 4.7.2), which removes the residue and maintains a specified impurity level to reduce scale formation. Because these functions involve the continual addition and loss of material, and because the volume changes, the water-steam interface level is critical.

Low water level affects the re-circulation of water to the boiler tubes and reduces the effectiveness of the water treatment. High level reduces the surface area, and can lead to water and dissolved solids to the steam distribution system. The objective is to maintain the water-steam interface at the specified level and provide a continuous mass balance by replacing every liter of steam and water removed with a liter of feed water.

The interface level is subject to many disturbances, primarily due to steam pressure. As steam pressure changes with the demand, there is a transient change in level due to the effect of pressure on entrained steam bubbles below the steam drum interface level. As pressure drops, a rise in level, called swell, occurs because the trapped bubbles enlarge. As pressure rises, a drop in the level called shrink occurs.

In this work, the single element system, which is the simplest approach in drum level control is used. The level is measured and feed water is regulated to maintain the level.

The required drum level is 400 mmH_2O. This is also the set point of the controller. The loop tuning of the controller is realized during run-time operation, and a few steps are followed :

1. The integral time of the controller is set at its maximum and the derivative time is set at its minimum, so proportional only control is provided. Then proportional band is reduced until oscillation begins. The period of this oscillation, which is also called the *natural period* is measured as the time between two successive crests or valleys.
2. The derivative time is set at 0,15 times the natural period, and the integral time is set at 0,4 times the natural period. There should be a 25% decrease in the new period of oscillation. If the new period is shorter than this, the derivative time is reduced; if the period is longer, the integral time is increased.
3. Then the proportional band is readjusted to achieve the desired degree of damping .

4.6.2 Drum Pressure Control

Drum pressure is another parameter controlled separately. The tuning method is the same as drum level control. The set point of the drum pressure is 11,5 bars. Again an UDC 3000 controller is used to control the pressure. Loop tuning procedure is again the same as the level control.

Drum pressure controller produces a current output which varies between 4 and 20 mA. This current output controls the by-pass flap actuator, which is proportional. By adjusting the position, the by pass flap controls the pressure.

The parameters of the controllers are given in Appendix-B.

4.7 OTHER FIELD INSTRUMENTS

Except the instruments described in previous sections, there are some auxiliary field instruments and systems which are monitored and controlled.

4.7.1 Pressure Indicators

Pressure indicators are necessary and used to provide the drum pressure locally. These indicators are located on the body of the drum and must not be moved.

4.7.2 Continuous Blow Down System

The high pressure drums have continuous blow down lines. These lines are controlled with an isolation valve and used to obtain the purity of the drum steam. To have a suitable steam flow, the conductivity of the drum water must be held at a constant value. If the conductivity increases, the continuous blow down valve opens and lets some mineralized water out, and decreases the conductivity.

4.7.3 Temperature Indicators

Temperature indicators are located on the boiler to make the operator able to monitor the temperature of some local areas.

4.7.4 Thermo Elements

To monitor and control some critical temperature values, the are located on the piping system. The sensor type of the thermo element can be thermocouple or Pt-100. Thermocouples are sensors which produce voltage with the change of the temperature while Pt-100 is a variable resistor.

CHAPTER FIVE
DISCUSSIONS AND CONCLUSIONS

Since number of the cogeneration systems increases day by day, the control problem of such systems are becoming more significant. The cogeneration systems are built to provide savings, therefore the efficiency is very important. A precise control system is desired in order to provide this efficient working.

One of the systems that was used in this work is one element level control. One element systems are sometimes insufficient to prevent swelling and shrinking described in previous chapter. Because one element level control systems depend on one parameter only, which is the signal coming from the level transmitter, swelling can cause the feed water valve close, and shrinking can cause the feed water valve open. In any case, an undesired condition occurs.

One way of obtaining a precise drum level control is to use three element control systems. Instead of one parameter, such systems control three parameters, and instead of feedback algorithm, involves feed forward algorithm. As told in Chapter 2, the feed forward systems are more expensive, but control is more precise.

The three element drum level control system adds a second control loop to manipulate the feed water valve. This system basically cascades the feed forward summer output of the two-element system into the feed water flow controller as a remote set point signal, as shown in Figure 5.1. This system provides close control during transient conditions because the two controllers provide independent tuning to minimize phasing interaction present in the two element approach.

The addition of a faster secondary loop assures an immediate correction for feed water disturbances. The drum level controller accurately compensates for effects of smaller unmeasured flows, such as blow down, volume changes, and mismatch between the two flow measurements. As in the two element system nearly all compensation for load changes is handled by the feed forward portion, while the drum level feedback loop provides only trimming action. An auto-manual station is provided to permit manual control of the feed water valve. This system can handle large and rapid load changes and feed water disturbances, regardless of boiler capacity.

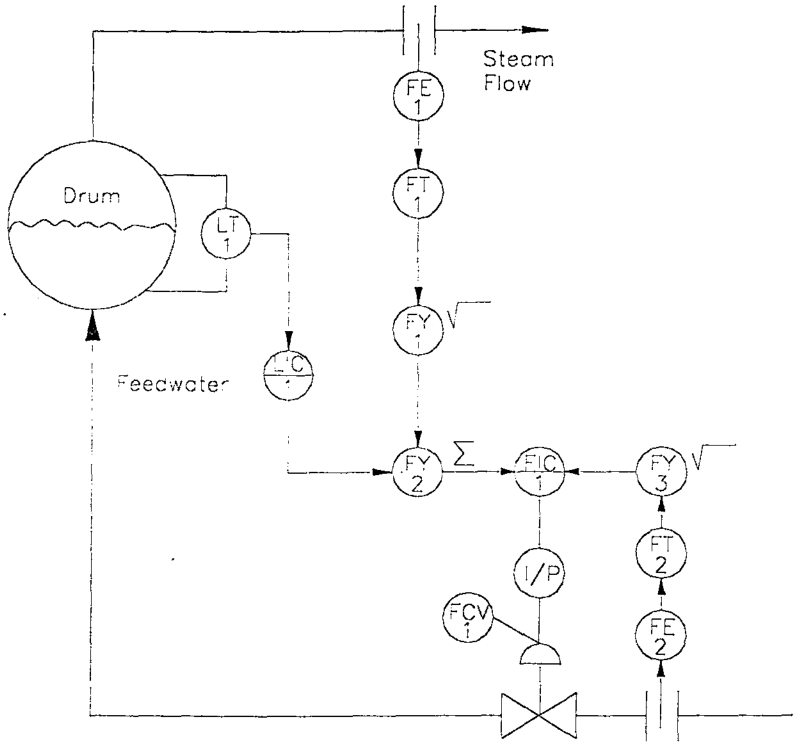


Figure 5.1 Three element system

To control the feed water, a remote set point, indicating, two mode controller used as a secondary controller in a cascade system. It includes square root extractions for the feed water transmitter plus an auto-manual control of the feed water valve. An approach is to use UDC 6000 instead of UDC 3000.

The internal cascade control property of the UDC 6000 controller is used. A cascade control system consists of one controller (the primary or master) controlling a variable that is to be kept constant value by adjusting the set point of a second controller (the secondary or slave) which controls another, faster variable that affects the first variable. The primary controller positions the set point of the secondary controller, and manipulates the control valve. The primary variable is slow, the secondary variable is much more faster. The secondary loop is introduced to reduce lags, make the whole operation more accurate.

The secondary controller may be regarded as composite final control element, positioned by the primary controller in the same way a single controller would position the control valve.

In order for cascade control to be effective, the response of the secondary loop must be faster than the response of the primary loop. Cascade control can improve systems where supply upsets are large and frequent, the primary variable responds slowly but large amplitude to supply upsets, and the supply variable can be controlled in a rapidly responding loop.

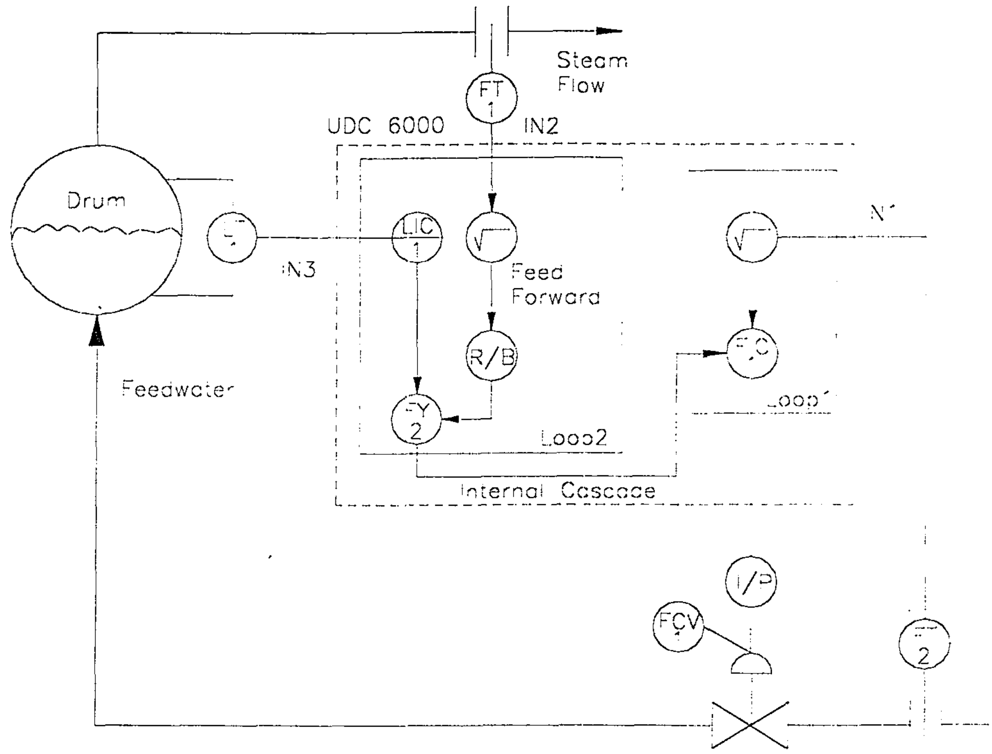


Figure 5.2 Three element drum level control using UDC 6000

In UDC 6000, steam flow and level are taken into the slave loop while the feed water flow is taken into the master loop as process variable.

Taking the steam flow as an input, the controller can sense the reason of the swelling and the shrinking, and understand if they are real or effects of steam flow. So the feed water valve control can be done more accurately. The boiler failure can be prevented.

Another way to build more accurate systems is to change the motor actuators of the flaps with pneumatic actuators. Motor actuators may fail easily, and they can cause problems in commissioning and operating, where pneumatic actuators are easier to maintain, control and operate.

In general, the designed system operates properly and uses the flue gas heat to produce steam. Some of the turbine interface signals are not required or play a significant role in the control, but they are monitored only for information. Some signals play important role and are critical for control.

The produced steam is approximately 11 tons per hour, and the proper operating value of the drum pressure is 11,5 bars, drum water level is 400 mm$H_2$0. These are the separate control loops which are controlled by UDC 3000 controllers.

As well as electrical systems, mechanical maintenance is also important, and many of the mechanical parts affect the efficiency of the boiler.

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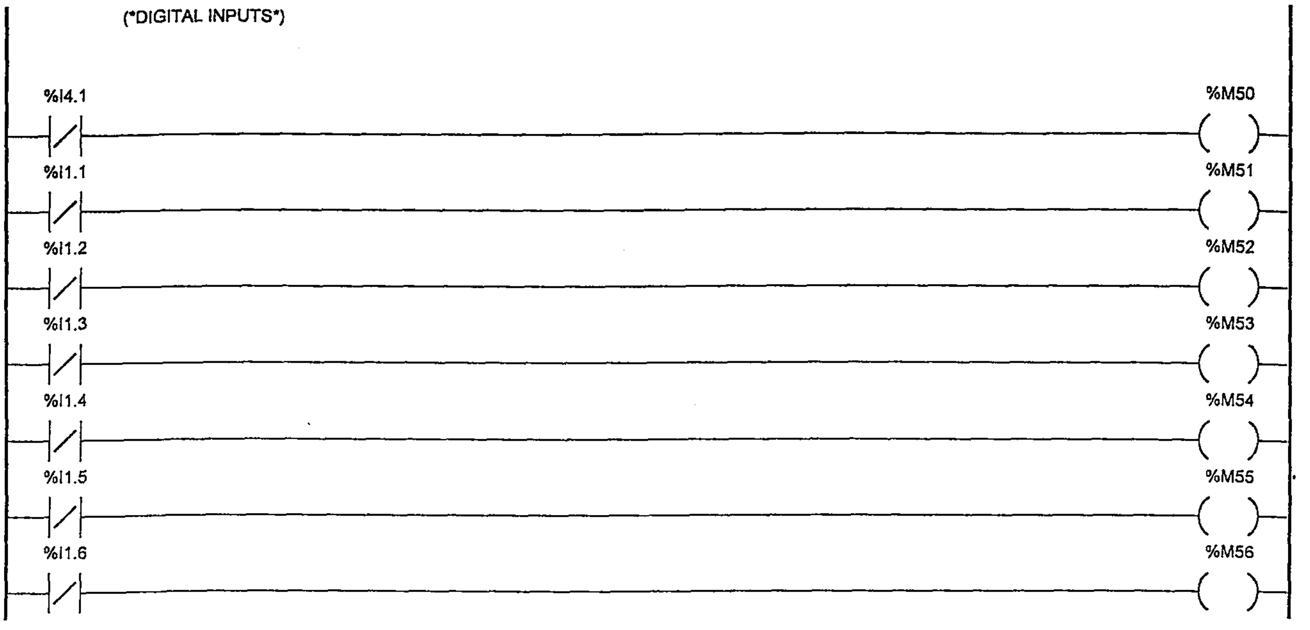
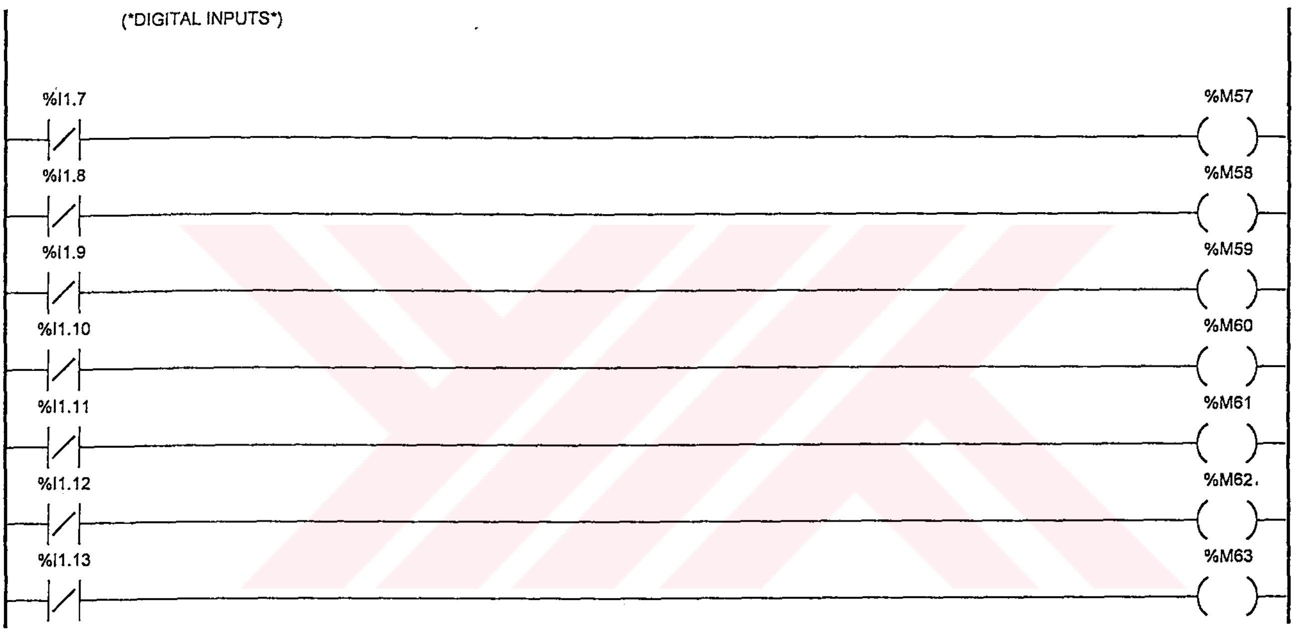
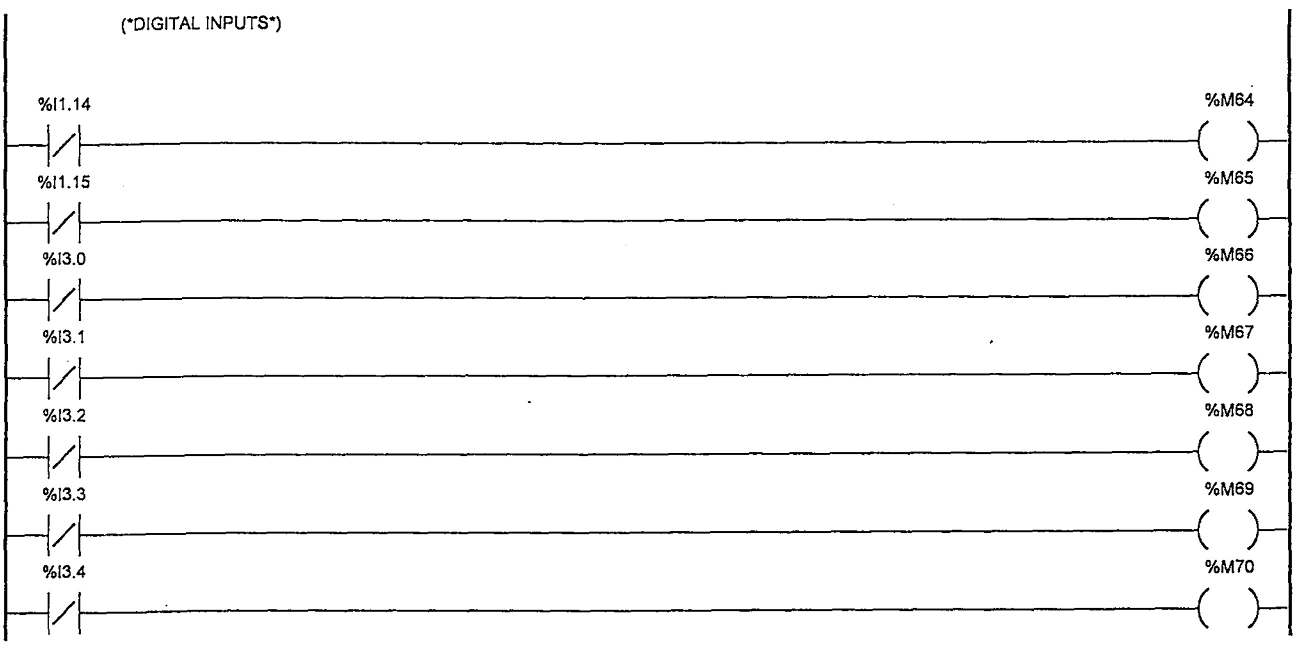
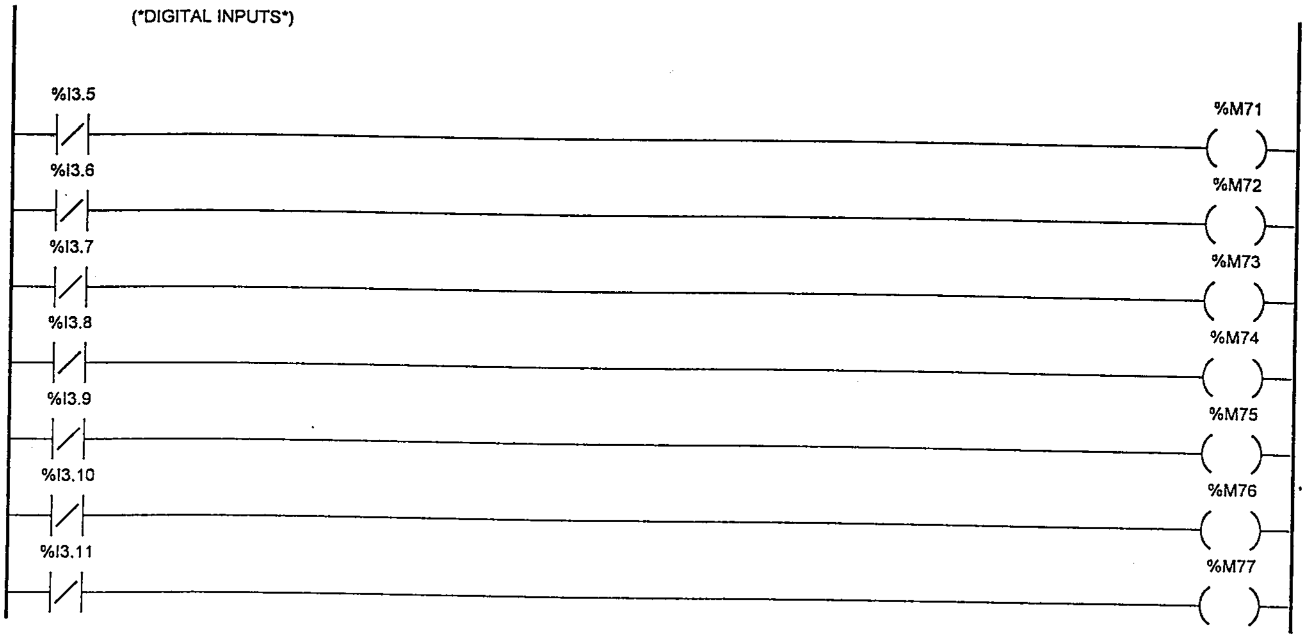
APPENDIX-A

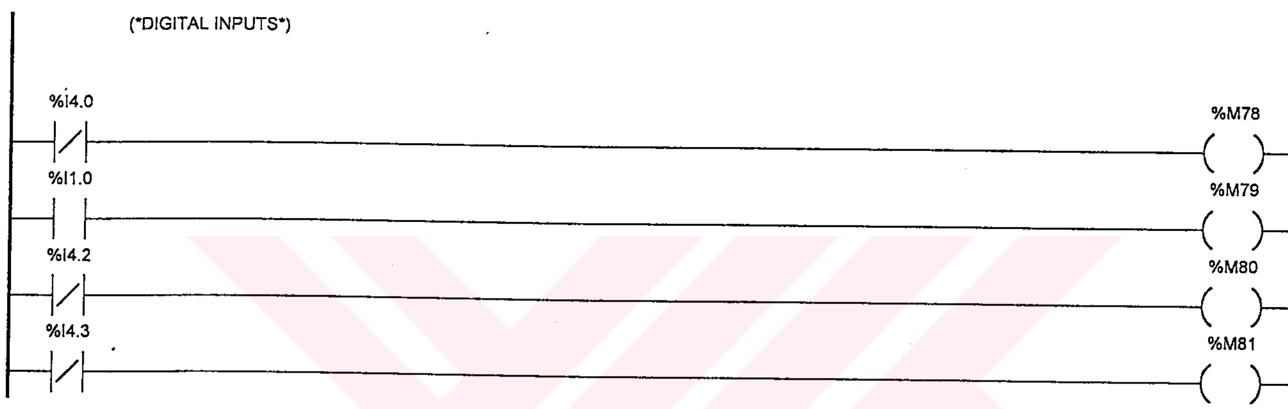
THE P&ID AND THE PLC PROGRAM OF THE WASTE HEAT RECOVERY BOILER CONTROL SYSTEM

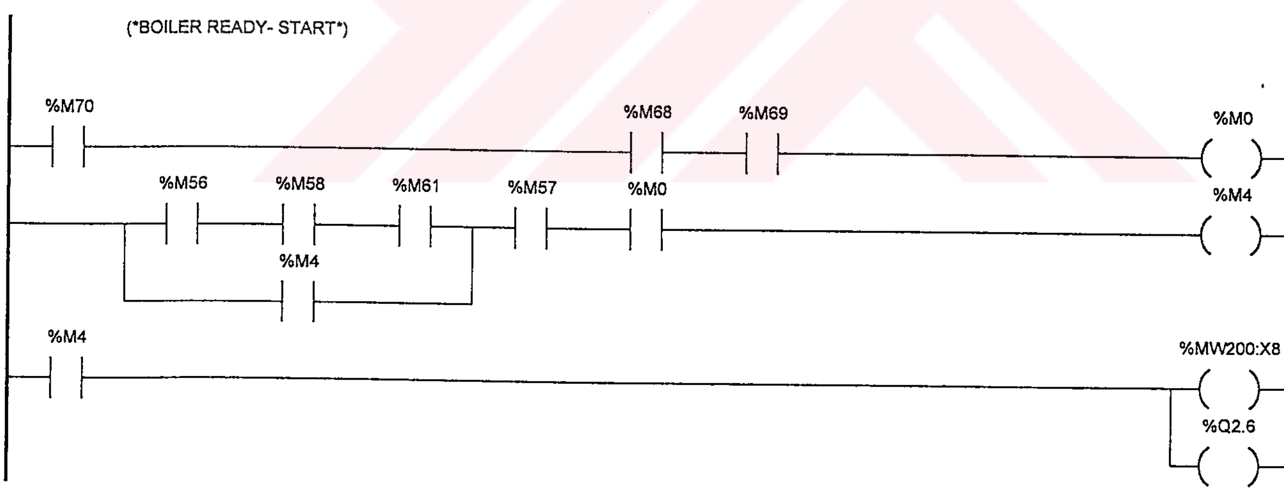

(*DIGITAL INPUTS*)
%I4.1
%M50
%I1.1
%M51
%I1.2
%M52
%I1.3
%M53
%I1.4
%M54
%I1.5
%M55
%I1.6
%M56

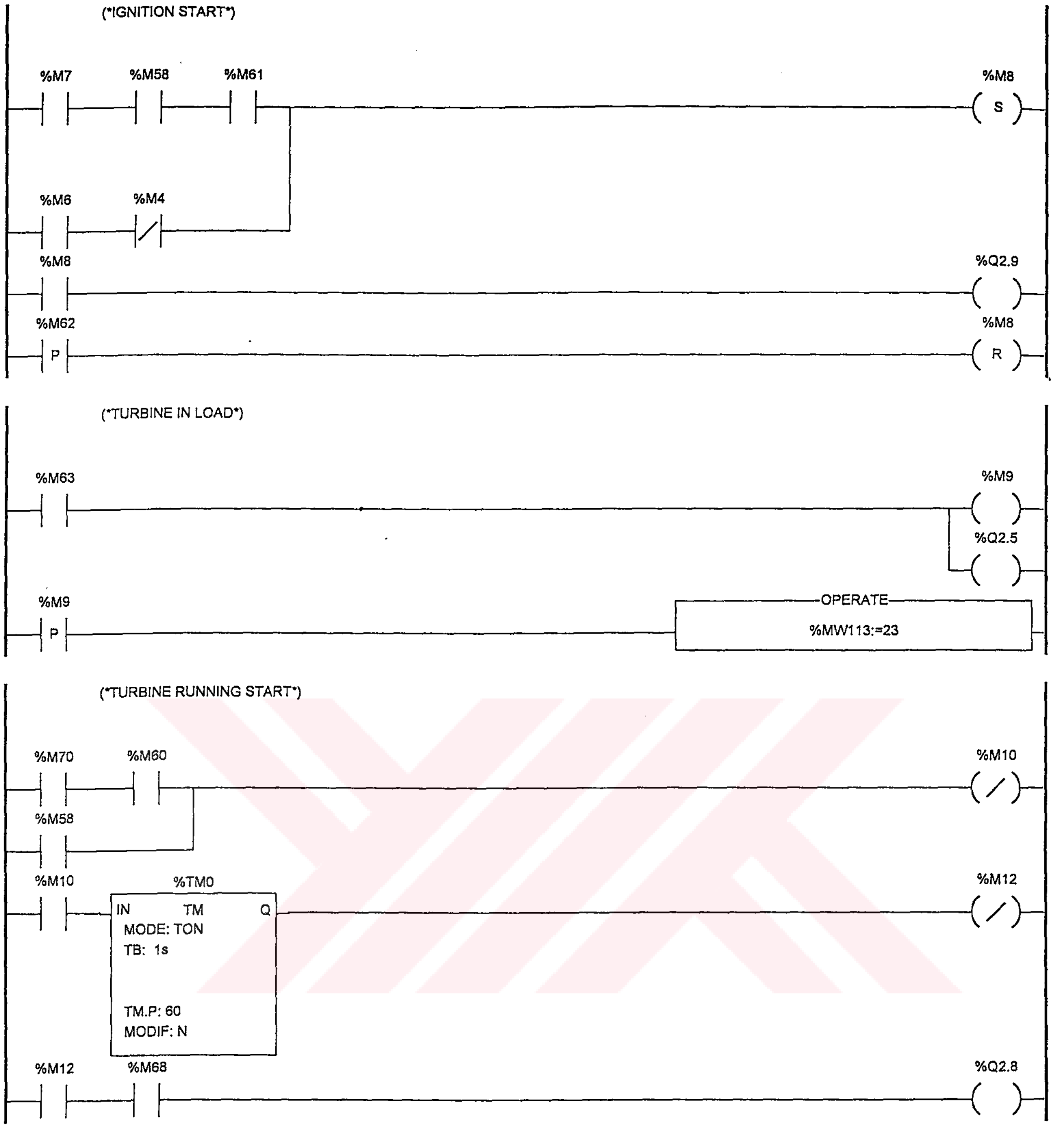

(*DIGITAL INPUTS*)
%I1.7
%M57
%I1.8
%M58
%I1.9
%M59
%I1.10
%M60
%I1.11
%M61
%I1.12
%M62
%I1.13
%M63

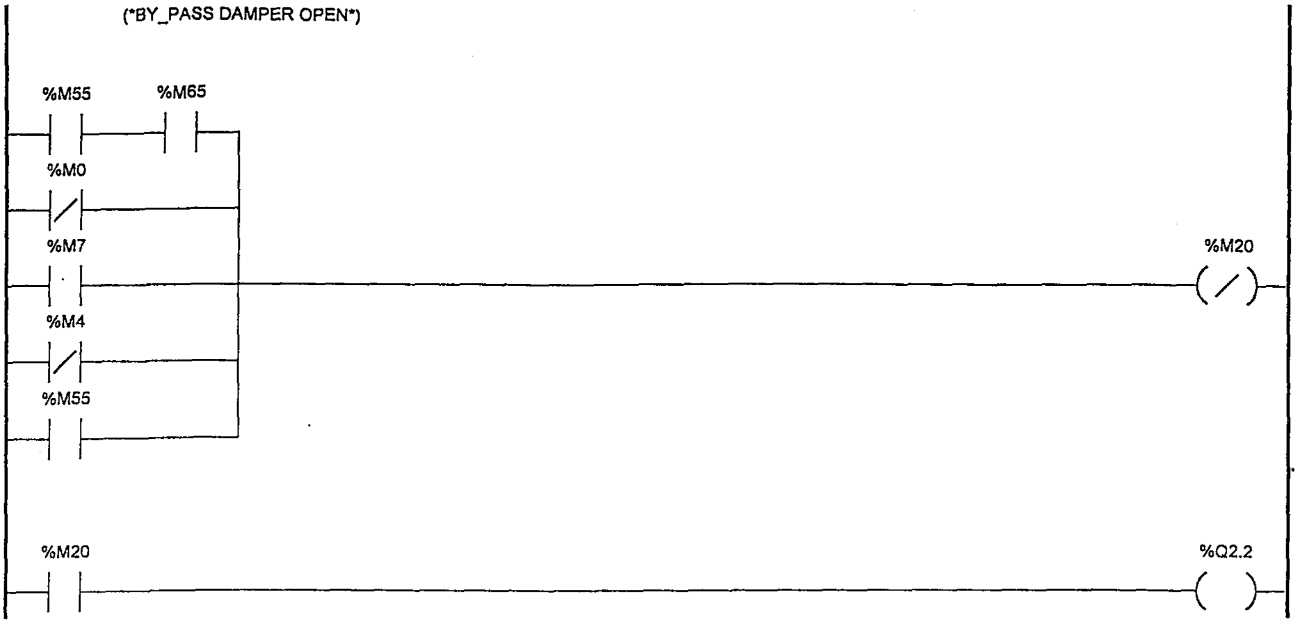

(*DIGITAL INPUTS*)
%I1.14
%M64
%I1.15
%M65
%I3.0
%M66
%I3.1
%M67
%I3.2
%M68
%I3.3
%M69
%I3.4
%M70

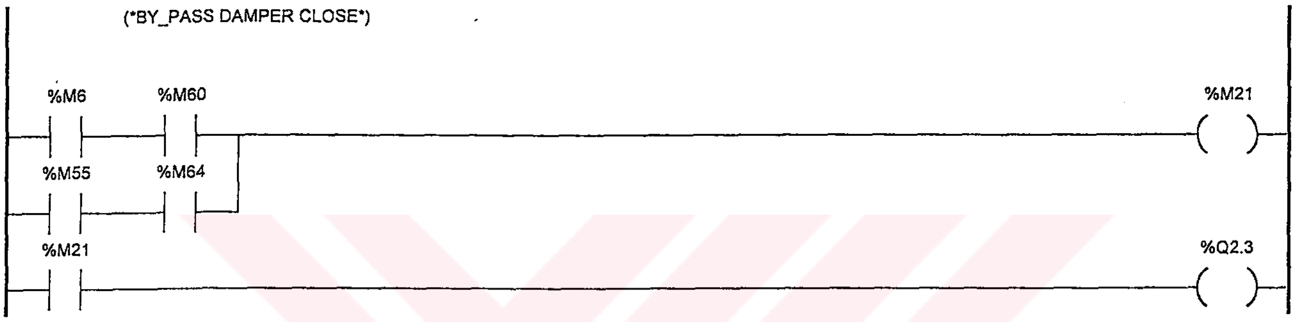

(*DIGITAL INPUTS*)
%I3.5
%M71
%I3.6
%M72
%I3.7
%M73
%I3.8
%M74
%I3.9
%M75
%I3.10
%M76
%I3.11
%M77

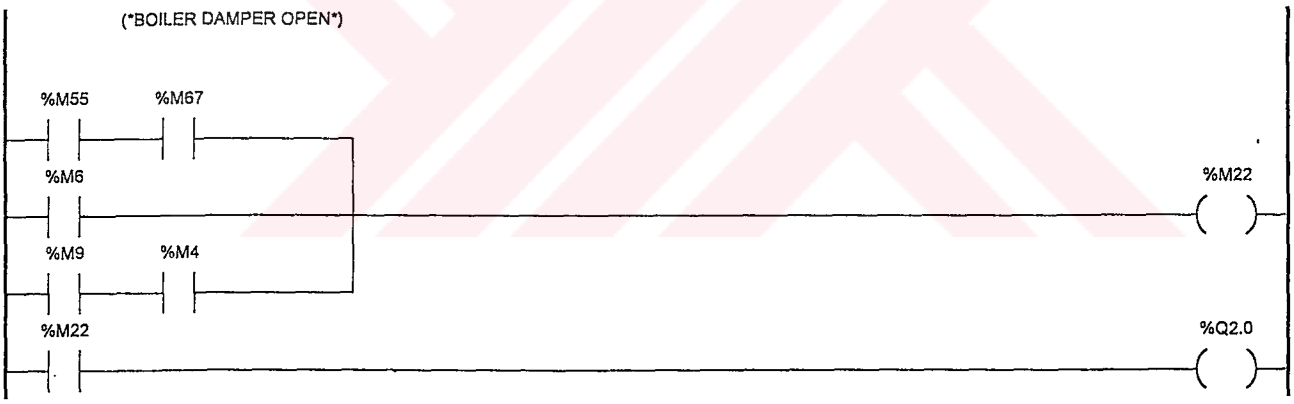

(*DIGITAL INPUTS*)
%I4.0
%M78
%I1.0
%M79
%I4.2
%M80
%I4.3
%M81

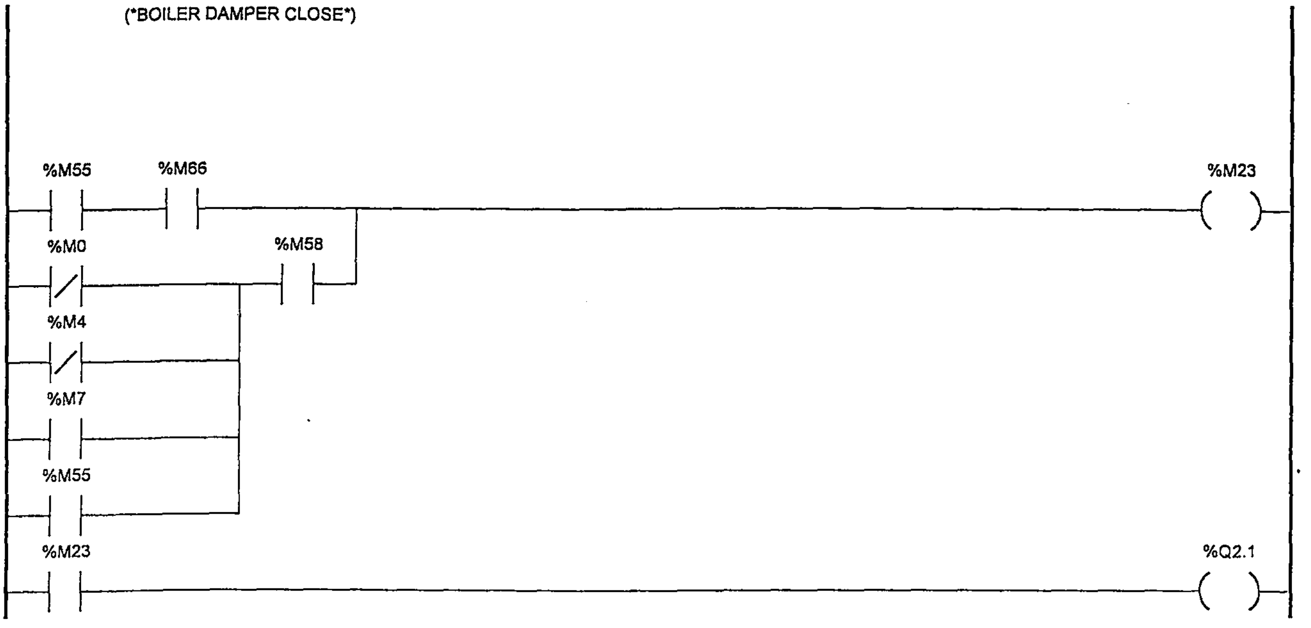

(*BOILER READY- START*)
%M70
%M68
%M69
%M0
%M56
%M58
%M61
%M57
%M0
%M4
%M4
%M4
%MW200:X8
%Q2.6

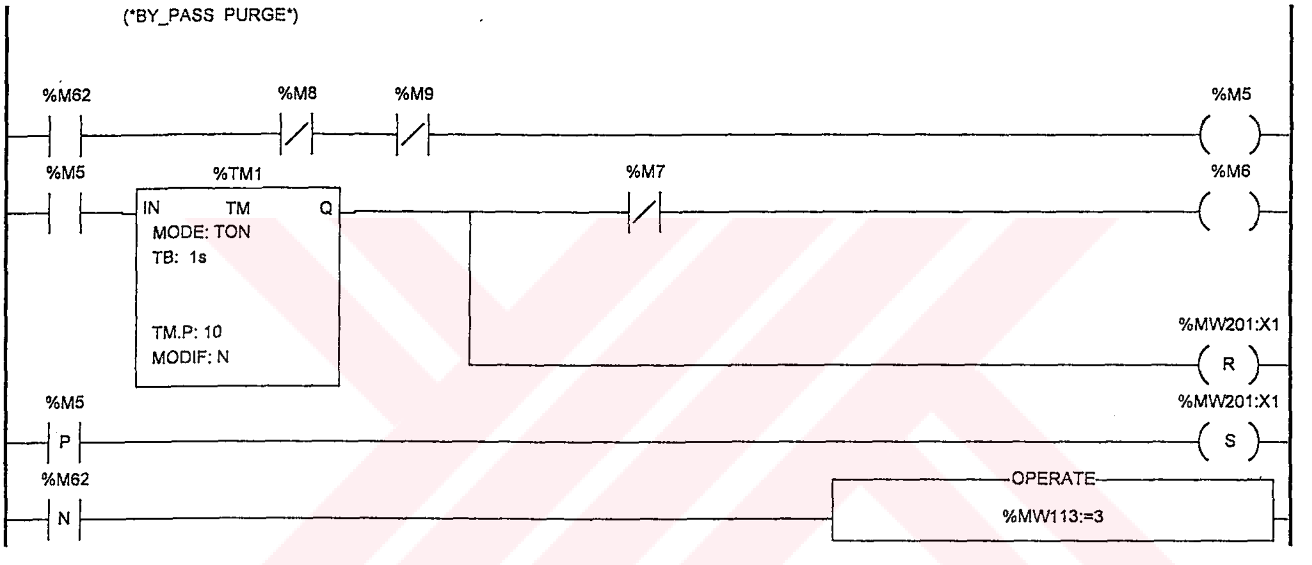

(*IGNITION START*)
%M7
%M58
%M61
%M8
S
%M6
%M4
%M8
%Q2.9
%M62
P
%M8
R
(*TURBINE IN LOAD*)
%M63
%M9
%Q2.5
%M9
P
OPERATE
%MW113:=23
(*TURBINE RUNNING START*)
%M70
%M60
%M10
%M58
%M10
%TM0
IN
TM
Q
MODE: TON
TB: 1s
TM.P: 60
MODIF: N
%M12
%M12
%M68
%Q2.8

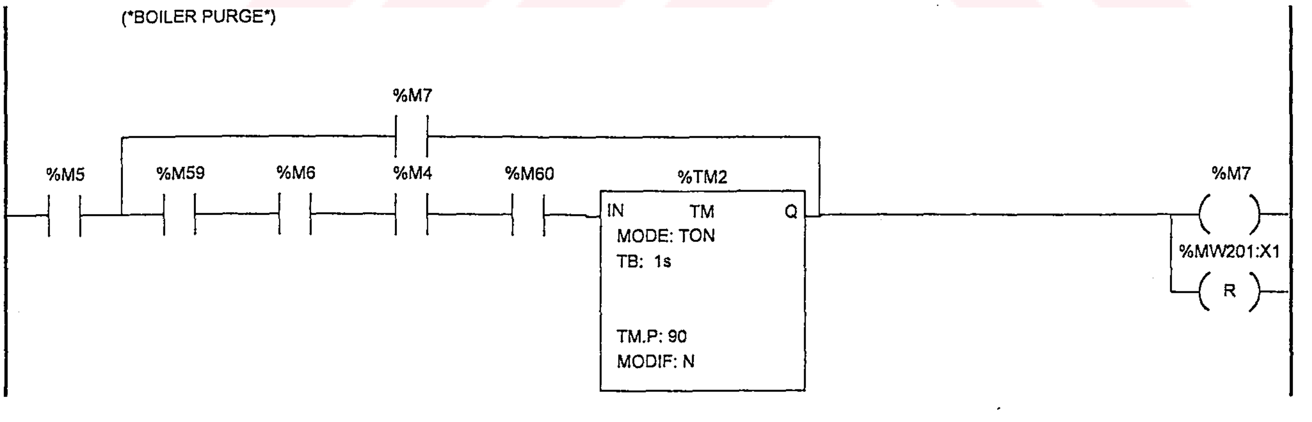

(*BY_PASS DAMPER OPEN*)
%M55
%M65
%M0
%M7
%M20
%M4
%M55
%M20
%Q2.2

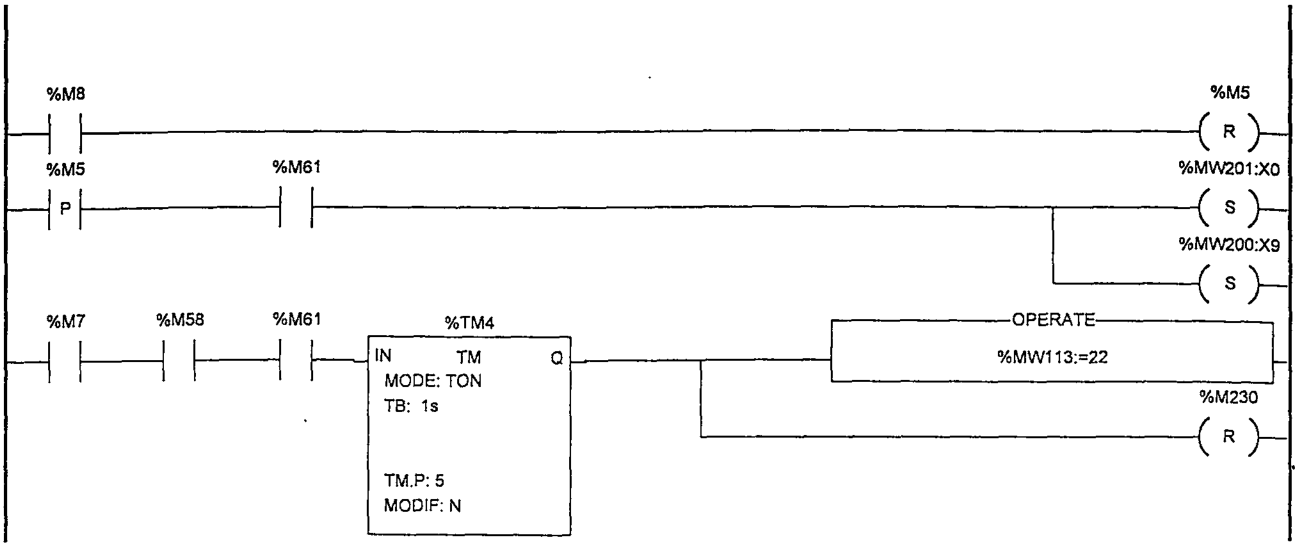

(*BY_PASS DAMPER CLOSE*)
%M6
%M60
%M21
%M55
%M64
%M21
%Q2.3

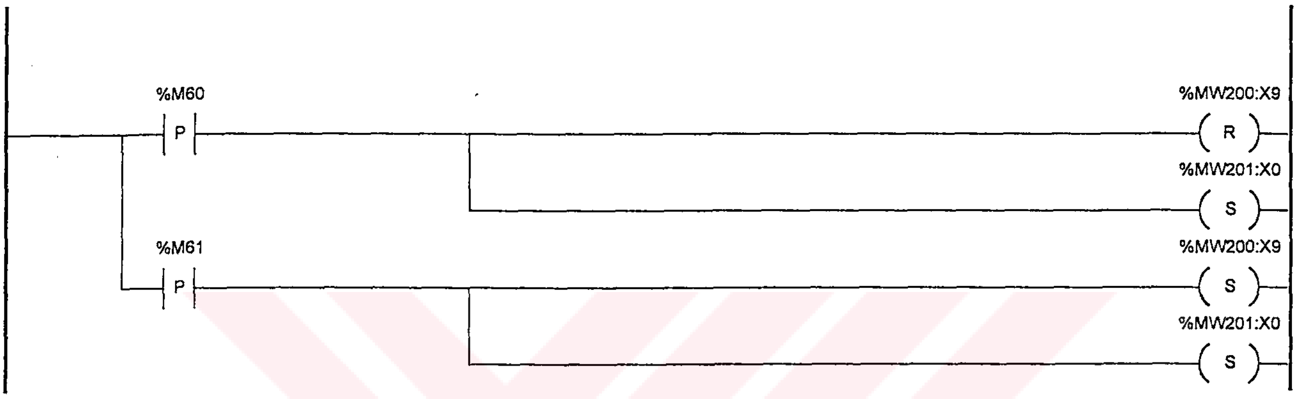

(*BOILER DAMPER OPEN*)
%M55
%M67
%M6
%M22
%M9
%M4
%M22
%Q2.0

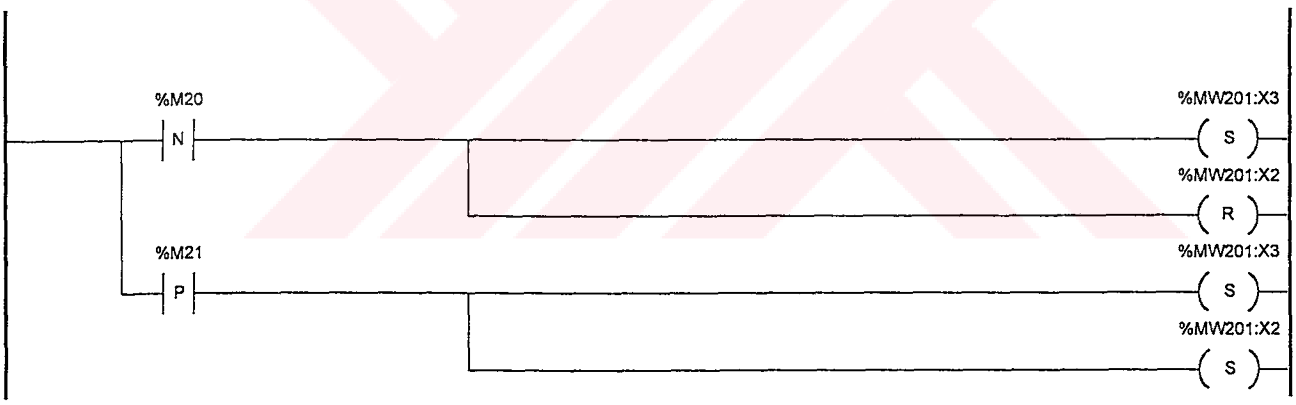

(*BOILER DAMPER CLOSE*)
%M55
%M66
%M23
%M0
%M58
%M4
%M7
%M55
%M23
%Q2.1

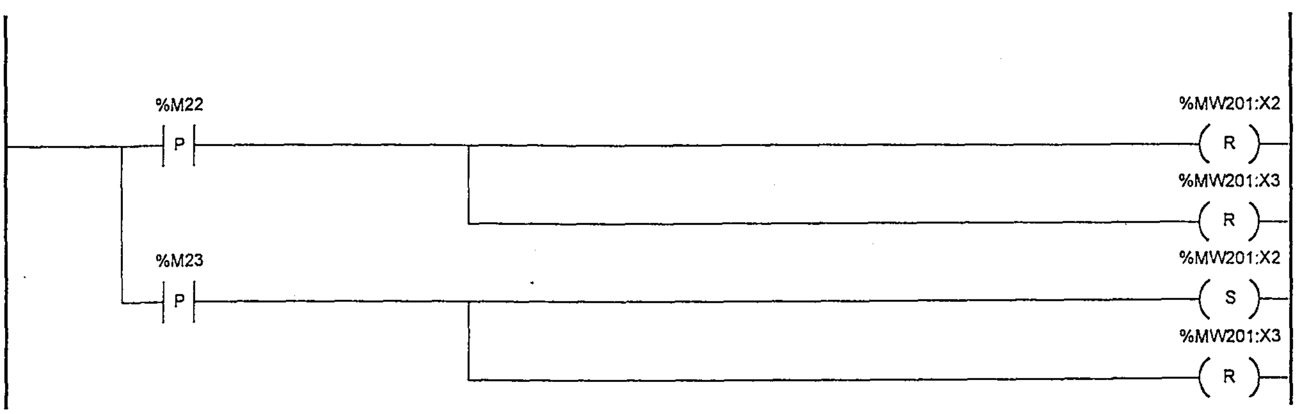

(*BY_PASS PURGE*)
%M62
%M8
%M9
%M5
%M5
%TM1
IN TM Q
MODE: TON
TB: 1s
TM.P: 10
MODIF: N
%M7
%M6
%MW201:X1
R
%M5
P
%MW201:X1
S
%M62
N
OPERATE
%MW113:=3

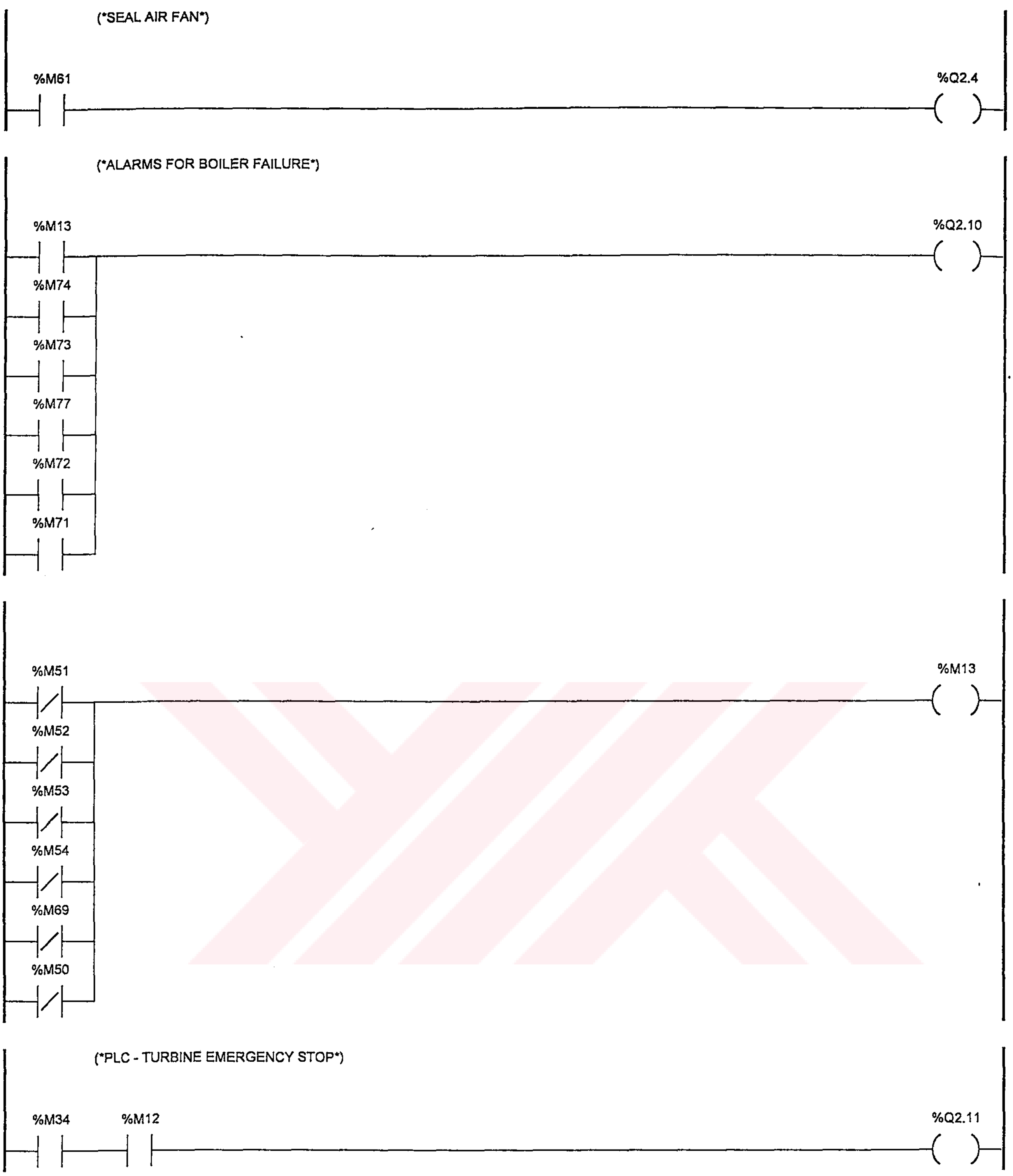

(*BOILER PURGE*)
%M7
%M5
%M59
%M6
%M4
%M60
%TM2
IN TM Q
MODE: TON
TB: 1s
TM.P: 90
MODIF: N
%M7
%MW201:X1
R

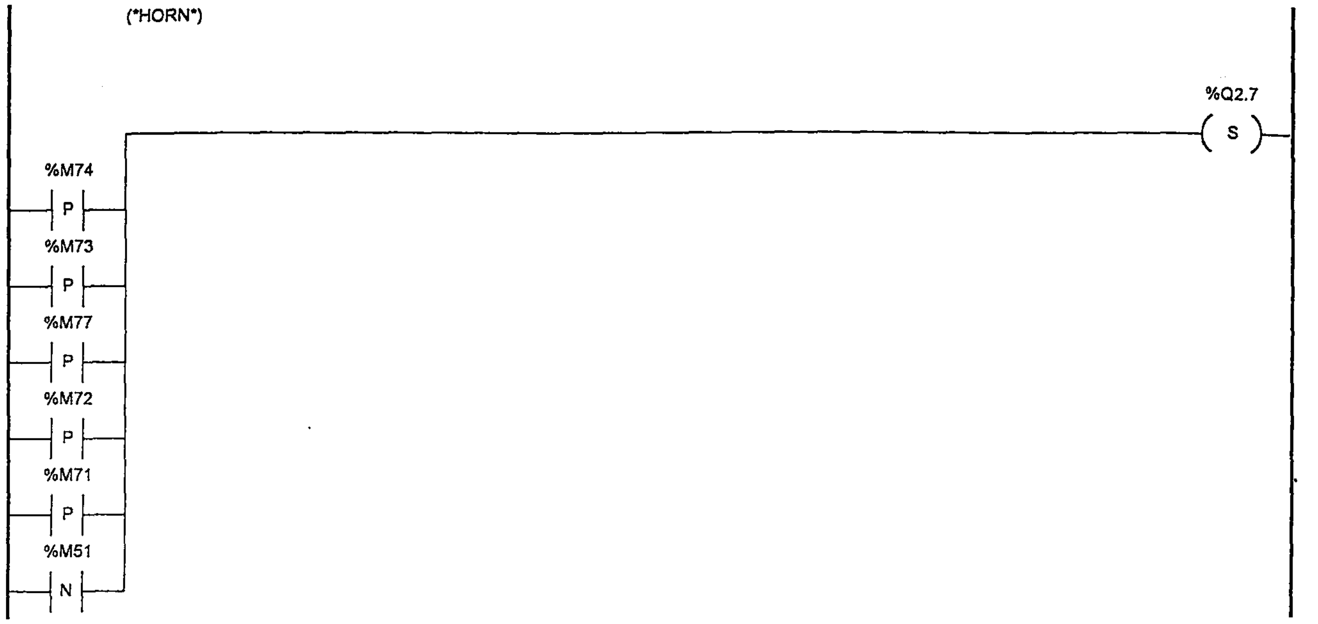

%M8
%M5
R
%M5
P
%M61
%MW201:X0
S
%MW200:X9
S
%M7
%M58
%M61
%TM4
IN
TM
Q
MODE: TON
TB: 1s
TM.P: 5
MODIF: N
OPERATE
%MW113:=22
%M230
R


%M60
P
%MW200:X9
R
%MW201:X0
S
%M61
P
%MW200:X9
S
%MW201:X0
S


%M20
N
%MW201:X3
S
%MW201:X2
R
%M21
P
%MW201:X3
S
%MW201:X2
S


%M22
P
%MW201:X2
R
%MW201:X3
R
%M23
P
%MW201:X2
S
%MW201:X3
R

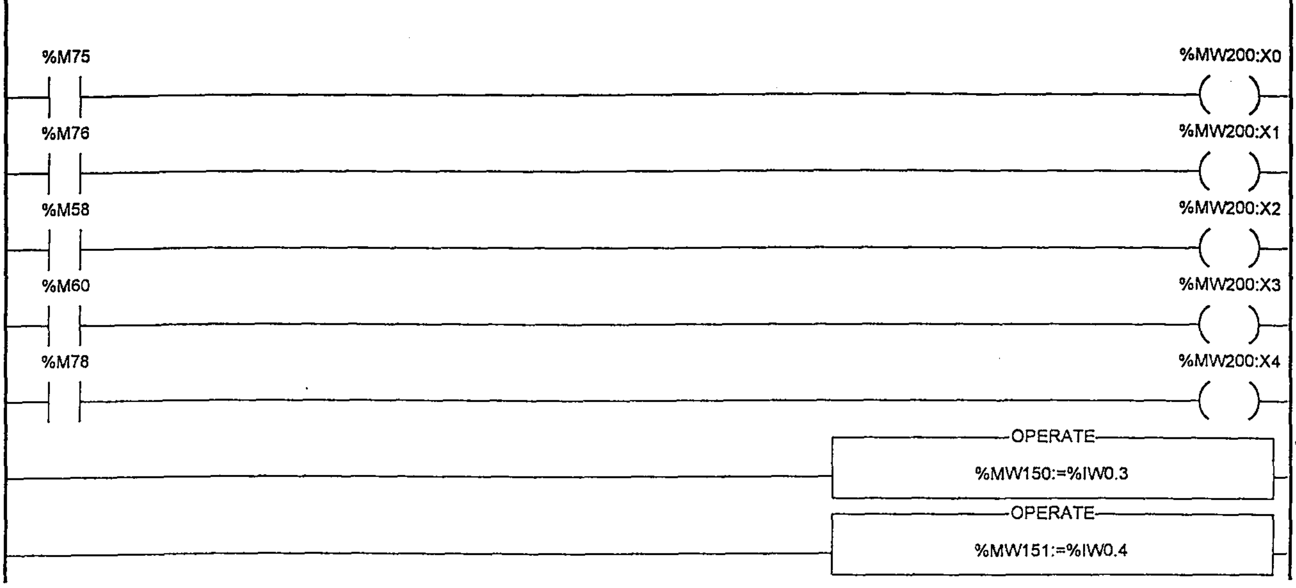

(*SEAL AIR FAN*)
%M61
%Q2.4
(*ALARMS FOR BOILER FAILURE*)
%M13
%M74
%M73
%M77
%M72
%M71
%Q2.10
%M51
%M52
%M53
%M54
%M69
%M50
%M13
(*PLC - TURBINE EMERGENCY STOP*)
%M34
%M12
%Q2.11


(*HORN*)
%Q2.7
S
%M74
P
%M73
P
%M77
P
%M72
P
%M71
P
%M51
N

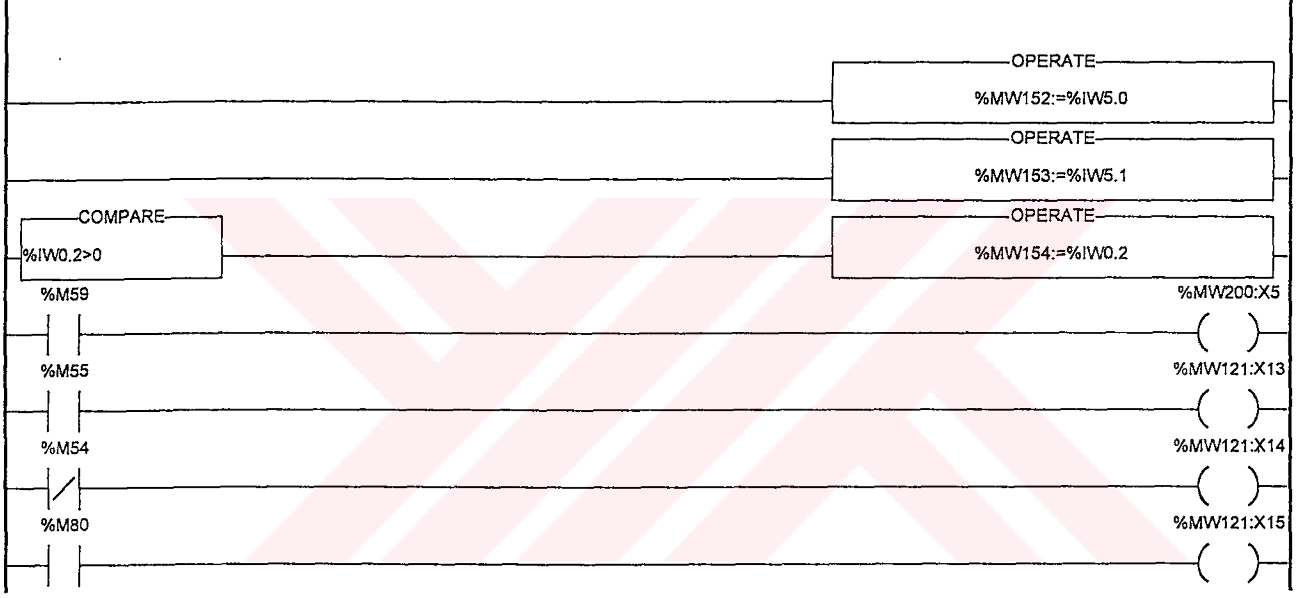

(*HORN 2*)
%M52
N
%Q2.7
S
%M53
N
%M68
N
%M69
N
%M50
N
%M54
N


(*HORN RESET*)
%M79
%Q2.7
R
%MW101:X13

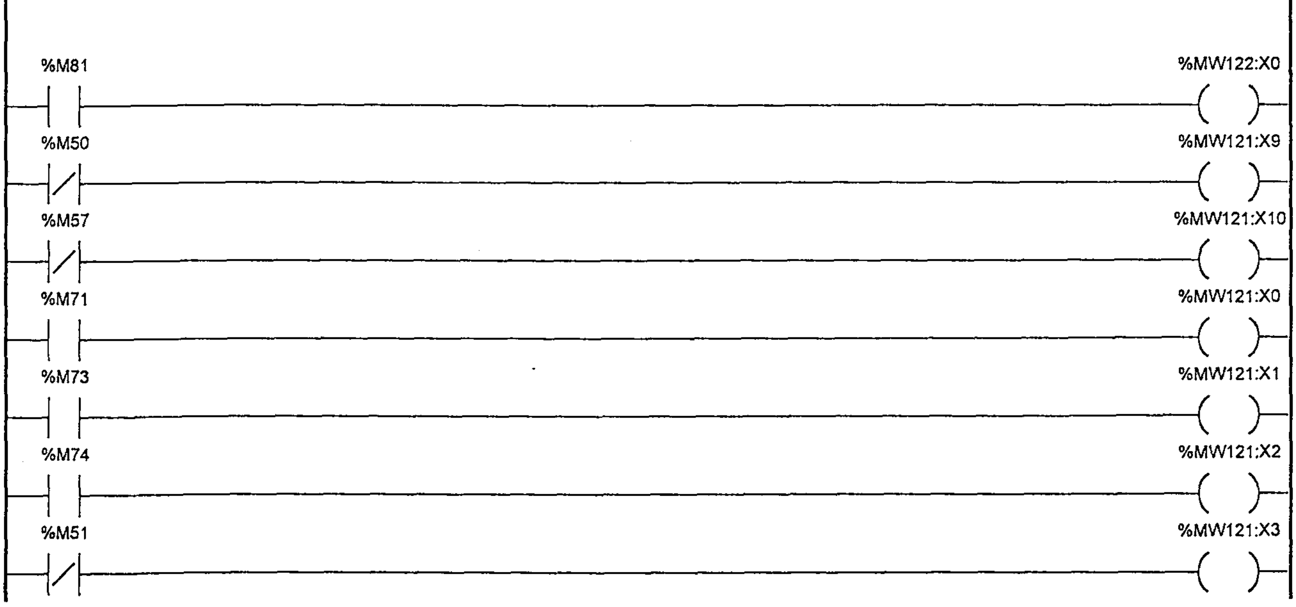
(*PLC - MONITOR COMMUNICATION*)

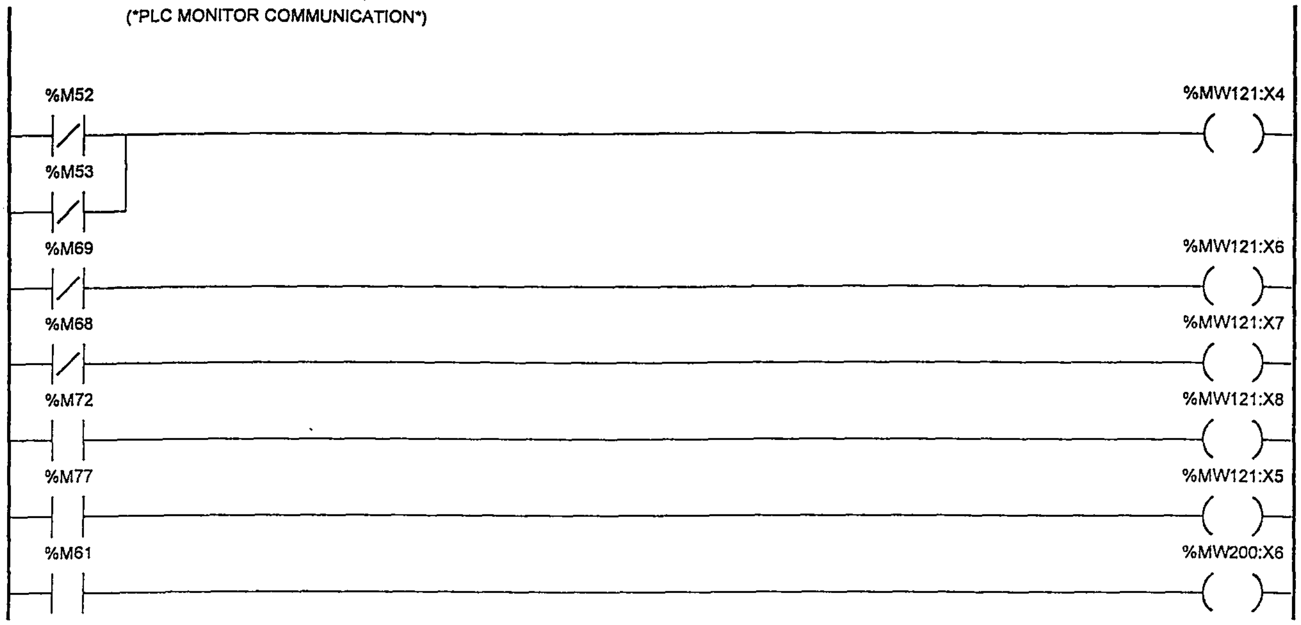


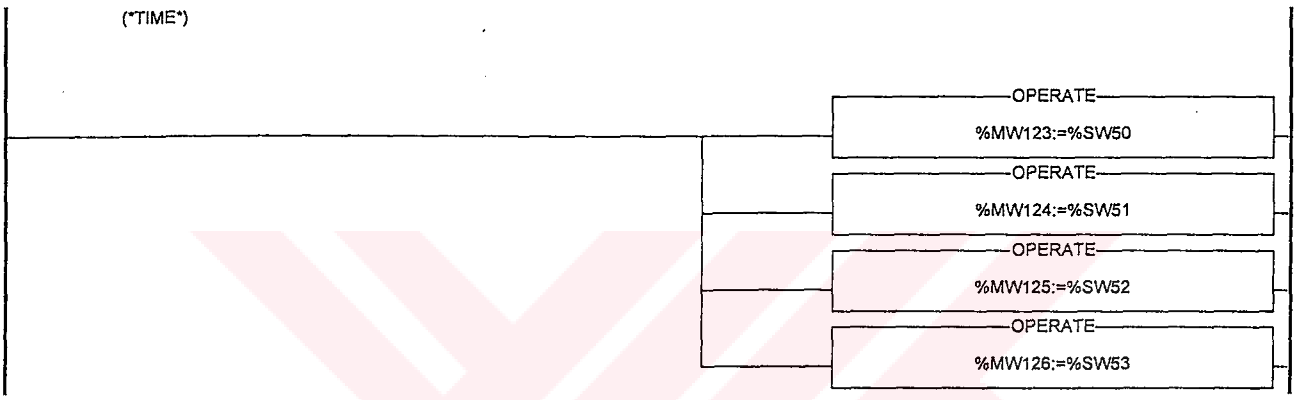
(*PLC - MONITOR COMMUNICATION*)

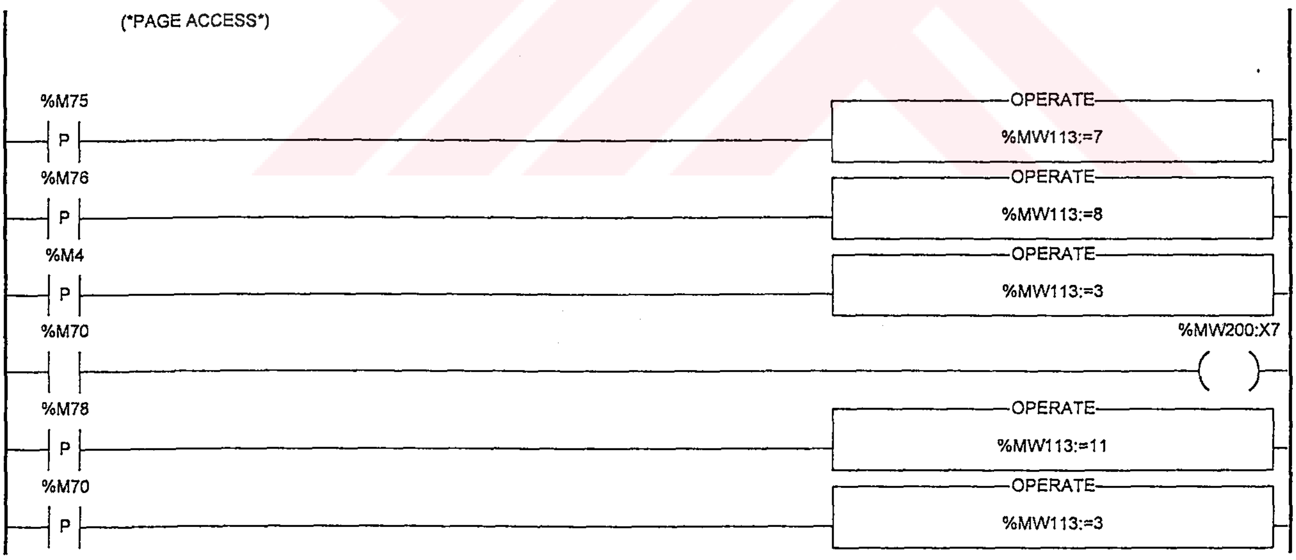


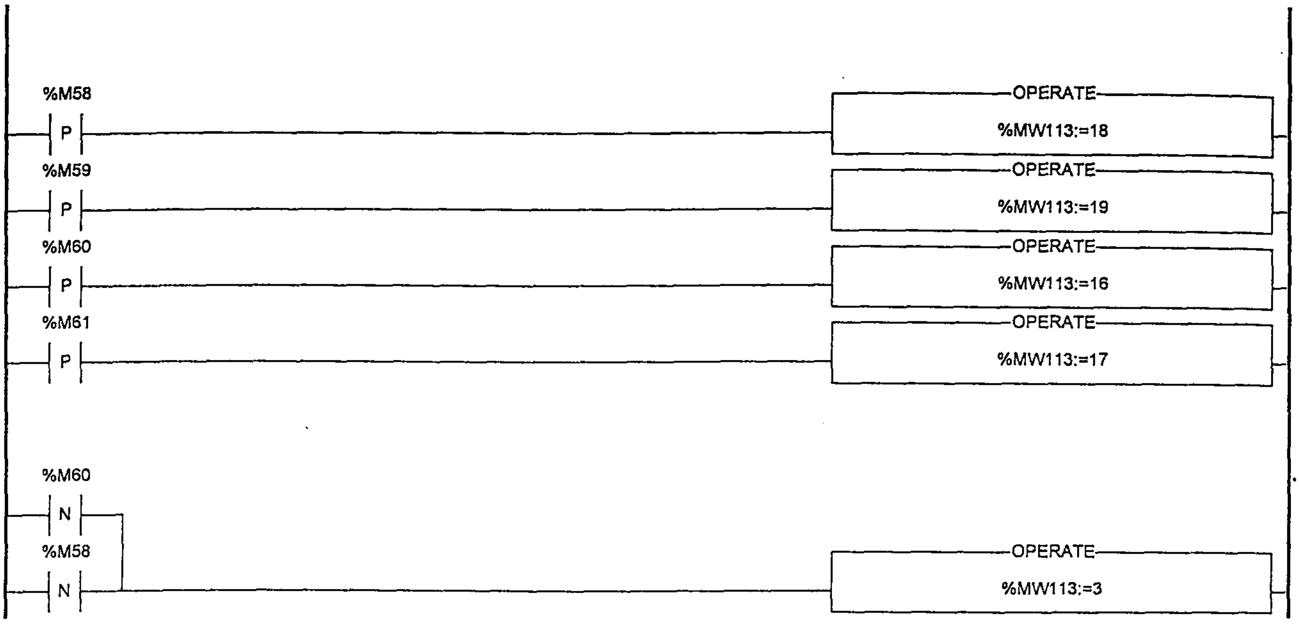
(*PLC - MONITOR COMMUNICATION*)

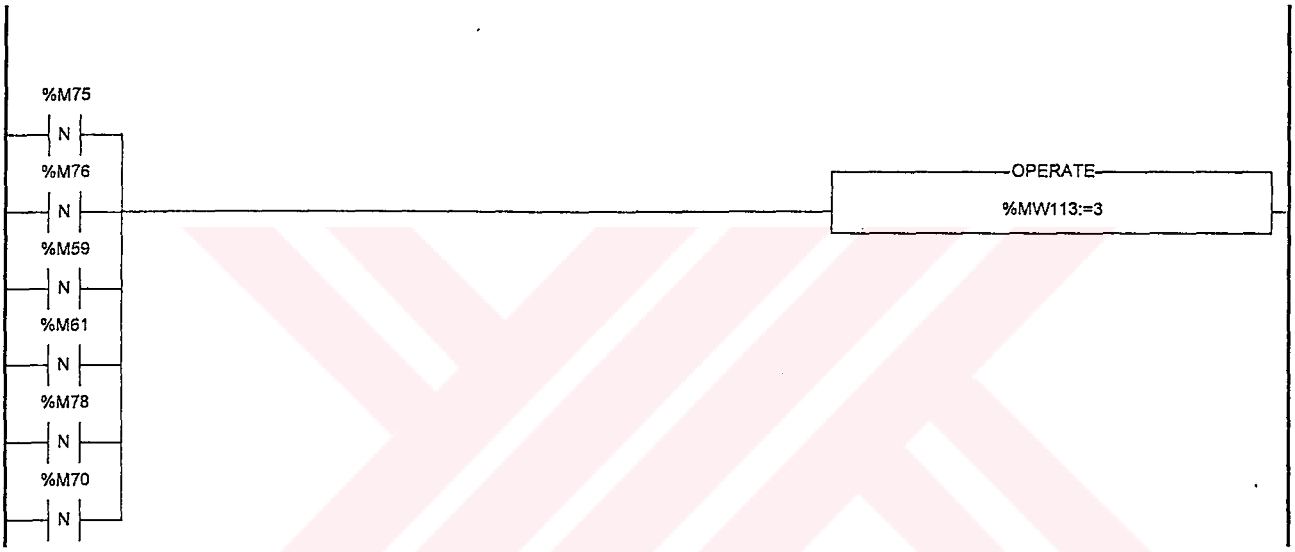


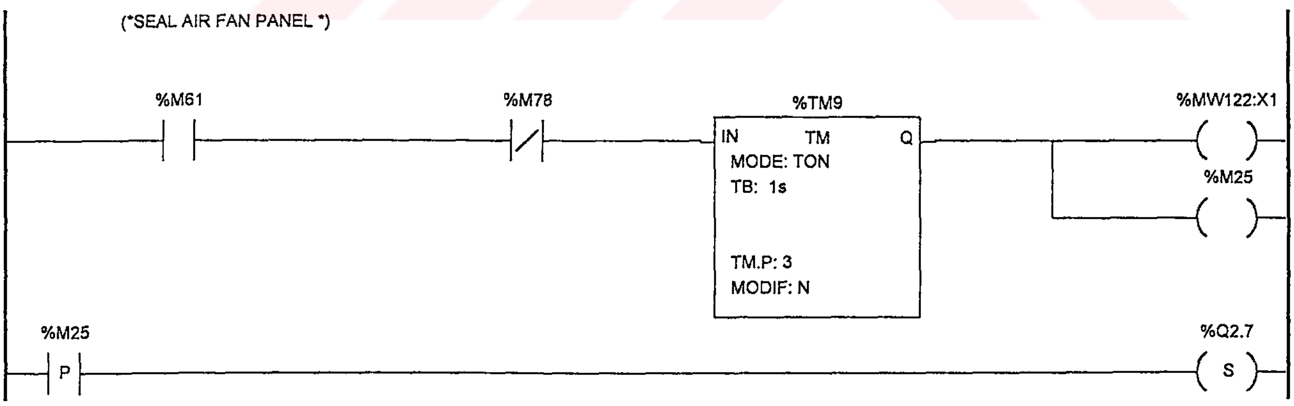

(*PLC MONITOR COMMUNICATION*)
%M52
%M53
%MW121:X4
%M69
%MW121:X6
%M68
%MW121:X7
%M72
%MW121:X8
%M77
%MW121:X5
%M61
%MW200:X6

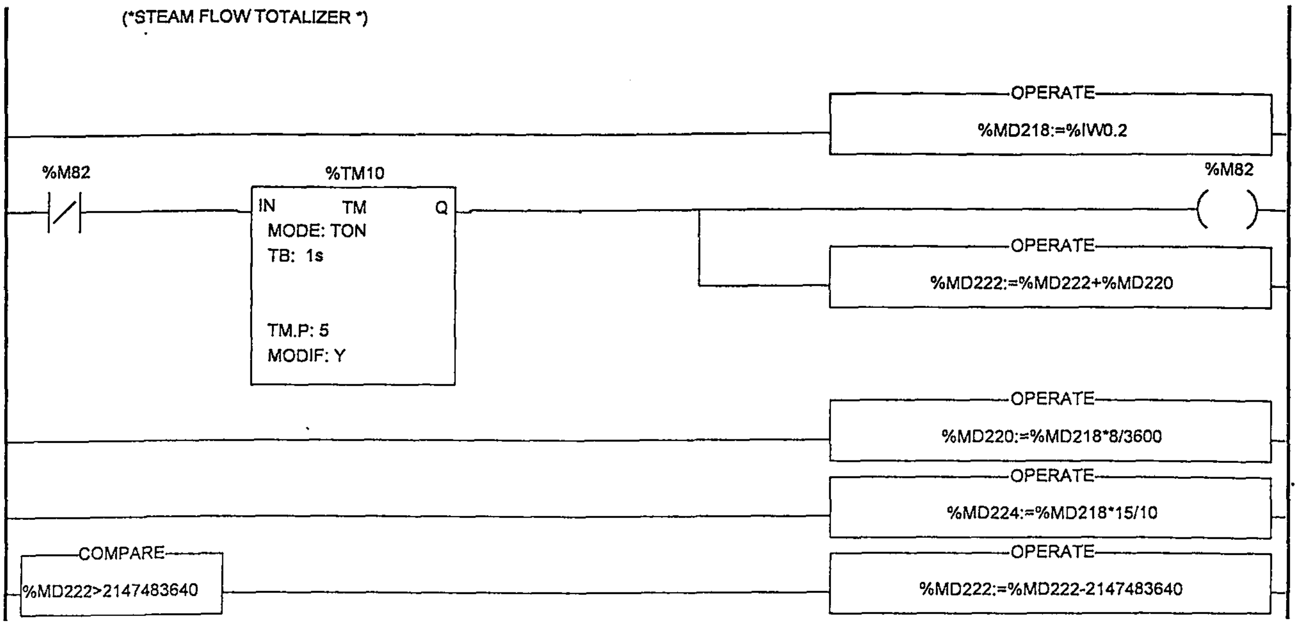

(*TIME*)
OPERATE
%MW123:=%SW50
OPERATE
%MW124:=%SW51
OPERATE
%MW125:=%SW52
OPERATE
%MW126:=%SW53

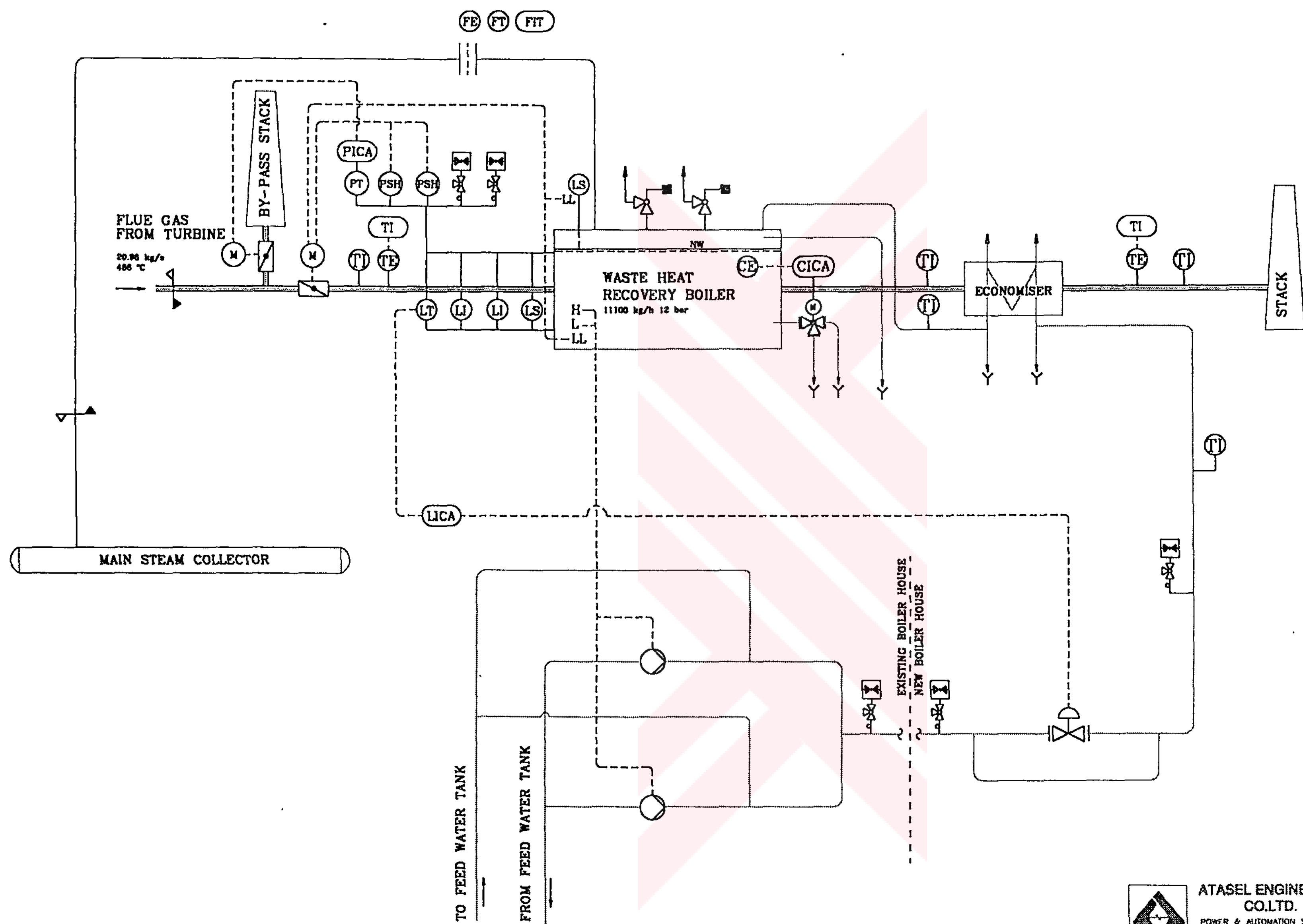

(*PAGE ACCESS*)
%M75
P
OPERATE
%MW113:=7
%M76
P
OPERATE
%MW113:=8
%M4
P
OPERATE
%MW113:=3
%M70
%MW200:X7
%M78
P
OPERATE
%MW113:=11
%M70
P
OPERATE
%MW113:=3


%M58
P
OPERATE
%MW113:=18
%M59
P
OPERATE
%MW113:=19
%M60
P
OPERATE
%MW113:=16
%M61
P
OPERATE
%MW113:=17
%M60
N
%M58
N
OPERATE
%MW113:=3


%M75
N
%M76
N
%M59
N
%M61
N
%M78
N
%M70
N
OPERATE
%MW113:=3


(*SEAL AIR FAN PANEL *)
%M61
%M78
%TM9
IN TM Q
MODE: TON
TB: 1s
TM.P: 3
MODIF: N
%MW122:X1
%M25
%M25
P
%Q2.7
S


(*STEAM FLOW TOTALIZER *)
OPERATE
%MD218:=%IW0.2
%M82
%TM10
IN
TM
Q
MODE: TON
TB: 1s
TM.P: 5
MODIF: Y
%M82
OPERATE
%MD222:=%MD222+%MD220
OPERATE
%MD220:=%MD218*8/3600
OPERATE
%MD224:=%MD218*15/10
COMPARE
%MD222>2147483640
OPERATE
%MD222:=%MD222-2147483640



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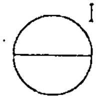
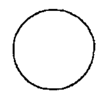
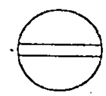
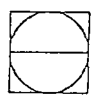
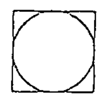
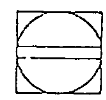
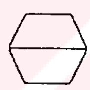
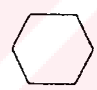
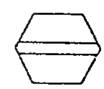
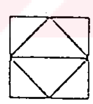
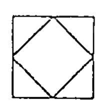
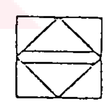
APPENDIX-B

PARAMETERS OF THE LEVEL AND PRESSURE CONTROLLERS

PARAMETER	PRESSURE	LEVEL
GAIN	2,5	3
RATE MIN	0,5	1
RSET MIN	0,1	0,2
LOCKOUT	NONE	NONE
AUTO MAN	DISABLE	ENABLE
RUN/HOLD	DISABLE	DISABLE
CONTROLLER ALG	PID A	PID A
DECIMAL	XX.XX	XXX.X
UNITS	NONE	NONE
IN1 TYPE	4-20	4-20
XMITTER	LINEAR	LINEAR
IN1 HI	12	410
IN1 LO	0	0
BIAS IN1	0	0
FILTER 1	0	0
BURNOUT	UP	DOWN
PWR FREQ	50	50
FAILSAFE	0	100
PB or GAIN	GAIN	GAIN
MIN or RPM	MIN	MIN
SP HI LIMIT	12	450
SP LO LIMIT	8	380

APPENDIX-C

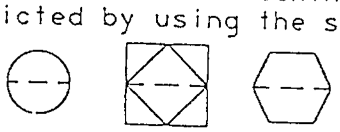
GENERAL INSTRUMENT OR FUNCTION SYMBOLS IN PROCESS AUTOMATION SYSTEMS

	PRIMARY LOCATION *** NORMALLY ACCESSIBLE TO OPERATOR	FIELD MOUNTED	AUXILIARY LOCATION *** NORMALLY ACCESSIBLE TO OPERATOR
DISCRETE INSTRUMENTS	1 * IPI ** 	2 	3 
SHARED DISPLAY, SHARED CONTROL	4 	5 	6 
COMPUTER FUNCTION	7 	8 	9 
PROGRAMMABLE LOGIC CONTROL	10 	11 	12 

* Symbol size may vary according to the user's needs and the type of document. A suggested square and circle size for large diagrams is shown above. Consistency is recommended.

** Abbreviations of the user's choice such as IP1 (Instrument Panel #1), IC2 (Instrument Console #2), CC3 (Computer Console #3), etc., may be used when it is necessary to specify instrument or function location.

*** Normally inaccessible or behind-the-panel devices or functions may be depicted by using the same symbols but with dashed horizontal bars, i.e.

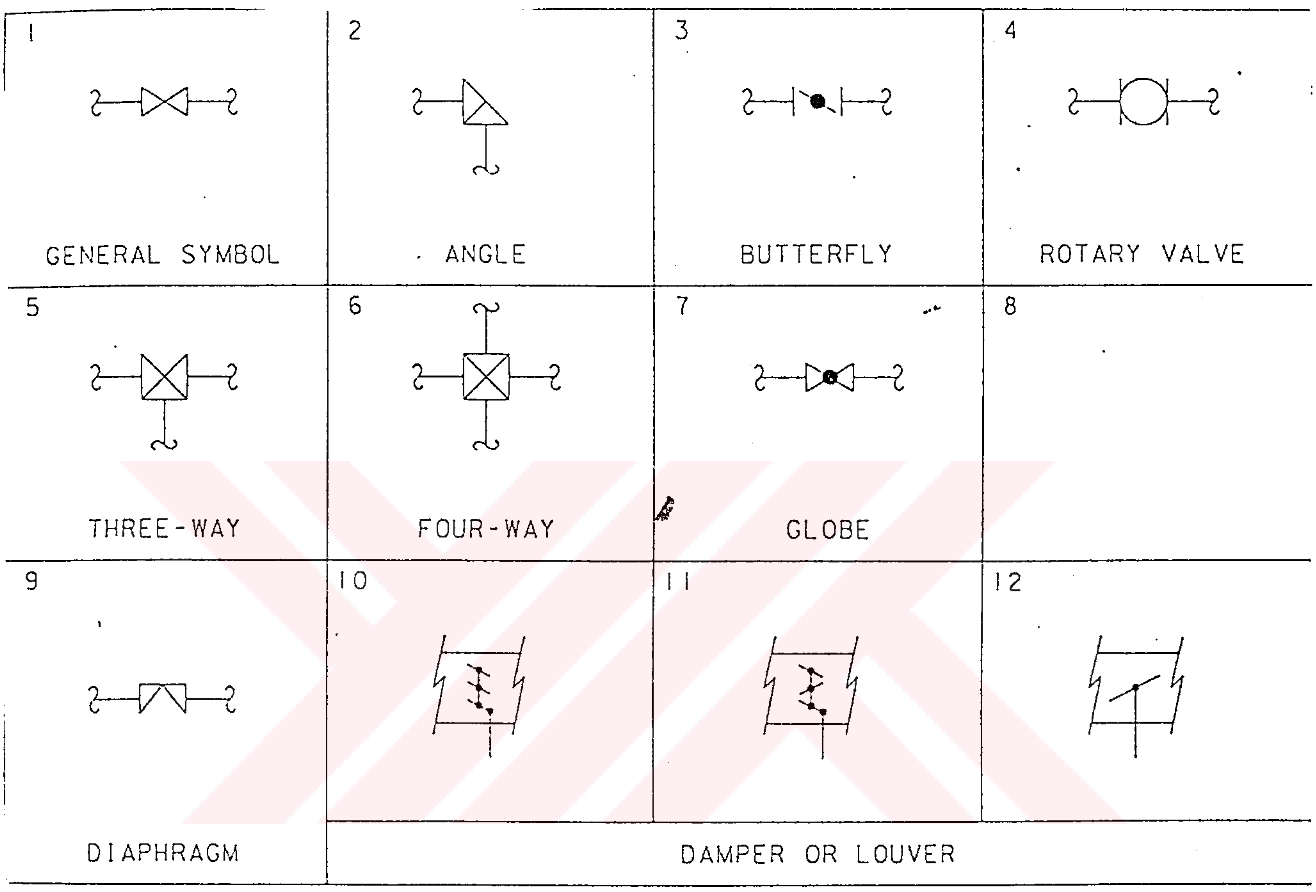


13	14 6TE 2584-23 INSTRUMENT WITH LONG TAG NUMBER	15 INSTRUMENTS SHARING COMMON HOUSING *
16 PILOT LIGHT	17 C 12 PANEL MOUNTED PATCHBOARD POINT 12	18 P ** PURGE OR FLUSHING DEVICE
19 R ** RESET FOR LATCH-TYPE ACTUATOR	20 DIAPHRAGM SEAL	21 I ** *** UNDEFINED INTERLOCK LOGIC

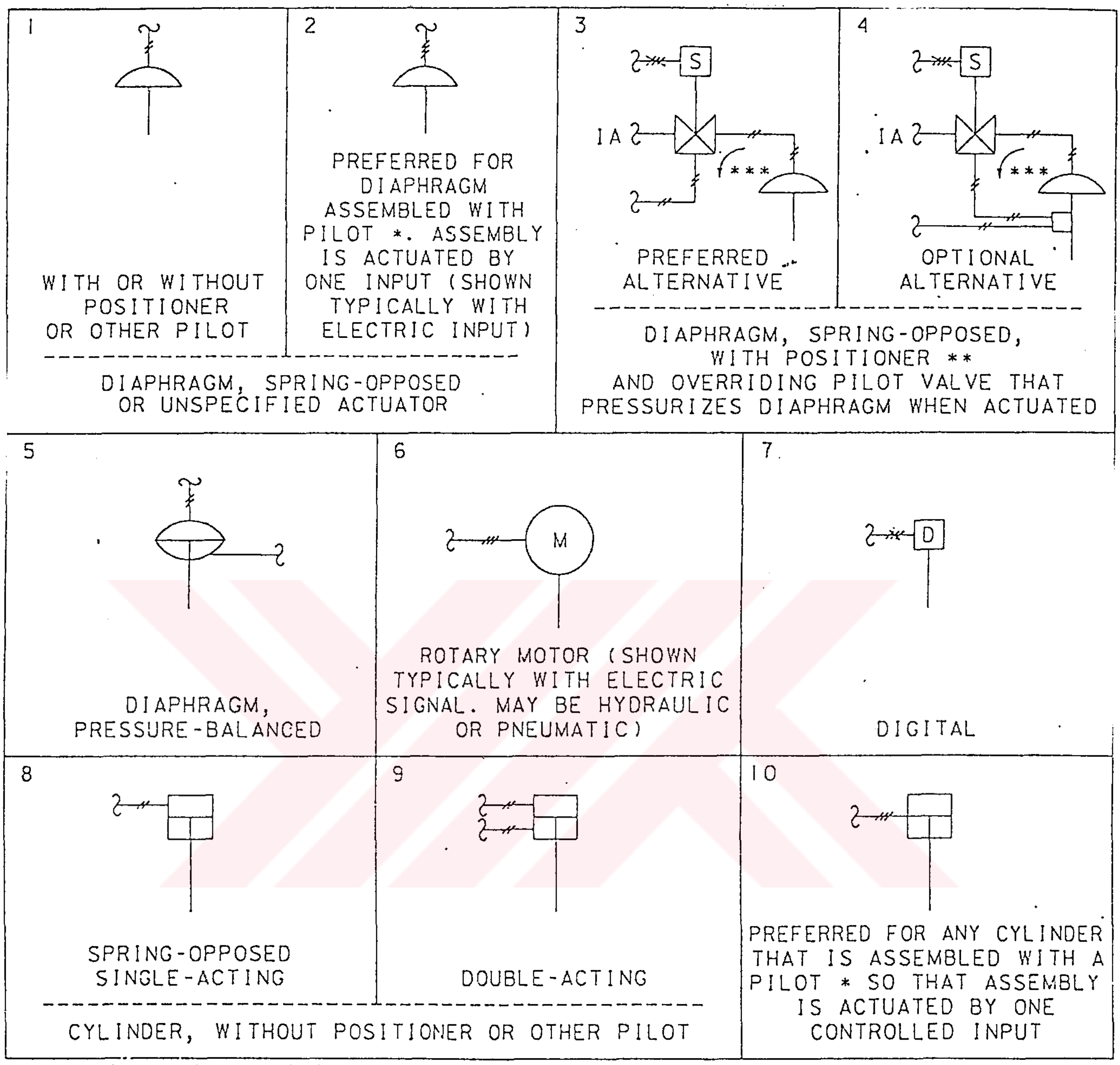
* It is not mandatory to show a common housing.

** These diamonds are approximately half the size of the larger ones.

*** For specific logic symbols, see ANSI/ISA Standard S5.2.



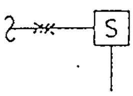
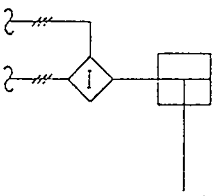
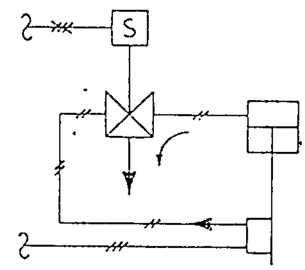
Further information may be added adjacent to the body symbol either by note or code number.

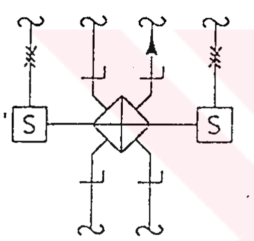
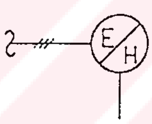
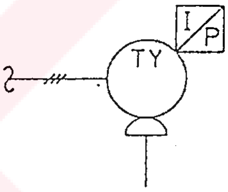


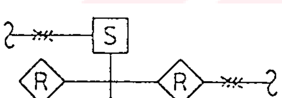
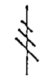
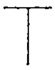
* Pilot may be positioner, solenoid valve, signal converter, etc.

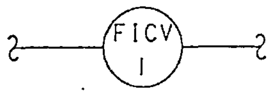
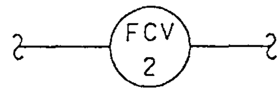
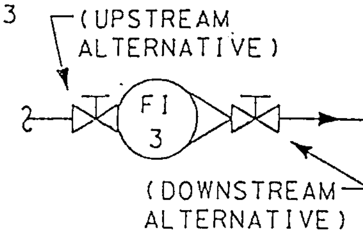
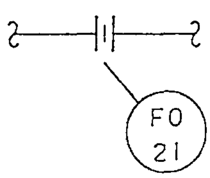
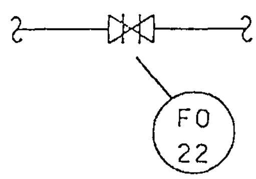
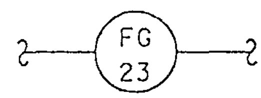
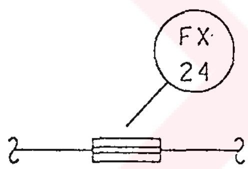
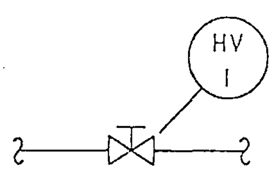
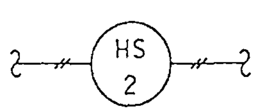
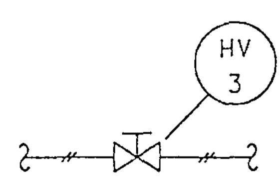
** The positioner need not be shown unless an intermediate device is on its output. The positioner tagging, ZC, need not be used even if the positioner is shown. The positioner symbol, a box drawn on the actuator shaft, is the same for all types of actuators. When the symbol is used, the type of instrument signal, i.e., pneumatic, electric, etc., is drawn as appropriate. If the positioner symbol is used and there is no intermediate device on its output, then the positioner output signal need not be shown.

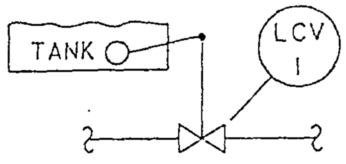
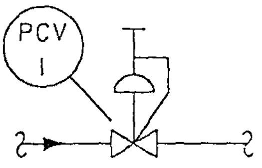
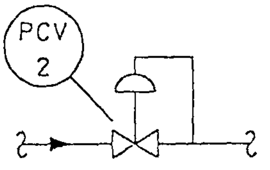
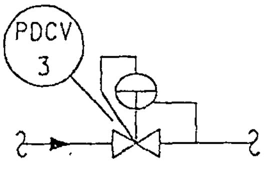
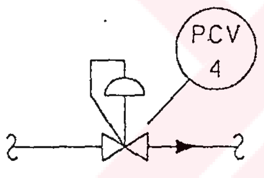
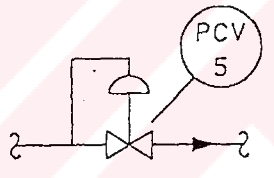
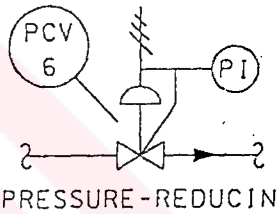
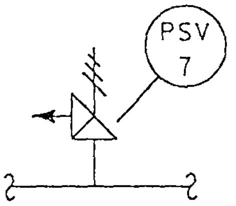
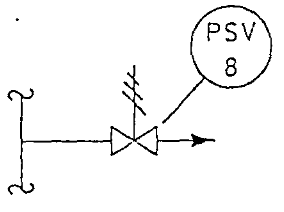
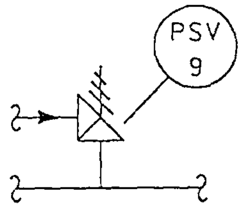
*** The arrow represents the path from a common to a fail open port. It does not correspond necessarily to the direction of fluid flow.

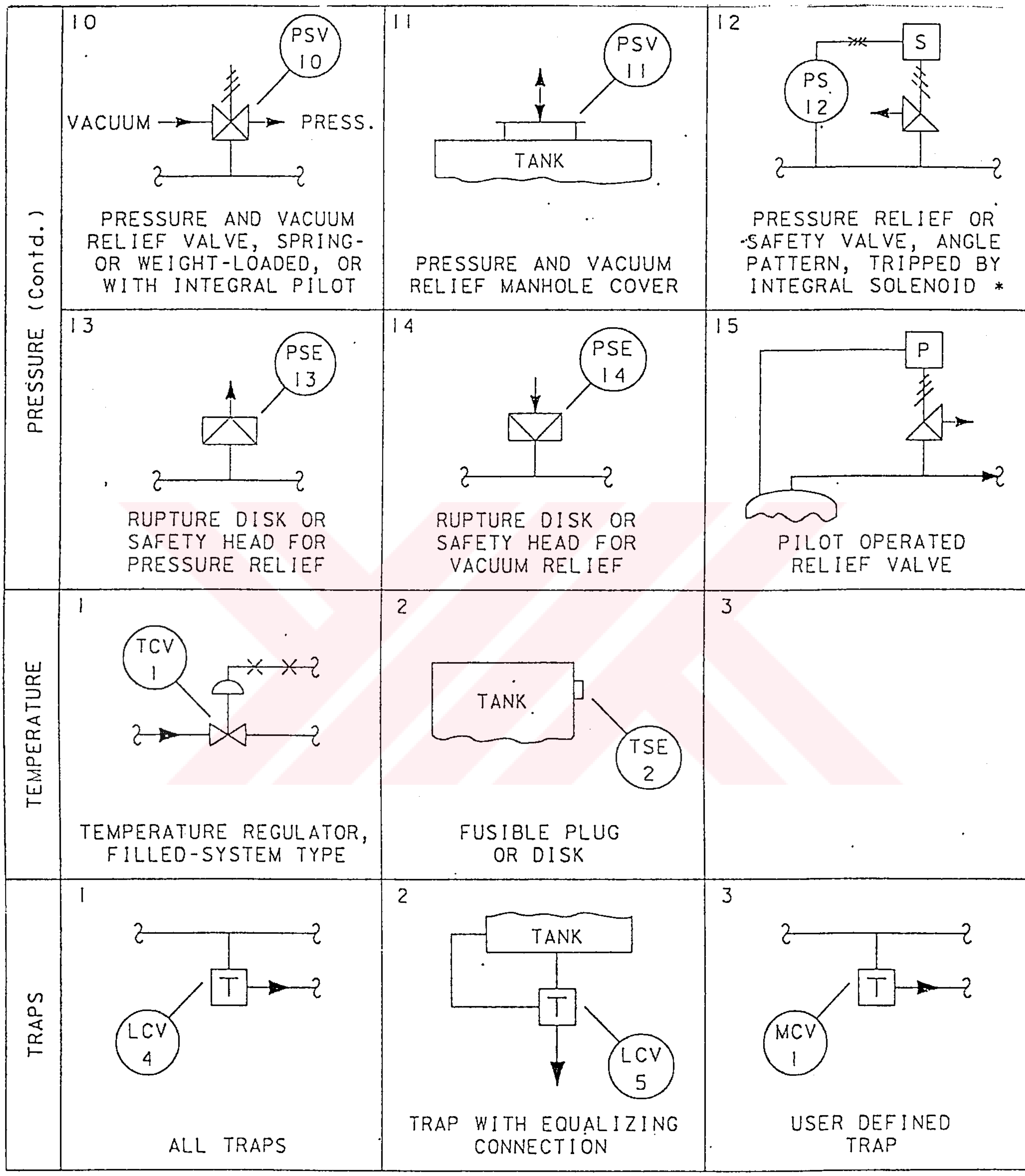
11	12	13
 SOLENOID	 PREFERRED ALTERNATIVE. A BUBBLE WITH INSTRUMENT TAGGING, E.G., TY-1, MAY BE USED INSTEAD OF THE INTERLOCK SYMBOL ◇I	 SINGLE-ACTING CYLINDER (IMPLIED I/P)
	CYLINDER WITH POSITIONER AND OVERRIDING PILOT VALVE	

14	15	16
 DUAL SOLENOIDS SWITCHING 4-WAY HYDRAULIC VALVE	 ELECTROHYDRAULIC	 VALVE ACTUATOR WITH ATTACHED ELECTRO-PNEUMATIC CONVERTER

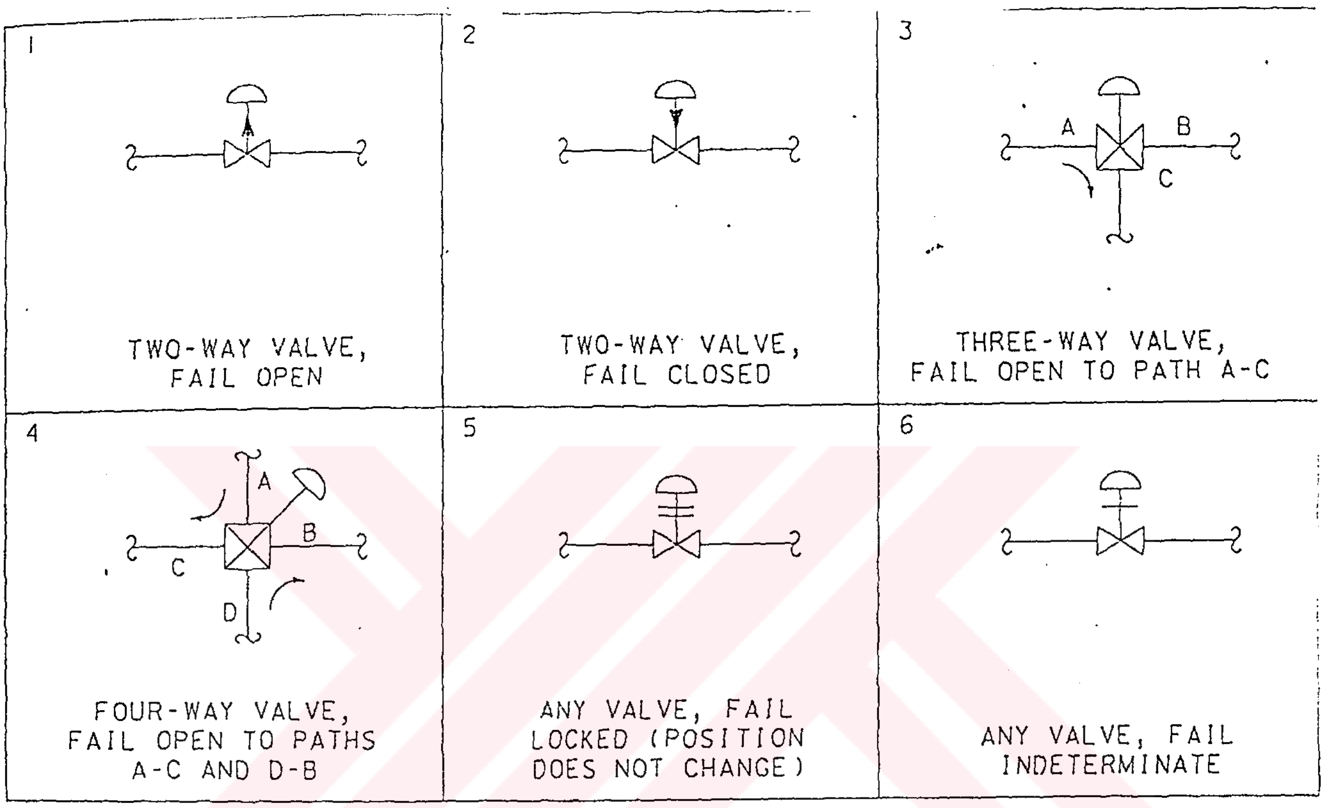
17	18	19
 (MANUAL RESET) (REMOTE RESET) LATCH-TYPE ACTUATOR WITH RESET (SHOWN TYPICALLY FOR SOLENOID ACTUATOR AND TYPICALLY WITH ELECTRIC SIGNAL FOR REMOTE RESET, WITH MANUAL RESET ALTERNATIVE)	 FOR PRESSURE RELIEF OR SAFETY VALVES ONLY: DENOTES A SPRING, WEIGHT, OR INTEGRAL PILOT	 HAND ACTUATOR OR HANDWHEEL

FLOW	1  AUTOMATIC REGULATOR WITH INTEGRAL FLOW INDICATION	2  AUTOMATIC REGULATOR WITHOUT INDICATION	3  INDICATING VARIABLE AREA METER WITH INTEGRAL MANUAL THROTTLE VALVE
	4  RESTRICTION ORIFICE (ORIFICE PLATE, CAPILLARY TUBE OR MULTI-STAGE TYPE, ETC.) IN PROCESS LINE	5  RESTRICTION ORIFICE DRILLED IN VALVE (INSTRUMENT TAG NUMBER MAY BE OMITTED IF VALVE IS OTHERWISE IDENTIFIED)	6  FLOW SIGHT GLASS, PLAIN OR WITH PADDLE WHEEL, FLAPPER, ETC.
	7  FLOW STRAIGHTENING VANE (USE OF TAG NUMBER IS OPTIONAL. THE LOOP NUMBER MAY BE THE SAME AS THAT OF THE ASSOCIATED PRIMARY ELEMENT)	8	9
HAND	1  HAND CONTROL VALVE IN PROCESS LINE	2  HAND-ACTUATED ON-OFF SWITCHING VALVE IN PNEUMATIC SIGNAL LINE	3  HAND CONTROL VALVE IN SIGNAL LINE,

LEVEL	1  LEVEL REGULATOR WITH MECHANICAL LINKAGE	2	3
PRESSURE	1  PRESSURE-REDUCING REGULATOR, SELF-CONTAINED, WITH HANDWHEEL ADJUSTABLE SET POINT	2  PRESSURE-REDUCING REGULATOR WITH EXTERNAL PRESSURE TAP	3  DIFFERENTIAL-PRESSURE-REDUCING REGULATOR WITH INTERNAL AND EXTERNAL PRESSURE TAPS
	4  BACKPRESSURE REGULATOR, SELF-CONTAINED	5  BACKPRESSURE REGULATOR WITH EXTERNAL PRESSURE TAP	6  PRESSURE-REDUCING REGULATOR WITH INTEGRAL OUTLET PRESSURE RELIEF VALVE, AND OPTIONAL PRESSURE INDICATOR (TYPICAL AIR SET)
	7  PRESSURE RELIEF OR SAFETY VALVE, GENERAL SYMBOL	8  PRESSURE RELIEF OR SAFETY VALVE, STRAIGHT-THROUGH PATTERN, SPRING- OR WEIGHT-LOADED, OR WITH INTEGRAL PILOT	9  VACUUM RELIEF VALVE, GENERAL SYMBOL

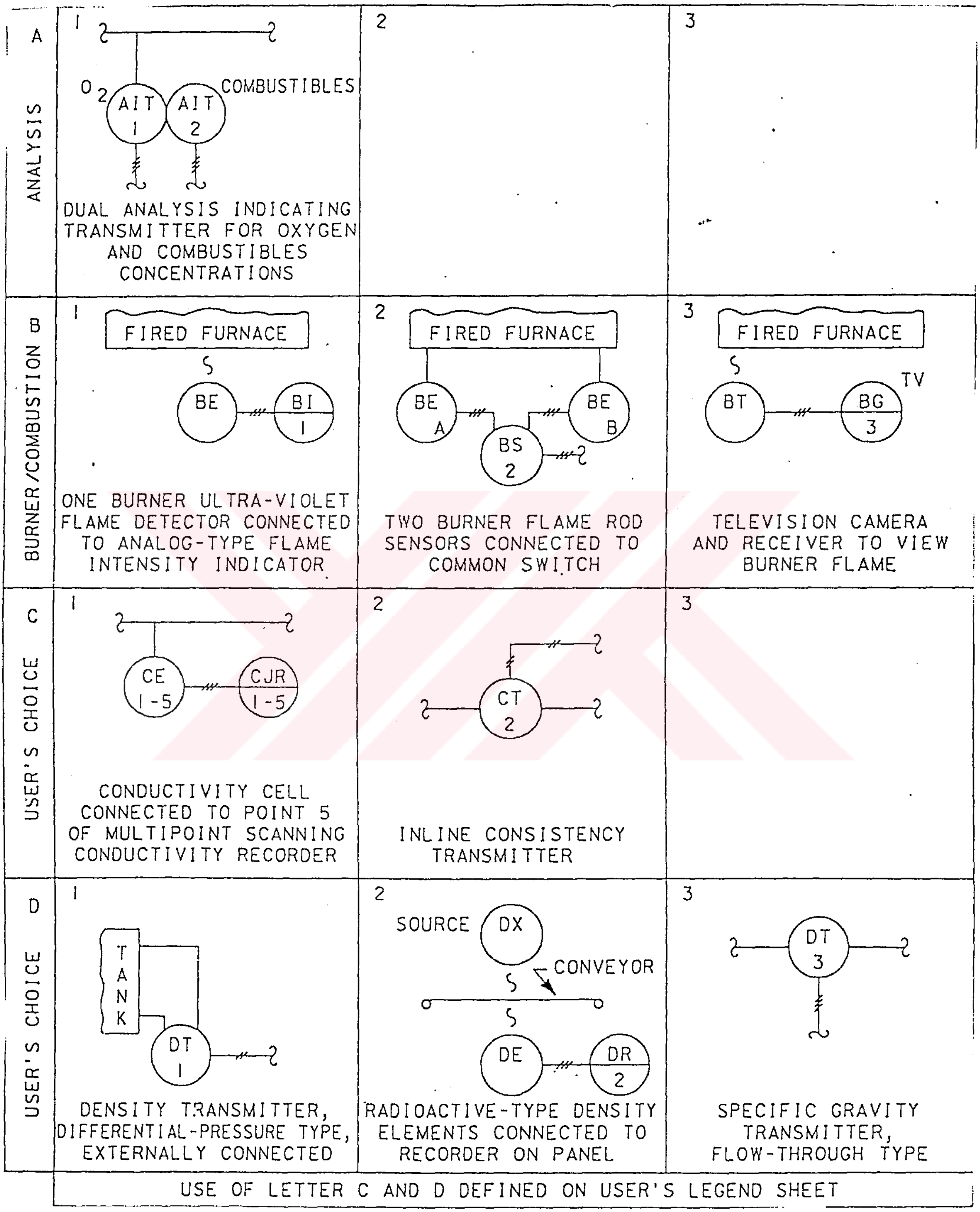


* The solenoid-tripped pressure relief valve is one of the class of power-actuated relief valves and is grouped with the other types of relief valves even though it is not entirely a self-actuated device.



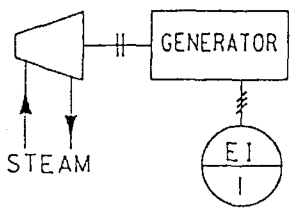
The failure modes indicated are those commonly defined by the term, "shelf-position". As an alternative to the arrows and bars, the following abbreviations may be employed:

FO - Fail Open
FC - Fail Closed
FL - Fail Locked (last position)
FI - Fail Indeterminate


A
ANALYSIS
1
O2
AIT 1
AIT 2
COMBUSTIBLES
DUAL ANALYSIS INDICATING TRANSMITTER FOR OXYGEN AND COMBUSTIBLES CONCENTRATIONS
2
3
B
BURNER/COMBUSTION
1
FIRED FURNACE
BE
BI 1
ONE BURNER ULTRA-VIOLET FLAME DETECTOR CONNECTED TO ANALOG-TYPE FLAME INTENSITY INDICATOR
2
FIRED FURNACE
BE A
BE B
BS 2
TWO BURNER FLAME ROD SENSORS CONNECTED TO COMMON SWITCH
3
FIRED FURNACE
BT
BG 3
TV
TELEVISION CAMERA AND RECEIVER TO VIEW BURNER FLAME
C
USER'S CHOICE
1
CE 1-5
CJR 1-5
CONDUCTIVITY CELL CONNECTED TO POINT 5 OF MULTIPOINT SCANNING CONDUCTIVITY RECORDER
2
CT 2
INLINE CONSISTENCY TRANSMITTER
3
D
USER'S CHOICE
1
TANK
DT 1
DENSITY TRANSMITTER, DIFFERENTIAL-PRESSURE TYPE, EXTERNALLY CONNECTED
2
SOURCE
DX
CONVEYOR
DE
DR 2
RADIOACTIVE-TYPE DENSITY ELEMENTS CONNECTED TO RECORDER ON PANEL
3
DT 3
SPECIFIC GRAVITY TRANSMITTER, FLOW-THROUGH TYPE
USE OF LETTER C AND D DEFINED ON USER'S LEGEND SHEET

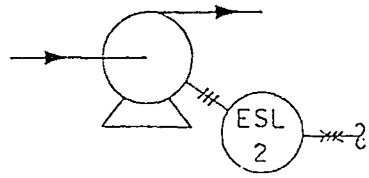
E — VOLTAGE

1



INDICATING VOLTMETER CONNECTED TO TURBINE-GENERATOR

2

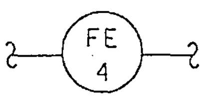


LOW-VOLTAGE SWITCH CONNECTED TO PUMP MOTOR

3

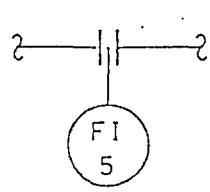
F — FLOW RATE

1



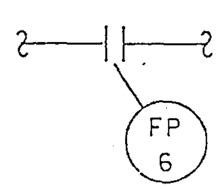
GENERAL SYMBOL THE WORDS LAMINAR, ETC., MAY BE ADDED

2



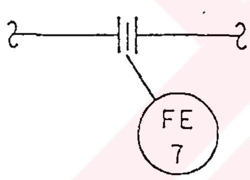
ORIFICE PLATE WITH FLANGE OR CORNER TAPS CONNECTED TO DIFFERENTIAL-PRESSURE TYPE FLOW INDICATOR

3



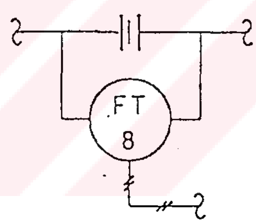
FLANGE OR CORNER TAP TEST CONNECTIONS WITHOUT ORIFICE PLATE

4



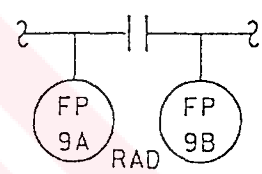
ORIFICE PLATE WITH VENA CONTRACTA TAPS

5



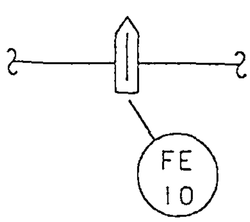
ORIFICE PLATE WITH VENA CONTRACTA, RADIUS, OR PIPE TAPS CONNECTED TO DIFFERENTIAL-PRESSURE-TYPE FLOW TRANSMITTER

6



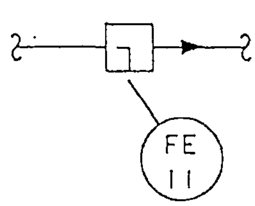
RADIUS TAP TEST CONNECTIONS WITHOUT ORIFICE PLATE

7



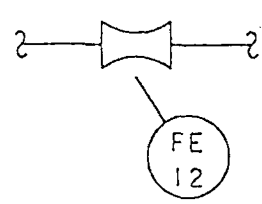
ORIFICE PLATE IN QUICK-CHANGE FITTING

8

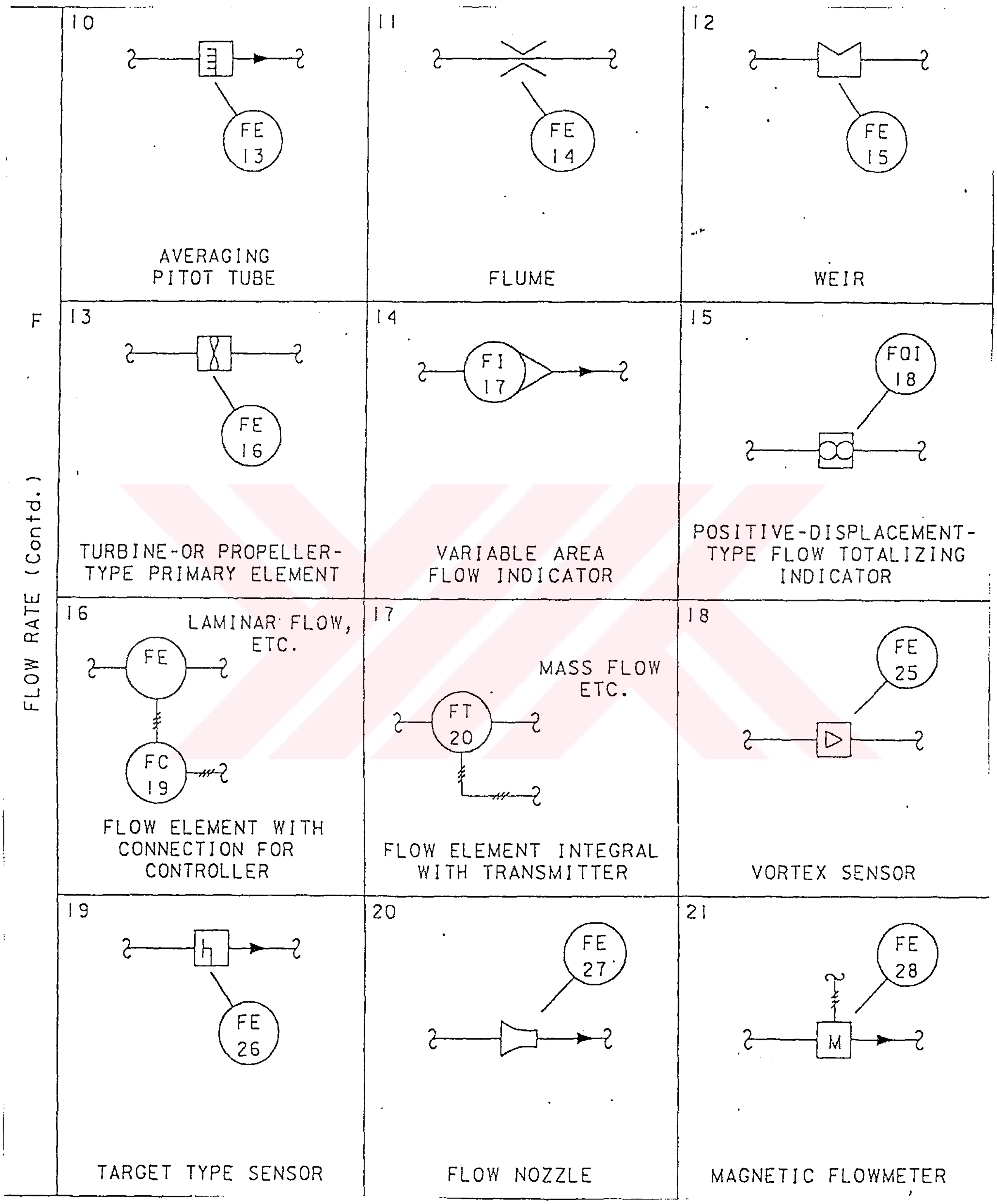


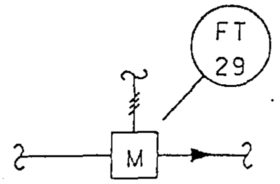
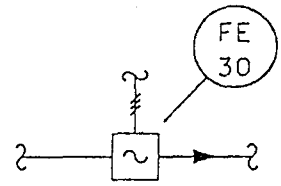
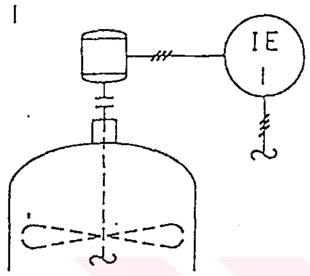
SINGLE PORT PITOT TUBE OR PITOT-VENTURI TUBE

9



VENTURI TUBE


F
FLOW RATE (Contd.)
10
FE 13
AVERAGING PITOT TUBE
11
FE 14
FLUME
12
FE 15
WEIR
13
FE 16
TURBINE-OR PROPELLER-TYPE PRIMARY ELEMENT
14
FI 17
VARIABLE AREA FLOW INDICATOR
15
FQI 18
POSITIVE-DISPLACEMENT-TYPE FLOW TOTALIZING INDICATOR
16
LAMINAR FLOW, ETC.
FE
FC 19
FLOW ELEMENT WITH CONNECTION FOR CONTROLLER
17
MASS FLOW ETC.
FT 20
FLOW ELEMENT INTEGRAL WITH TRANSMITTER
18
FE 25
VORTEX SENSOR
19
FE 26
TARGET TYPE SENSOR
20
FE 27
FLOW NOZZLE
21
FE 28
M
MAGNETIC FLOWMETER

<table>
<tr>
<td>FLOW RATE (Cont'd.) F</td>
<td>22

MAGNETIC FLOWMETER WITH INTEGRAL TRANSMITTER</td>
<td>23

SONIC FLOWMETER "DOPPLER" OR "TRANSIT TIME" MAY BE ADDED</td>
<td>24</td>
</tr>
<tr>
<td>I CURRENT</td>
<td>1

CURRENT TRANSFORMER MEASURING CURRENT OF ELECTRIC MOTOR</td>
<td>2</td>
<td>3</td>
</tr>
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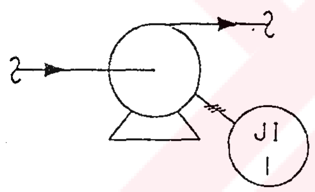
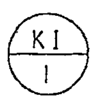
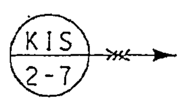
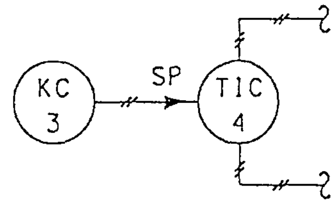
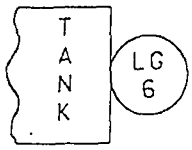
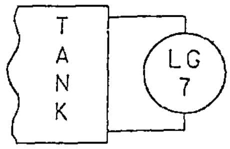
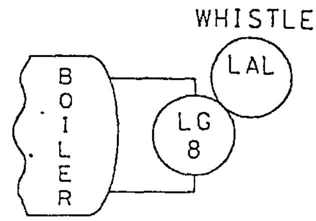
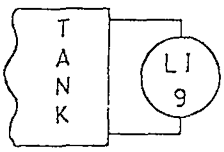
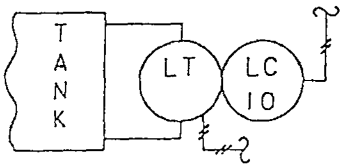
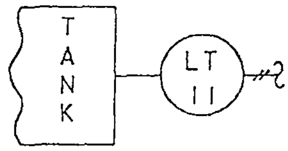
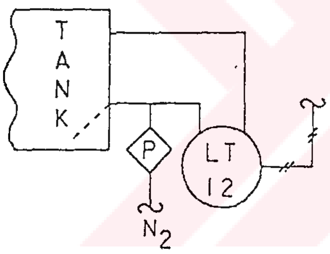
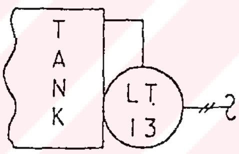
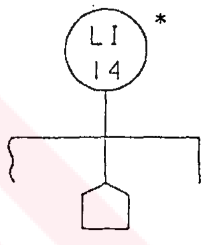
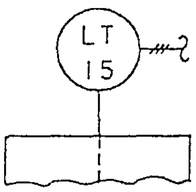
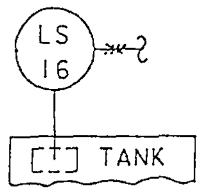
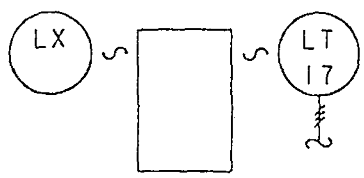
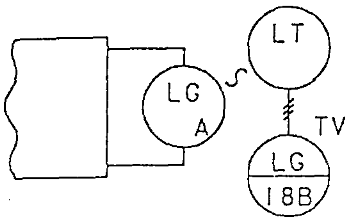
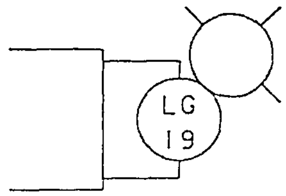
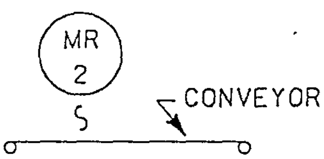
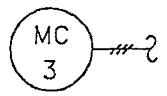
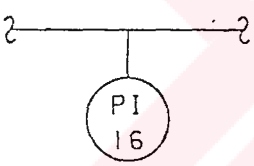
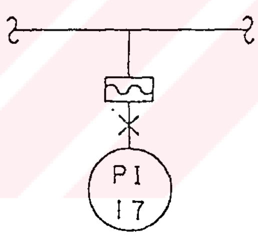
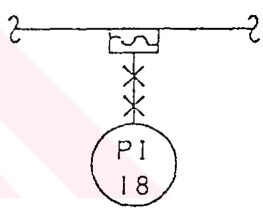
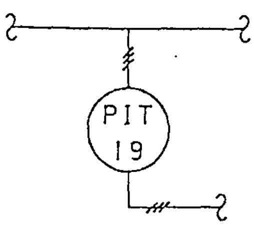
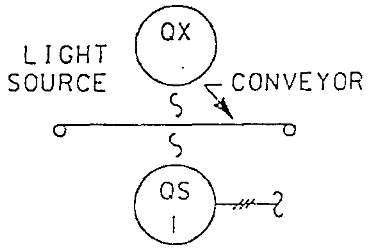
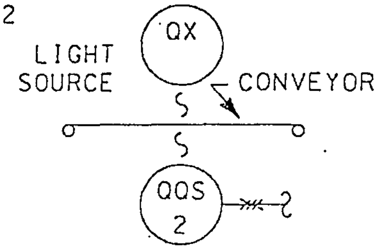
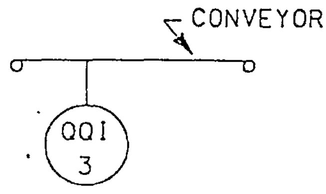
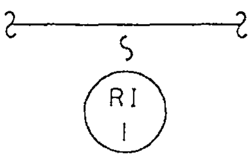
<td>J POWER</td>
<td>1

INDICATING WATTMETER CONNECTED TO PUMP MOTOR</td>
<td>2</td>
<td>3</td>
</tr>
<tr>
<td>K TIME OR TIME-SCHEDULE</td>
<td>1

CLOCK</td>
<td>2

MULTIPOINT ON-OFF TIME SEQUENCING PROGRAMMER POINT 7</td>
<td>3

TIME-SCHEDULE CONTROLLER, ANALOG TYPE, OR SELF-CONTAINED FUNCTION GENERATOR</td>
</tr>
</table>

LEVEL L

1  GAGE GLASS, INTEGRALLY MOUNTED ON TANK	2  GAGE GLASS, EXTERNALLY CONNECTED	3  WATER COLUMN WITH INTEGRAL GAGE GLASS AND ALARM WHISTLE
4  LEVEL INDICATOR, WITH TWO CONNECTIONS	5  DUPLEX LEVEL TRANSMITTER-CONTROLLER, WITH TWO CONNECTIONS	6  LEVEL TRANSMITTER, WITH ONE CONNECTION
7  LEVEL TRANSMITTER, DIFFERENTIAL-PRESSURE TYPE, EXTERNALLY CONNECTED, WITH DIP TUBE	8  LEVEL TRANSMITTER, DIFFERENTIAL-PRESSURE TYPE, MOUNTED ON TANK	9  LEVEL INDICATOR, FLOAT TYPE
10  CAPACITANCE OR DIELECTRIC TYPE LEVEL ELEMENT CONNECTED TO LEVEL TRANSMITTER (TAG LEVEL ELEMENT LE-15)	11  LEVEL SWITCH, PADDLE WHEEL OR LEVER TYPE, TO MEASURE LEVEL OF SOLIDS	12  RADIOACTIVE- OR SONIC-TYPE LEVEL TRANSMITTER WITH INTEGRAL SENSOR

* Notations such as "mounted at grade" may be added.

L LEVEL (Cont'd.)	13  REMOTE VIEWING OF GAGE GLASS BY USE OF TELEVISION	14  LEVEL GLASS WITH ILLUMINATOR	15
M USER'S CHOICE	1  MOISTURE RECORDER (IF THERE IS A SEPARATE PRIMARY ELEMENT, IT SHOULD BE TAGGED ME-2	2  SELF-CONTAINED HUMIDITY CONTROLLER IN ROOM	
	USE OF LETTER M TO BE DEFINED IN USER'S LEGEND		
P PRESSURE OR VACUUM	1  PRESSURE INDICATOR, DIRECT-CONNECTED	2  WITH PRESSURE LEAD LINE PRESSURE INDICATOR CONNECTED TO DIAPHRAGM SEAL WITH FILLED SYSTEM	3  LINE-MOUNTED.
	4  PRESSURE ELEMENT, STRAIN-GAGE TYPE, CONNECTED TO PRESSURE INDICATING TRANSMITTER (TAG STRAIN GAGE PE-19)	5	6

<table>
<tr><td>Q
QUANTITY</td>
<td>1

COUNTING SWITCH, PHOTO-ELECTRIC TYPE, WITH SWITCH ACTION FOR EACH EVENT</td>
<td>2

COUNTING SWITCH, PHOTO-ELECTRIC TYPE, WITH SWITCH ACTION BASED ON CUMULATIVE TOTAL</td>
<td>3

INDICATING COUNTER, MECHANICAL TYPE</td></tr>
<tr><td>R
RADIATION</td>
<td>1

RADIATION INDICATOR</td>
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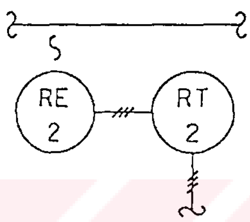
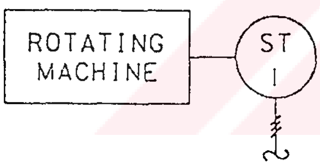
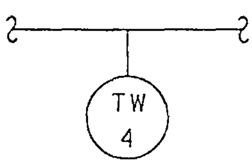
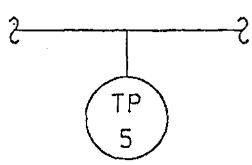
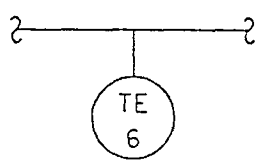
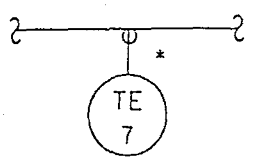

RADIATION MEASURING ELEMENT AND TRANSMITTER</td>
<td>3</td></tr>
<tr><td>S
SPEED OR FREQUENCY</td>
<td>1

SPEED TRANSMITTER</td>
<td>2</td>
<td>3</td></tr>
<tr><td>T
TEMPERATURE</td>
<td>1

TEMPERATURE CONNECTION WITH WELL</td>
<td>2

TEMPERATURE TEST CONNECTION WITHOUT WELL</td>
<td>3

TEMPERATURE ELEMENT WITHOUT WELL (ELEMENT NOT CONNECTED TO SECONDARY INSTRUMENT)</td></tr>
</table>

T

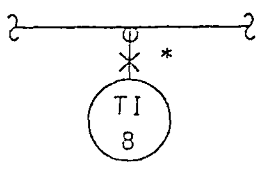
TEMPERATURE (Contd.)

4



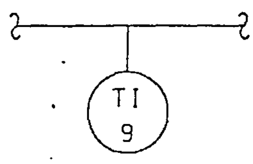
TEMPERATURE ELEMENT WITH WELL (ELEMENT NOT CONNECTED TO SECONDARY INSTRUMENT)

5



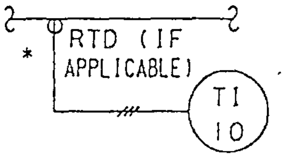
FILLED-SYSTEM-TYPE TEMPERATURE INDICATOR WITH WELL

6



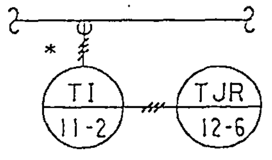
BIMETALLIC-TYPE THERMOMETER, GLASS THERMOMETER, OR OTHER LOCAL UNCLASSIFIED TEMPERATURE INDICATOR

7



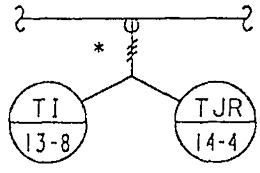
THERMOCOUPLE, RESISTANCE BULB (RTD) OR THERMISTOR (TH) CONNECTED TO TEMPERATURE INDICATOR (TAG ELEMENT TE-10)

8



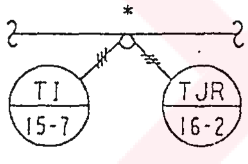
THERMOCOUPLE CONNECTED TO MULTIPOINT INDICATOR RECORDING ON MULTIPOINT SCANNING RECORDER (TAG ELEMENT TE-11-2)

9



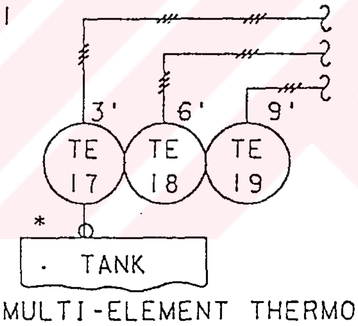
THERMOCOUPLE PARALLEL-WIRED TO MULTIPOINT INDICATOR AND MULTIPOINT SCANNING RECORDER (TAG ELEMENT TE-13-8/14-4)

10



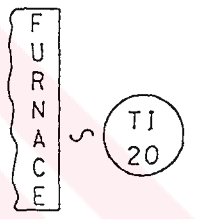
DUAL OR DUPLEX THERMOCOUPLE CONNECTED TO MULTIPOINT INDICATOR AND MULTIPOINT SCANNING RECORDER (TAG ELEMENT TE-15-7/16-2)

11



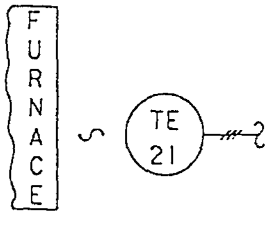
MULTI-ELEMENT THERMOCOUPLE FOR DIFFERENT ELEVATIONS, WITH WELL IN TANK

12



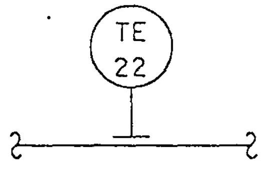
THERMAL-RADIATION TYPE TEMPERATURE INDICATOR, SELF-CONTAINED

13



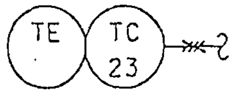
THERMAL-RADIATION-TYPE TEMPERATURE ELEMENT

14



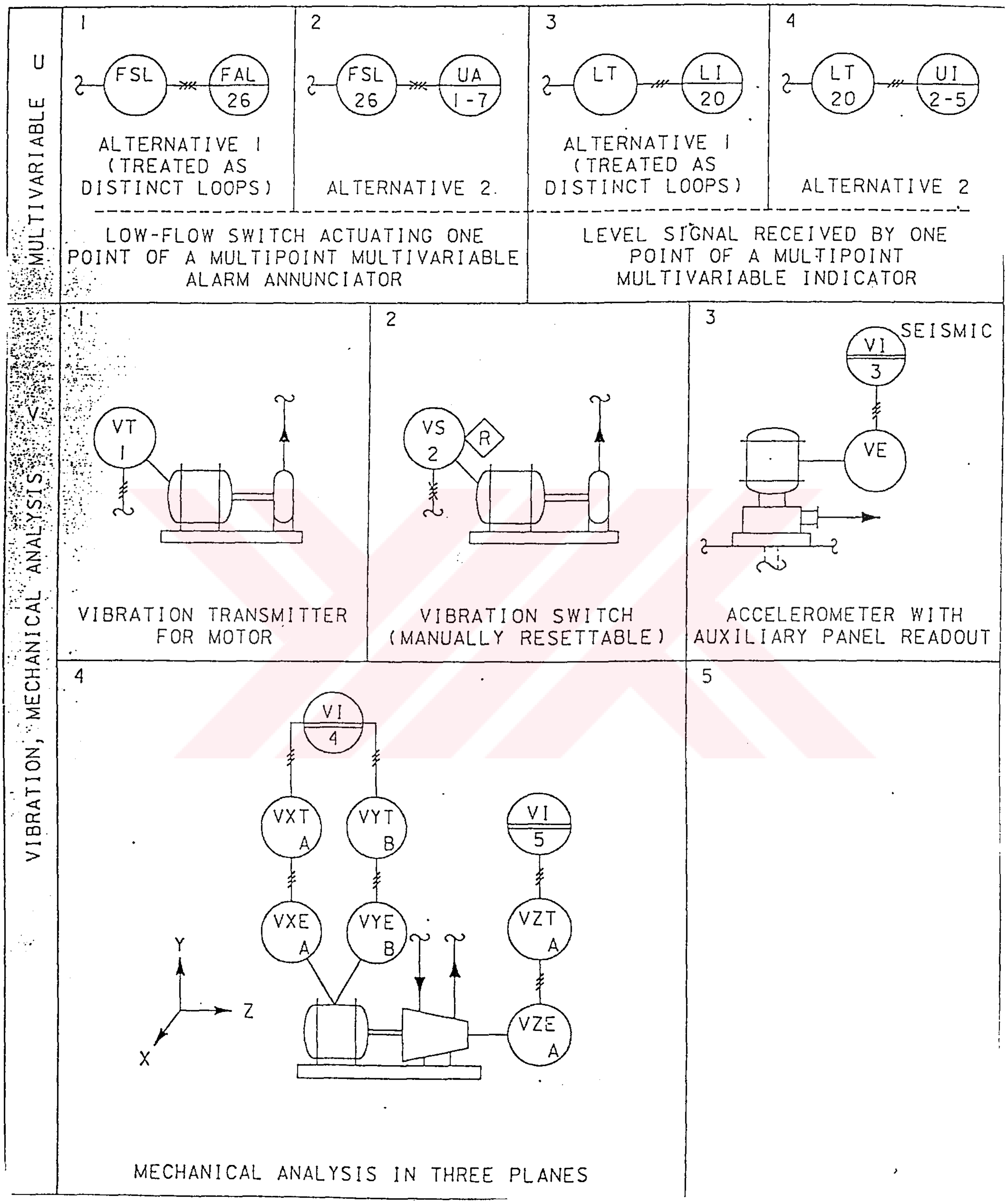
SURFACE-MOUNTED TEMPERATURE SENSOR

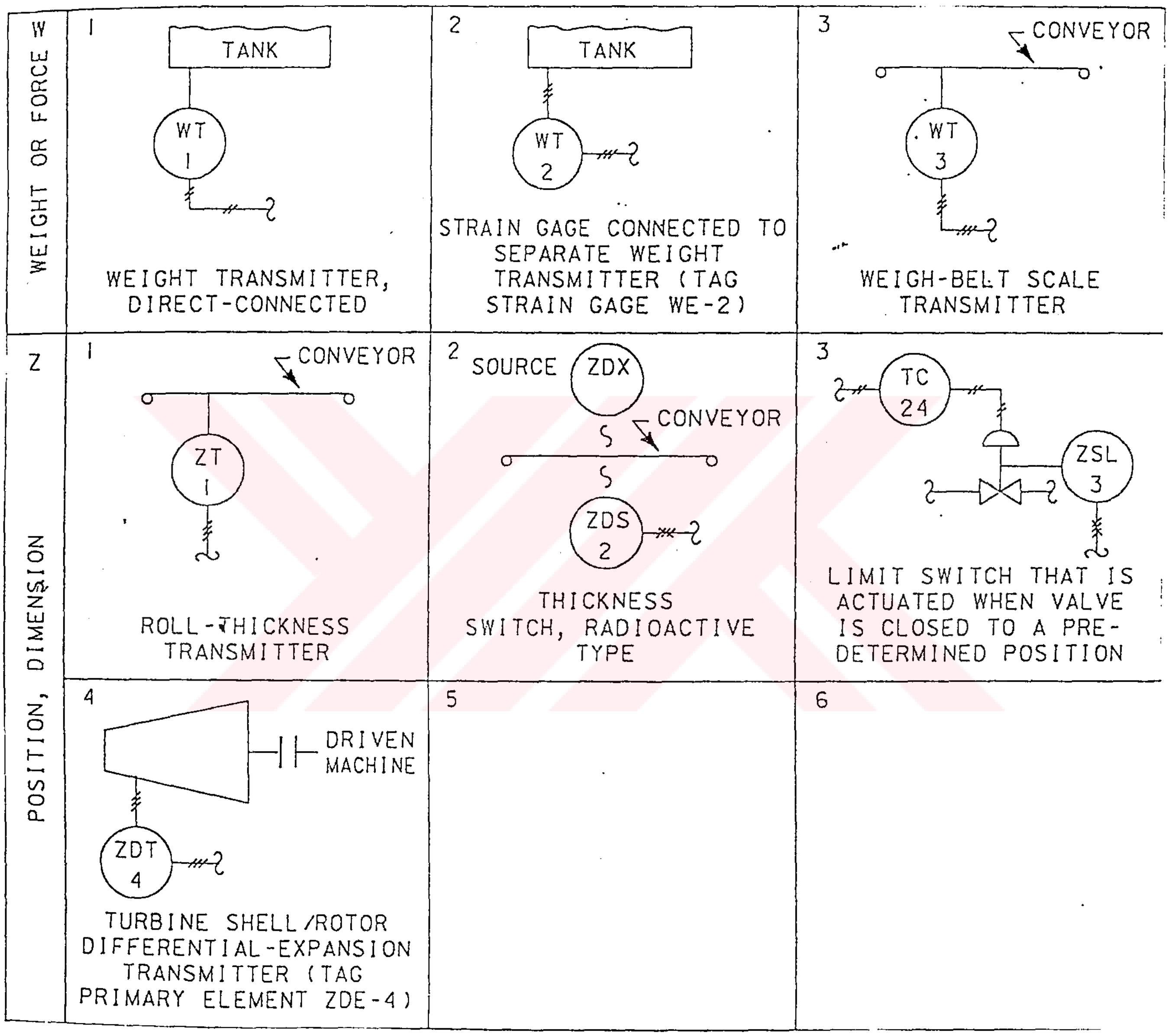
15

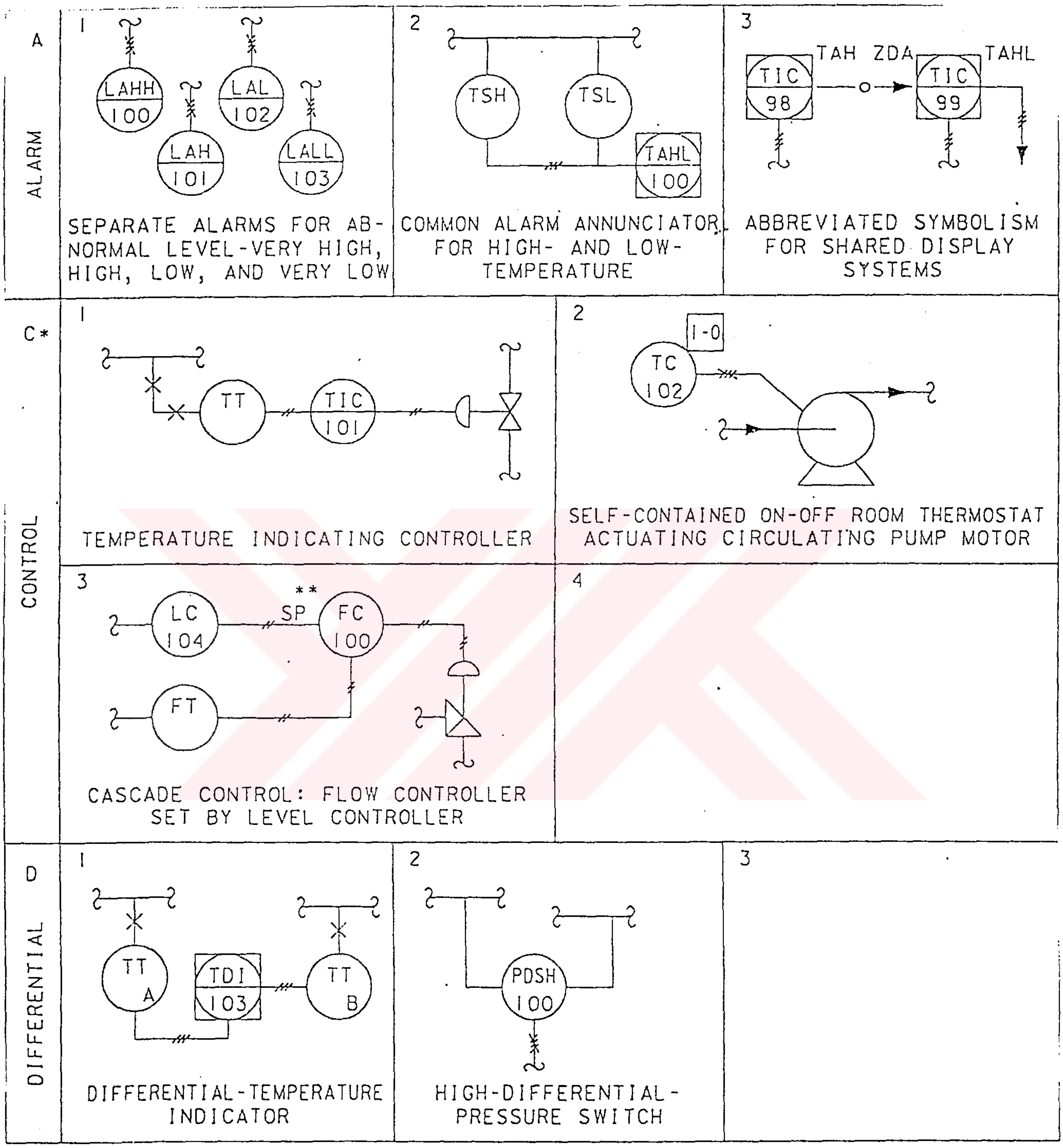


THERMOSTAT SENSING AMBIENT TEMPERATURE

* Use of the thermowell symbol is optional. However, use or omission of the symbol should be consistent throughout a project.


U
MULTIVARIABLE
1
FSL
FAL 26
ALTERNATIVE 1 (TREATED AS DISTINCT LOOPS)
2
FSL 26
UA 1-7
ALTERNATIVE 2.
LOW-FLOW SWITCH ACTUATING ONE POINT OF A MULTIPOINT MULTIVARIABLE ALARM ANNUNCIATOR
3
LT
LI 20
ALTERNATIVE 1 (TREATED AS DISTINCT LOOPS)
4
LT 20
UI 2-5
ALTERNATIVE 2
LEVEL SIGNAL RECEIVED BY ONE POINT OF A MULTIPOINT MULTIVARIABLE INDICATOR
V
VIBRATION, MECHANICAL ANALYSIS
1
VT 1
VIBRATION TRANSMITTER FOR MOTOR
2
VS 2
R
VIBRATION SWITCH (MANUALLY RESETTABLE)
3
SEISMIC
VI 3
VE
ACCELEROMETER WITH AUXILIARY PANEL READOUT
4
VI 4
VXT A
VYT B
VXE A
VYE B
VI 5
VZT A
VZE A
Y
Z
X
MECHANICAL ANALYSIS IN THREE PLANES
5


W
WEIGHT OR FORCE
1
TANK
WT
1
WEIGHT TRANSMITTER, DIRECT-CONNECTED
2
TANK
WT
2
STRAIN GAGE CONNECTED TO SEPARATE WEIGHT TRANSMITTER (TAG STRAIN GAGE WE-2)
3
CONVEYOR
WT
3
WEIGH-BELT SCALE TRANSMITTER
Z
POSITION, DIMENSION
1
CONVEYOR
ZT
1
ROLL-THICKNESS TRANSMITTER
2
SOURCE
ZDX
CONVEYOR
ZDS
2
THICKNESS SWITCH, RADIOACTIVE TYPE
3
TC
24
ZSL
3
LIMIT SWITCH THAT IS ACTUATED WHEN VALVE IS CLOSED TO A PRE-DETERMINED POSITION
4
DRIVEN MACHINE
ZDT
4
TURBINE SHELL/ROTOR DIFFERENTIAL-EXPANSION TRANSMITTER (TAG PRIMARY ELEMENT ZDE-4)
5
6

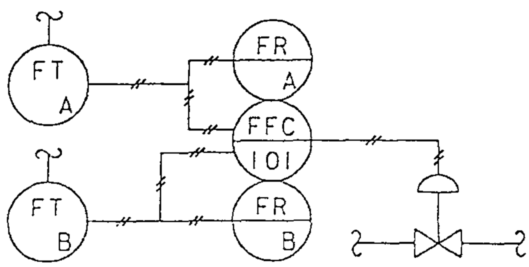


* It is expected that control modes will not be designated on a diagram. However, designations may be used outside the controller symbol, if desired, in combinations such as [%], [∫], [1-0].

** A controller is understood to have integral manual set-point adjustment unless means of remote adjustment is indicated. The remote set-point designation is SP.

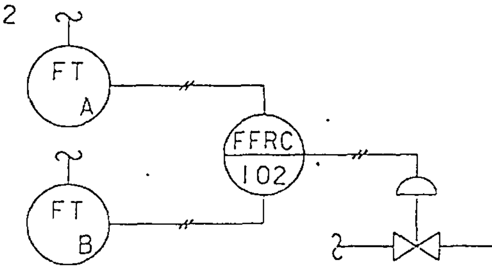
F RATIO

1



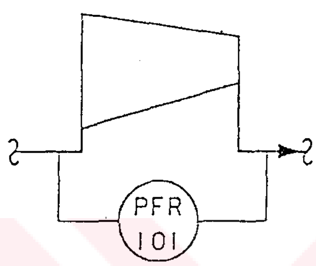
FLOW-RATIO CONTROLLER WITH TWO PENS TO RECORD FLOW

2



FLOW-RATIO CONTROLLER WITH ONE PEN TO RECORD FLOW-RATIO

3

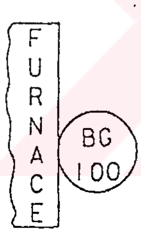


DIRECT-CONNECTED COMPRESSION-RATIO RECORDER

4

G VIEWING DEVICE, GLASS

1



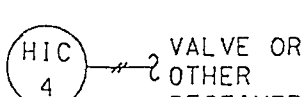
SIGHT GLASS FOR INTERNAL VIEWING

2

3

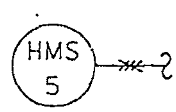
H HAND

1



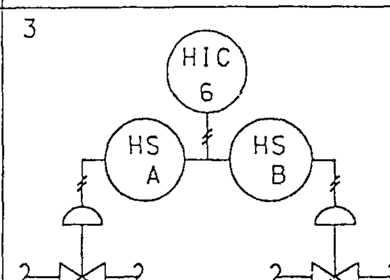
MANUAL LOADING STATION WITH OUTPUT GAGE

2



HAND-ACTUATED ELECTRIC SWITCH, MOMENTARY

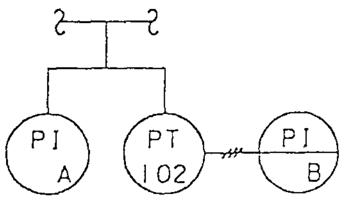
3



MANUAL LOADING STATION WITH HAND ACTUATED SWITCHES

I — INDICATE

1



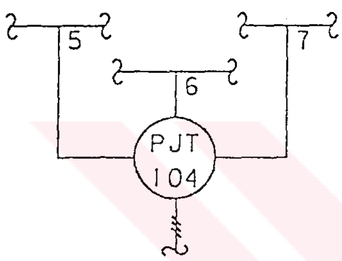
LOCAL PRESSURE INDICATOR AND PRESSURE TRANSMITTER WITH COMMON TAP AND PANEL-MOUNTED PRESSURE INDICATOR

2

3

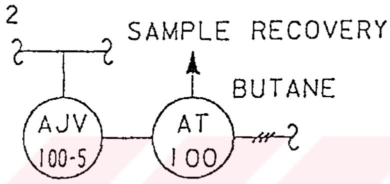
J — SCAN

1



PRESSURE-SCANNING TRANSMITTER CONNECTED TO PROCESS POINTS 5, 6, 7

2

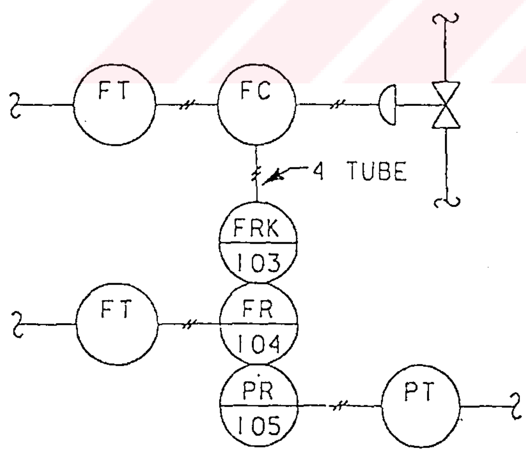


SAMPLE LINE CONNECTED TO BUTANE-CONCENTRATION TRANSMITTER THROUGH EXTERNAL SAMPLE-SCANNING VALVE

3

K — CONTROL STATION

1

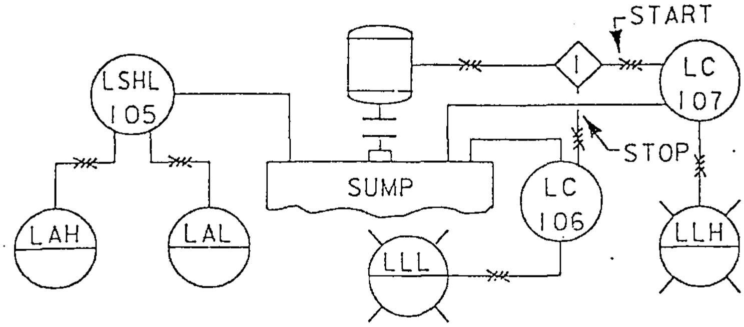


RECORDING FLOW CONTROL STATION PANEL MOUNTED, WITH ADDITIONAL FLOW AND PRESSURE PENS, AND LOCAL CONTROLLER

2

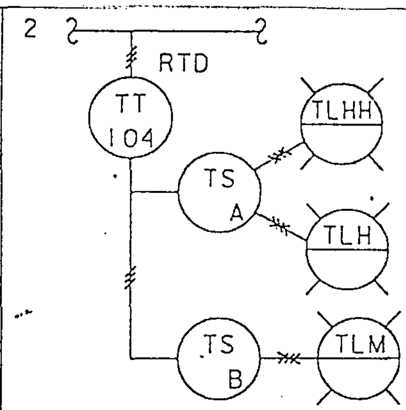
L — LIGHT OR LOW

1



DIFFERENTIAL-GAP CONTROL OF SUMP LEVEL THROUGH STARTING AND STOPPING SUMP PUMP BY LC-107 AND LC-106 THAT ALSO ACTUATE HIGH- AND LOW-LEVEL PILOT LIGHTS. HIGH- AND LOW-LEVEL ALARMS ARE ACTUATED BY LSHL-105

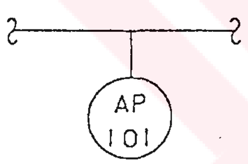
2



PILOT LIGHTS TO SIGNAL THAT TEMPERATURE HAS RISEN TO INTERMEDIATE, HIGH, AND VERY HIGH VALUES

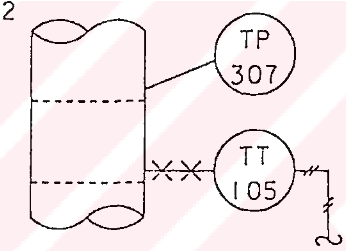
P — POINT

1



ANALYSIS TEST SAMPLE POINT

2

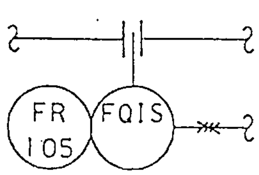


DISTILLATION COLUMN WITH CONNECTION FOR ALTERNATIVE LOCATION OF SENSOR

3

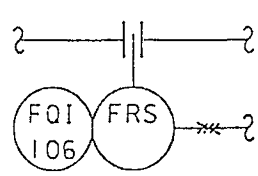
Q — INTEGRATE OR TOTALIZE

1



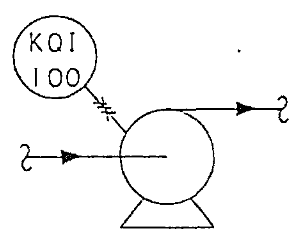
DIFFERENTIAL-PRESSURE-TYPE FLOW METER WITH (1) RECORDING OF FLOW RATE, (2) INDICATION OF INTEGRATED FLOW, AND (3) SWITCH ACTUATED BY INTEGRATED FLOW.

2

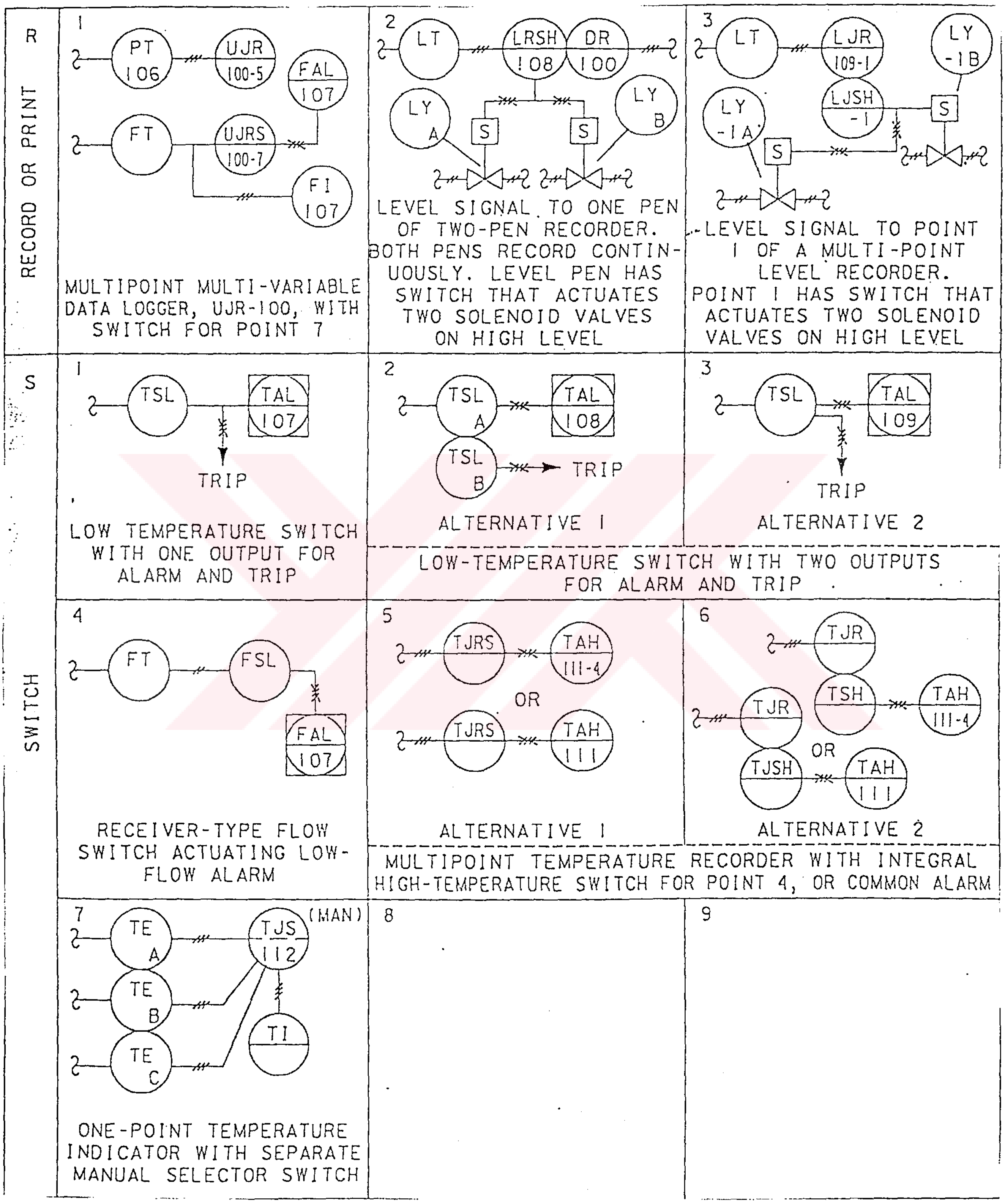


DIFFERENTIAL-PRESSURE-TYPE FLOW METER WITH (1) RECORDING OF FLOW RATE, (2) INDICATION OF INTEGRATED FLOW, AND (3) SWITCH ACTUATED BY FLOW RATE.

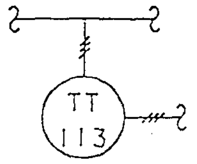
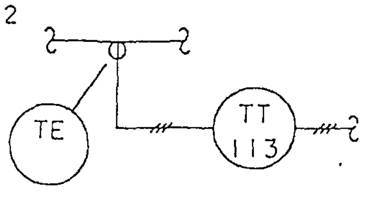
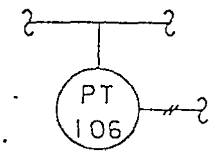
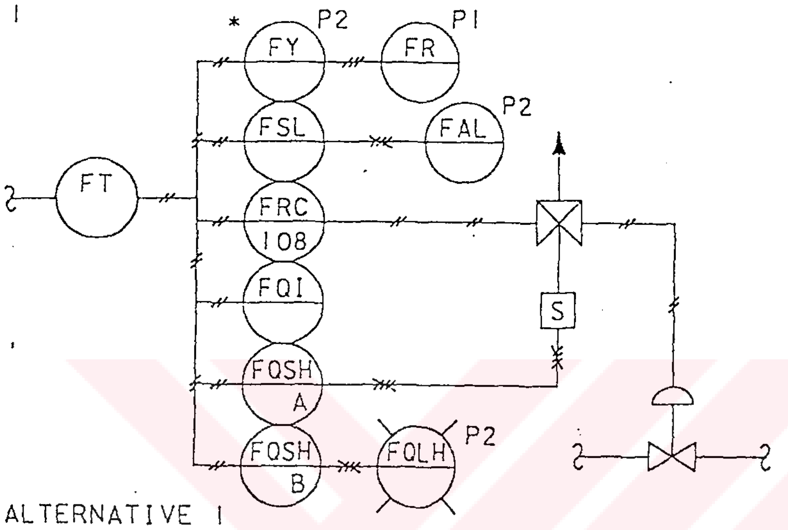
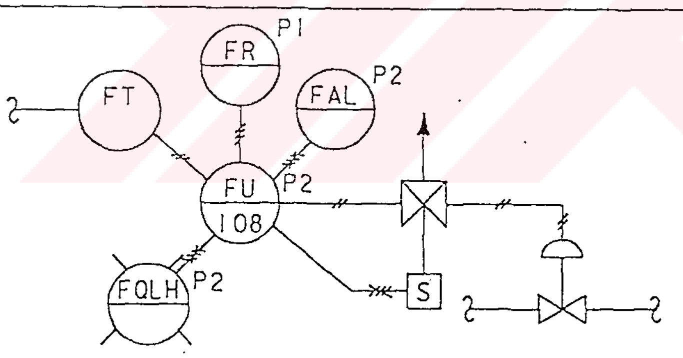
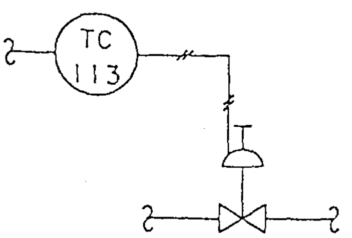
3



RUNNING-TIME TOTALIZER CONNECTED TO PUMP MOTOR



R
RECORD OR PRINT
1
PT 106
UJR 100-5
FAL 107
FT
UJRS 100-7
FI 107
MULTIPOINT MULTI-VARIABLE DATA LOGGER, UJR-100, WITH SWITCH FOR POINT 7
2
LT
LRSH 108
DR 100
LY A
S
S
LY B
LEVEL SIGNAL TO ONE PEN OF TWO-PEN RECORDER. BOTH PENS RECORD CONTINUOUSLY. LEVEL PEN HAS SWITCH THAT ACTUATES TWO SOLENOID VALVES ON HIGH LEVEL
3
LT
LJR 109-1
LY -1B
LY -1A
LJSH -1
S
S
LEVEL SIGNAL TO POINT 1 OF A MULTI-POINT LEVEL RECORDER. POINT 1 HAS SWITCH THAT ACTUATES TWO SOLENOID VALVES ON HIGH LEVEL
S
SWITCH
1
TSL
TAL 107
TRIP
LOW TEMPERATURE SWITCH WITH ONE OUTPUT FOR ALARM AND TRIP
2
TSL A
TAL 108
TSL B
TRIP
ALTERNATIVE 1
3
TSL
TAL 109
TRIP
ALTERNATIVE 2
LOW-TEMPERATURE SWITCH WITH TWO OUTPUTS FOR ALARM AND TRIP
4
FT
FSL
FAL 107
RECEIVER-TYPE FLOW SWITCH ACTUATING LOW-FLOW ALARM
5
TJRS
TAH 111-4
OR
TJRS
TAH 111
ALTERNATIVE 1
6
TJR
TSH
TAH 111-4
TJR
OR
TJSH
TAH 111
ALTERNATIVE 2
MULTIPOINT TEMPERATURE RECORDER WITH INTEGRAL HIGH-TEMPERATURE SWITCH FOR POINT 4, OR COMMON ALARM
7
TE A
TE B
TE C
TJS 112
(MAN)
TI
ONE-POINT TEMPERATURE INDICATOR WITH SEPARATE MANUAL SELECTOR SWITCH
8
9

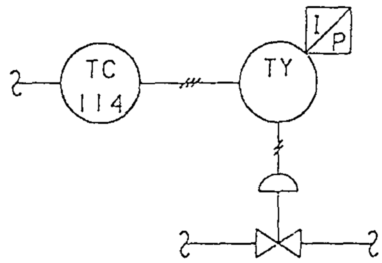
	1	2	3
T TRANSMIT	 TRANSMITTER WITH THERMO-COUPLE INPUT AND ELECTRIC OUTPUT*	 ALTERNATIVE TO 1	 TRANSMITTER WITH PNEUMATIC OUTPUT
U MULTIFUNCTION	1  ALTERNATIVE 1 2  ALTERNATIVE 2		FLOW SIGNAL RECEIVED BY PANEL P2 INSTRUMENT THAT INDICATES AND RECORDS FLOW, HAS SWITCH TO ACTUATE LOW-FLOW ALARM, HAS A CONTROLLER TO ACTUATE A VALVE, RELAYS THE MEASUREMENT TO A RECORDER ON PANEL P1, INTEGRATES THE FLOW, INDICATES THE INTEGRATED FLOW, HAS A SWITCH TO ACTUATE A SOLENOID VALVE AFTER A GIVEN INTEGRATED FLOW HAS PASSED, AND HAS ANOTHER SWITCH TO ACTUATE A PILOT LIGHT AFTER ANOTHER INTEGRATED FLOW HAS PASSED
V VALVE, DAMPER, OR LOUVER	 CONTROL VALVE WITH TOP-MOUNTED HANDJACK		

* See definition of converter versus transmitter.

Y

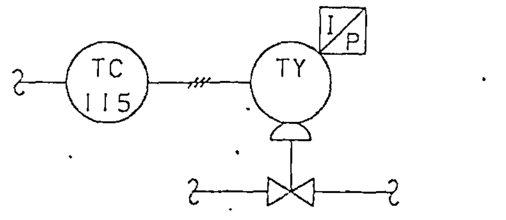
COMPUTE OR RELAY

1



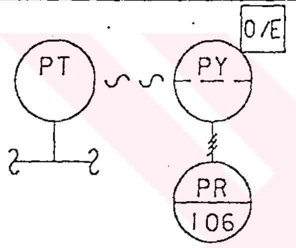
ELECTRIC CURRENT SIGNAL ACTUATING PNEUMATIC CONTROL VALVE WITH SEPARATELY MOUNTED ELECTRO-PNEUMATIC CONVERTER. THE CONVERTER SYMBOL MAY BE OMITTED

2



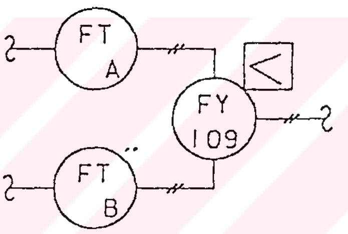
ELECTRIC CURRENT SIGNAL TO PNEUMATIC CONTROL VALVE FURNISHED WITH ATTACHED ELECTRO-PNEUMATIC SIGNAL CONVERTER. THE CONVERTER SYMBOL MAY BE OMITTED

3



PRESSURE TRANSMITTER WITH RADIO (OR LASER) OUTPUT, RADIO- (OR LASER-) TO-VOLTAGE CONVERTER, AND PRESSURE RECORDER

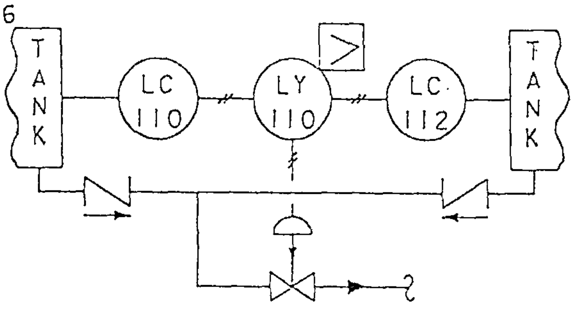
4



SELECTOR RELAY WHOSE OUTPUT REPRESENTS LOWER FLOW OF FT-109A OR FT-109B

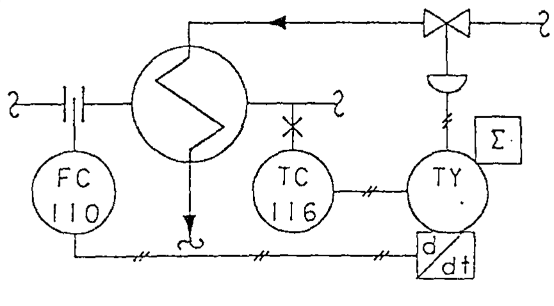
5

6

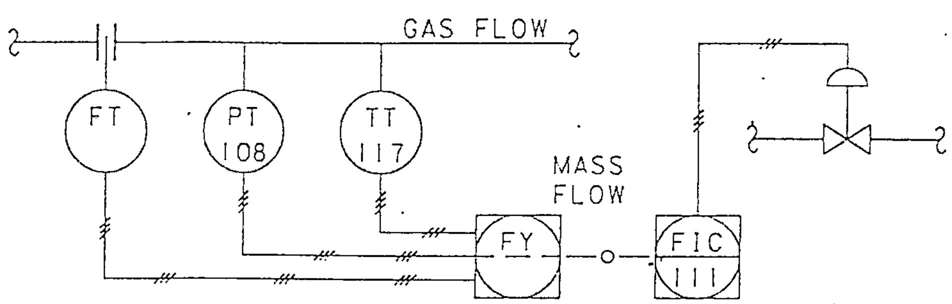
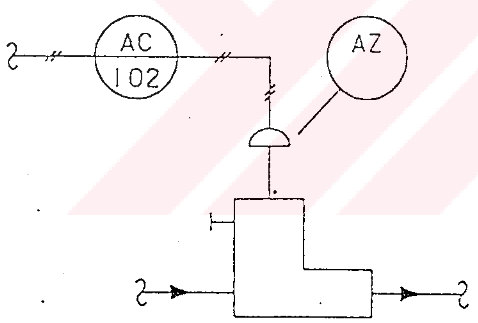
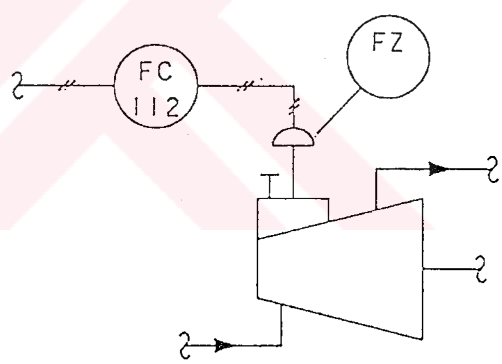


TANK OUTLET VALVE TO OPEN AS REQUIRED BY THE HIGHER OF TWO LEVELS

7



TEMPERATURE CONTROL WITH FLOW-ANTICIPATING RELAY

Y COMPUTE OR RELAY (Contd.)	8  MASS-FLOW COMPUTATION PERFORMED BY MASS-FLOW COMPUTING RELAY FY-111 HAVING LINEAR INPUTS FOR PRESSURE AND TEMPERATURE AND A NON-LINEAR INPUT FOR FLOW	
Z DRIVE, ACTUATE, OR UNCLASSIFIED FINAL CONTROL ELEMENT	1  PROPORTIONING PUMP WITH AUTOMATIC AND MANUAL STROKE CONTROL	2  TURBINE WITH AUTOMATIC AND MANUAL SPEED CHANGER

APPENDIX-D

DEFINITIONS OF THE FREQUENTLY USED PROCESS AUTOMATION TERMS

Accessible - A term applied to a device or *function* that can be used or be seen by an operator for the purpose of performing control actions, e.g., *set point* changes, auto-manual transfer, or on-off actions

Alarm - A device or *function* that signals the existence of an abnormal condition by means of an audible or visible discrete change, or both, intended to attract attention

It is not recommended that the term *alarm switch* or *alarm* be used to designate a device whose operation is simply to close or open a circuit may or may not be used for normal or abnormal interlock, start-up, shut down, actuation of an *alarm device* or the like. The first device is properly designated as a level *switch,* a flow *switch,* etc, because "switching" is what the device does. The device may be designated as an *alarm,* only the device itself contains the *alarm function*

Assignable - a term applied to a feature permitting the channeling (or directing) of a signal from one device to another without the need for switching, patching, or changes in wiring.

Auto-Manual Station - Synonym for *control station.*

Balloon - Synonym for *bubble*

Behind the Panel - A term applied to a location that is within the area that contains the *instrument panel,* its associated rack mounted hardware, or is enclosed within the *panel. Behind the Panel* devices are not *accessible* for the operator's normal use, and are not designated as *local* or front of *panel mounted.* In a very broad sense, *"Behind the Panel"* is equivalent to " not normally *accessible* to the operator"

Binary - A term applied to a signal or device that has only two discrete positions or states. When used in simplest form, as in "*binary* signal" (as opposed to "analog signal"), the term denotes an "on-off" or "high-low" state, i.e., one which does not represent continuously varying quantities

Board - Synonym for panel

Bubble - The circular symbol used to denote and identify the purpose of an *instrument* or a *function.* It may contain a tag number. Synonym for *balloon*

Computing Device - A device or a *function* that performs one or more calculations or logic operations, or both, and transmits one or more resultant output signals. A *computing device* is sometimes called a *computing relay*

Configurable - A term applied to a device or a system whose functional characteristics can be selected or rearranged through programming or other methods. The concept excludes rewiring as a means of altering the configuration.

Controller - A device having an output that varies to regulate a controlled variable in a specified manner. A *controller* may be a self contained analog or *digital instrument,* or it may be the equivalent of such an *instrument* in a shared controlled system.

An automatic *controller* varies its output automatically in response to a direct or indirect input of a measured *process variable.* A manual *controller* is a *manual loading station,* and its output is not dependent on a measured *process variable* but can only be varied by manual adjustment.

A *controller* may be integral with other functional elements of a control *loop.*

Control Station - A *manual loading station* that also provides switching between manual and automatic control modes of a control *loop.* It is also known as an *auto-manual station.* In addition, the operator interface of a *distributed control system* may be regarded as a *control station*

Control Valve - A device, other than a common, hand actuated ON-OFF valve or self actuated check valve, that directly manipulates the flow of one or more fluid process streams.

It is expected that use of the designation "hand *control valve* " will be limited to hand actuated valves that are used for process throttling, or require *identification* as an *instrument.*

Converter - A device that receives information in one form of an instrument signal and transmits an output signal in another form.

An *instrument* which changes a sensor's standard signal is properly designated as a *transmitter,* not a *converter.* Typically, a temperature element (TE) may connect to a *transmitter* (TT), not to a *converter.*

A *converter* is also referred to as a *transducer;* however, "*transducer* " is a completely general term, and its use specifically for signal conversion is not recommended.

Digital - A term applied to a signal or device that uses *binary* digits to represent continuous values or discrete states

Distributed Control System - A system which, while being functionality integrated, consists of subsystems which may be physically separate and remotely located from one to another.

Final Control Element - The device that directly controls the value of the manipulated variable of a controlled *loop.* Often the *final control element* is *a control valve*

Function - The purpose of, or an action performed by a device

Identification - The sequence of letters or digits, or both, used to designate an individual *instrument or loop*

Instrument - *A* device used directly or indirectly to measure and/or control a variable. The term includes *primary elements*, *final control elements, computing devices,* and electrical devices such as annunciators, *switches,* and push buttons. The term does not apply to parts (e.g. a receiver bellows or a resistor) that are internal components of an *instrument*

Instrumentation - A collection of *instruments* or their application for the purpose of observation, *measurement,* control, or any combination of these.

Local - The location of an *instrument* that is neither in nor on a *panel or* console, nor is it mounted in a control room. *Local instruments* are commonly in the vicinity of plant subsystems or sub-areas. The term *"local panel instrument"* should not be confused with *"local instrument"*

Loop - A combination of two or more *instruments* or control *functions* arranged so that signals pass from one to another for the purpose of *measurement* and/or control of a *process variable*

Manual Loading Station - A device or a *function* having a manually adjustable output that is used to actuate one or more remote devices. The station does not provide switching between manual and automatic control modes of a control *loop.* The station may have integral indicators, lights, or other features. It is also known as a manual station or a manual loader.

Measurement - The determination of the existence or the magnitude of a variable

Monitor - A general term for an *instrument or instrument system* used to measure or sense the status or magnitude of one or more variables for the purpose of deriving useful information. The term *monitor* is very nonspecific, sometimes meaning an analyzer, indicator, or *alarm* . *Monitor* can also be used as a verb

Monitor Light - Synonym for *pilot light*

Panel - A structure that has a group of *instruments* mounted on it, houses the operator-process interface, and is chosen to have a unique designation. The *panel* may consist of one or more sections, cubicles, consoles, or desks. Synonym for *board*

Panel Mounted - A term applied to an *instrument* that is mounted on a *panel* or console and is *accessible* for an operator's normal use. A *function* that is normally *accessible* to an operator in a *shared display* system is the equivalent of a discrete *panel mounted* device

Pilot Light - A light that indicates which of a number of normal conditions of a system or device exists. It is unlike an *alarm light,* which indicates abnormal condition. The *pilot light* is also known as a *monitor light*

Primary Element - Synonym for *sensor*

Process - Any operation or sequence of operations involving a change of energy, state, composition, dimension, or other properties that may be defined with respect to a datum

Process Variable - Any variable property of a *process.* The term *process variable* is used in this standard to apply to all variables other than *instrument* signals

Program - A repeatable sequence of actions that defines the status of outputs as a fixed relationship to a set of inputs

Programmable Logic Controller - A *controller,* usually with multiple inputs and outputs, that contains an alterable *program*

Relay - A device whose *function* is to pass on information in an unchanged form or in some modified form. *Relay* is often used to mean *computing device.* The latter term is preferred

The term "*relay* " also is applied specifically to an electric, pneumatic, or hydraulic *switch* that is actuated by a signal. The term also is applied to *functions* performed by a *relay*

Scan - To sample, in a predetermined manner, each of a number of variables intermittently. The *function* of a scanning device is often to ascertain the state or value of a variable. The device may be associated with other *functions* such as recording or alarming

Sensor - That part of a *loop*