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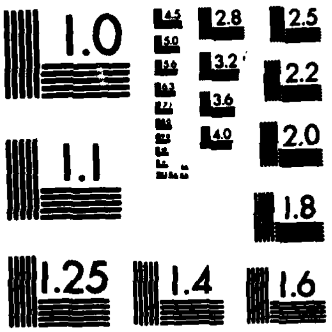

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# CR 83.014

NAVAL CIVIL ENGINEERING LABORATORY
Port Hueneme, California

Sponsored by
Navy Energy and Natural Resources R&D
Office, Washington, DC
Naval Facilities Engineering Command
Alexandria, Virginia

# BOILER CONTROL SYSTEMS OXYGEN TRIM SYSTEMS MANUAL

February 1983

An Investigation Conducted by
ULTRASYSTEMS, INC.
2400 Michelson Drive
Irvine, California

N62474-81-C-9388

Approved for public release; distribution unlimited

# METRIC CONVERSION FACTORS

## Approximate Conversions to Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| in | inches | *2.5 | centimeters | cm |
| ft | feet | 30 | centimeters | cm |
| yd | yards | 0.9 | meters | m |
| mi | miles | 1.6 | kilometers | km |
| | | **AREA** | | |
| $in^2$ | square inches | 6.5 | square centimeters | $cm^2$ |
| $ft^2$ | square feet | 0.09 | square meters | $m^2$ |
| $yd^2$ | square yards | 0.8 | square meters | $m^2$ |
| $mi^2$ | square miles | 2.6 | square kilometers | $km^2$ |
| | acres | 0.4 | hectares | ha |
| | | **MASS (weight)** | | |
| oz | ounces | 28 | grams | g |
| lb | pounds | 0.45 | kilograms | kg |
| | short tons (2,000 lb) | 0.9 | tonnes | t |
| | | **VOLUME** | | |
| tsp | teaspoons | 5 | milliliters | ml |
| Tbsp | tablespoons | 15 | milliliters | ml |
| fl oz | fluid ounces | 30 | milliliters | ml |
| c | cups | 0.24 | liters | l |
| pt | pints | 0.47 | liters | l |
| qt | quarts | 0.95 | liters | l |
| gal | gallons | 3.8 | liters | l |
| $ft^3$ | cubic feet | 0.03 | cubic meters | $m^3$ |
| $yd^3$ | cubic yards | 0.76 | cubic meters | $m^3$ |
| | | **TEMPERATURE (exact)** | | |
| °F | Fahrenheit temperature | 5/9 (after subtracting 32) | Celsius temperature | °C |

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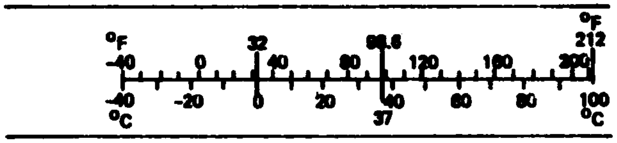
*1 in = 2.54 (exactly). For other exact conversions and more detailed tables, see NBS Misc. Publ. 286, Units of Weights and Measures, Price $2.25, SD Catalog No. C13.10:286.

## Approximate Conversions from Metric Measures

| Symbol | When You Know | Multiply by | To Find | Symbol |
|---|---|---|---|---|
| | | **LENGTH** | | |
| mm | millimeters | 0.04 | inches | in |
| cm | centimeters | 0.4 | inches | in |
| m | meters | 3.3 | feet | ft |
| m | meters | 1.1 | yards | yd |
| km | kilometers | 0.6 | miles | mi |
| | | **AREA** | | |
| $cm^2$ | square centimeters | 0.16 | square inches | $in^2$ |
| $m^2$ | square meters | 1.2 | square yards | $yd^2$ |
| $km^2$ | square kilometers | 0.4 | square miles | $mi^2$ |
| ha | hectares (10,000 $m^2$) | 2.5 | acres | |
| | | **MASS (weight)** | | |
| g | grams | 0.035 | ounces | oz |
| kg | kilograms | 2.2 | pounds | lb |
| t | tonnes (1,000 kg) | 1.1 | short tons | |
| | | **VOLUME** | | |
| ml | milliliters | 0.03 | fluid ounces | fl oz |
| l | liters | 2.1 | pints | pt |
| l | liters | 1.06 | quarts | qt |
| l | liters | 0.26 | gallons | gal |
| $m^3$ | cubic meters | 35 | cubic feet | $ft^3$ |
| $m^3$ | cubic meters | 1.3 | cubic yards | $yd^3$ |
| | | **TEMPERATURE (exact)** | | |
| °C | Celsius temperature | 9/5 (then add 32) | Fahrenheit temperature | °F |



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Report is educational material for boiler operating personnel describing the principles which govern excess-air trim systems and their application to industrial boiler combustion control for the purpose of increasing the boiler's efficiency.

# OXYGEN TRIM SYSTEMS MANUAL

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# 1.0 INTRODUCTION

The Oxygen Trim Systems Manual is intended to serve as a guide for boiler operating personnel in understanding the concepts and principles which govern combustion air trim systems and their application to industrial boiler combustion control for the purpose of increasing the boiler efficiency. The Oxygen Trim Systems Manual also serves to familiarize the boiler operating personnel with the various trim systems that are commercially available, using different constituents of the flue gas as a control parameter.

The manual is generally confined to oil and gas-fired heating boilers in the 60 million BTU per hour capacity range, but many of the concepts and principles discussed are applicable to boilers of any size.

Combustion air trim systems employing carbon dioxide, oxygen, and carbon monoxide as a control parameter, singly or in combination, are covered. Smoke prevention and control is also discussed. Section 2.0 is devoted to terminology and definitions of technical and non-technical terms peculiar to combustion control, with which the user might not be familiar. This was done so that the manual be self-contained to the extent practicable. Section 3.0 consists of a simplified theoretical background; it deals with basic requirements for good combustion, flue-gas analysis and measurement, and how these measurements can be used to improve the boiler efficiency. Section 4.0 identifies the various combustion air trim systems that can be added to the combustion control loop of existing heating boilers for the purpose of optimizing the boiler efficiency. Section 5.0 identifies the different kinds of analyzers that are used in various oxygen trim systems. Section 6.0 provides an evaluation of various trim systems and delineates the advantages and disadvantages of each system. Section 7.0 provides general procedures for addition of oxygen (air) trim systems to the combustion control loop of existing heating boilers including jackshaft, pneumatic and electric systems.

Section 8.0 presents a discussion of the $O_2$ trim offerings of the major manufacturers, while conclusions and recommendations are included as Section 2.0.

## 2.0 CONCLUSIONS AND RECOMMENDATIONS

### 2.1 Benefits

The simplicity, low cost, ruggedness, and ease of calibration of the zirconium oxide sensor has been a major factor in making $O_2$ trim practical for small heating boilers. The economies of their application are very impressive, for example:

If a conservative 2 percent fuel saving is assumed due to $O_2$ trim for a 60,000 PPH heating boiler which is operated for only 200 days per year at an average of 75 percent capacity, burning oil fuel at $30 per barrel, we get a yearly savings of approximately $32,000. This indicates that the $10,000 to $20,000 installed cost of an $O_2$ Trim system will payoff in 4 to 8 months.

The fuel savings is the major benefit, but other advantages of the $O_2$ Trim system are:

- Reduced operator effort.
- Lower pollutant emissions.
- Safer operation.
- No visible smoke.

### 2.2 Cautions

There are some cautions in the application of $O_2$ trim systems that must be strongly stated, as there is a great deal of misunderstanding about their effectiveness caused by the overselling of some sales representatives. The following warning statements should be carefully considered before purchase of any $O_2$ Trim system:

1. An $O_2$ Trim system will not make an old, tired boiler control system perform like new. As a matter of fact, it may not perform any better at all with $O_2$ Trim than it did without $O_2$ Trim.

2. If a very careful manual adjustment of a boiler control system, using an $O_2$ indicator or recorder, does not markedly improve the performance, the addition of an $O_2$ Trim system will not help.
3. If the "play" or "dead band" of a boiler control system is of a magnitude anywhere near the "trim range" of an $O_2$ trim system, the addition of an $O_2$ Trim system will not help.
4. The response characteristics of an $O_2$ Trim system must be such that interplay with the primary control system does not cause hunting or other dynamic misbehavior.
5. Infiltration of air into the flue gases must be avoided.
6. A lead-lag or other control technique must be used to prevent air/fuel ratio excursions, and possible smoke, on boiler load changes.
7. $O_2$ trim is not very effective on boilers which operate at low loads most of the time.
8. Selection of the sampling location(s) is very important in order to insure that a representative sample is taken for analysis, especially where a single probe location is used as with the in-situ analyser.

## 2.3 Recommendations

The benefits of an $O_2$ Trim system can be excellent if it is applied to a "tight" boiler control system with appropriate control characteristics. A recommended method for the Navy to obtain the benefits of $O_2$ Trim, without a disappointing experience, would be to combine it with the digital control system program suggested in the Task 4 Report. This suggested program would involve a field test of several $O_2$ Trim systems on different but geographically close boilers, in conjunction with the similar program for digital control systems. This program would encompass rotation of both operators and maintenance personnel, and the keeping of good performance and service records. Completion of this comparative evaluation test would give the Navy an excellent basis for future application of $O_2$ Trim systems to small heating boiler control systems.

# 3.0 THEORETICAL BACKGROUND

## 3.1 General

To burn a fuel oil or natural gas completely in a boiler furnace, four basic conditions must be fulfilled: (1) enough air must be supplied to support complete combustion, that is, to completely oxidize the combustible elements in the fuel, (2) fuel and air must be mixed thoroughly, (3) furnace temperature must be kept high enough to ignite incoming fuel-air mixture, and (4) the combustion zone of the furnace must have enough volume to allow time for completing the combustion reaction. This manual is primarily concerned with the first of these four basic conditions for good combustion; all four conditions interface with smoke formation and prevention, which will be discussed in Section 4.0 with reference to both gas and oil-fired boilers.

Combustion, or burning, is an oxidation reaction in which the combustible elements in the fuel combine with the oxygen in air to form various gases, the formation of which results in the release of large amounts of heat referred to as the heat of combustion. Note that the hydrocarbon compounds in the fuel "crack," or break down to their elements (carbon and hydrogen), when the fuel is sufficiently heated, and then the elements combine with the oxygen in air to release large amounts of heat. An exception to this occurs in a gas-fired boiler that uses a premix burner in which gas and air are mixed before ignition, where burning proceeds by hydroxylation; this is further discussed in Section 5.0, under smoke formation and prevention.

The exact amount of air required to burn a fuel completely is called the stoichiometric (theoretical) air or oxygen. In practice, however, more than this theoretical amount is needed. The additional amount of air needed to burn a fuel completely is called the excess air. For oil and gas-fired boilers, the "rule of thumb" is to provide 10 to 20 percent more air than the theoretical requirement to ensure complete combustion. The excess air supplied is controlled by the boiler combustion control system.

Complete combustion forms the gases carbon dioxide ($CO_2$), water vapor ($H_2O$), and sulfur dioxide ($SO_2$) if sulphur is present in the fuel. Gases leaving the furnace also contain carbon monoxide (CO), oxygen ($O_2$), and nitrogen ($N_2$). These gases, with other combustion products, are collectively referred to as the products of combustion or the flue gas. Carbon monoxide is formed as a result of incomplete combustion; it has a high heating value which is wasted. The oxygen comes from the excess air, and the nitrogen from the total air supply. Under poor combustion conditions, including insufficient excess air, combustible elements as well as hydrocarbon compounds pass through the furnace unburned and appear in the stack gas, along with smoke and soot.

Control of the combustion process described above generally involves regulation of fuel flow, air flow, and composition of the flue gas. In small industrial boilers the fuel and air flow usually is controlled as a function of the steam header pressure. Information about the composition of the flue gas has long been used by boiler operating personnel to reduce the amount of excess air to the minimum safe level, in order to optimize the combustion efficiency.

The concentration of each constituent of the flue gas can be measured, and this measurement can be used to increase the combustion efficiency. The flue gas constituents that are generally used as parameters, singly or in combination, to optimize the combustion efficiency are $CO_2$, $O_2$, CO, smoke, and combustibles; the latter, however, is usually measured in order to prevent explosion hazards. Carbon dioxide and excess oxygen in the flue gas are both indexes of excess air. The desirable $CO_2$ level depends on the fuel and optimum excess air.

Figure 3-1 shows the variations of $CO_2$ and $O_2$ with excess air for complete combustion of natural gas and fuel oils. Note that the desirable $O_2$ values are by far less dependent on the type of fuel. This, of course, is the reason why $O_2$ method of combustion optimization is preferred, particularly when the boiler is equipped to burn more than one type of fuel. However, when a boiler is fired with only one fuel, the $CO_2$ method of combustion optimization is just as effective. Carbon monoxide concentration is independent of excess air and is a direct measure of combustion efficiency. Smoke is also a measure of combustion efficiency.

The above discussion points up to the fact that a knowledge of flue-gas analysis and various methods of measuring the constituent gases $CO_2$, $O_2$, and CO will be helpful in understanding the principles of operation of oxygen trim systems which use $CO_2$, $O_2$, and CO as a control parameter. Therefore, the remaining portion of this section of the manual is devoted to flue-gas analysis and various methods of its measurements.

## 3.2 Flue-Gas Analysis

Carbon and hydrogen are the two main elements in fuels. When pure carbon is oxidized, it reacts with $O_2$ to form $CO_2$. Since air is 21 percent by volume oxygen and 79 percent nitrogen, each mole of oxygen ($O_2$) is accompanied by 3.76 (79/21 = 3.76) moles of nitrogen ($N_2$), which passes through the furnace unchanged. Hence, the combustion gases contain one mole of $O_2$ and 3.76 moles of $N_2$, which means that one volume of $CO_2$ is produced from one volume of $O_2$. This, in practical terms, is because a molecule of gases encountered in boiler plant combustion has the same volume when measured at the same temperature and pressure, even though the molecular weight of each gas is different.

The term hydrogen-carbon ratio (H-C), a measure of heating value in hydrocarbon fuels, is used to indicate the relationship between the hydrogen and carbon content of the fuel; it is the ratio by weight of hydrogen to carbon. The scale of H-C ratio of fuels is called the fuel scale; it varies from zero to 0.336. Carbon is at the zero end of the fuel scale since it contains no hydrogen, and methane ($CH_4$), the main constituent of natural gas, at the other (4 X 1.008/12 = 0.336). Burning methane involves combining the carbon with the oxygen in air to form $CO_2$, and the hydrogen with oxygen to form water. One molecule of methane, two molecules of oxygen and 7.52 (2 X 3.76 = 7.52) molecules of nitrogen, as shown below:

$CH_4$ + 2 molecules air ($O_2 + 3.76\ N_2$)   $CO_2 + 2H_2O = 7.52\ N_2$ + Heat

Note that the nitrogen is the same on both sides of the reaction equation.

In other words, the nitrogen goes through the furnace essentially unchanged. In order to reduce gas measurement to some standard base, it is standard practice to consider all flue-gas analyses on a dry basis, so that all water vapor in flue-gas analysis is condensed and removed.

Therefore, when burning methane, $CO_2$ will be 11.73 percent (1 divided by 1 + 7.52) of the total volume of combustion products with water of combustion removed. This can easily be verified from the right-hand side of the above reaction equation. Thus when burning pure carbon completely, the $CO_2$ is 21 percent of the combustion products by volume, as opposed to 11.73 percent by volume when burning methane. The desirable percentage of $CO_2$ in flue gas is between these two theoretical limits for common fuels, which depends on the hydrogen-carbon ratio of the fuel. Note that the higher the hydrogen-carbon ratio of a fuel on the fuel scale (0-0.336), the less is its heating value as well as the percentage of $CO_2$ for a given excess air. This is indicated in Figure 3-1.

The burning of pure carbon and methane just mentioned illustrated a stoichiometric (theoretical) combustion, since no excess air was included. In actual practice, excess air is required to ensure complete combustion. If, for example, 40 percent excess air was provided during the burning of carbon, the $O_2$ and $N_2$ percentages would increase by 40 percent. Since the amount of oxygen required to burn the carbon remains the same as before, 0.4 moles of oxygen and approximately 5.26 (1.4 X 3.76 = 5.26) moles of nitrogen appear in the products of combustion. Under these conditions, the $CO_2$ content of the flue gas is reduced to 15.1 (100 divided by 1 + 0.4 + 5.26 = 15.1) from the previous 21 percent, but approximately 6.0 percent excess oxygen also appears in the flue gas.

If there is insufficient excess air, all the carbon does not oxidize to $CO_2$, which means some carbon monoxide gas (CO) will appear in the flue gases. The usually accepted lower limit and upper limit of CO in oil and gas fired burners is 100 and 250 part per million (ppm), respectively. Carbon monoxide in excess of 250 ppm is an indication of combustion inefficiency, and is usually accompanied by smoke, so that enough excess air should be provided to prevent excessive carbon monoxide in the flue gases. Insufficient excess air can cause unsafe conditions in the furnace.

The amount of excess air that should be provided with a given set of conditions can best be determined by testing the flue gas for $CO_2$ percentage. The object is to attain the highest amount of $CO_2$ by using the smallest amount of excess air without producing CO. For oil and gas-fired boilers usually 10 to 20 percent excess air is provided. Note that this is the same as 2.1 to 4.2 percent by volume oxygen. The corresponding $CO_2$ percentage for fuel oil is about 15 percent, and for natural gas about 11 percent. Note that these percentages are average and vary with the grade of oil and composition of natural gas, that is, the hydrogen-carbon ratio.

## 3.3 Orsat Analyzer

One of the most reliable and inexpensive methods of measuring the percentage of $CO_2$ is by using a hand-operated Orsat gas analyzer. Most boiler rooms have an Orsat analyzer, but it does not lend itself to automatic control, since it is a "wet" test and is not suitable for continuous analysis. It is used during boiler performance test and start-up as well as for combustion conditions in the furnace, on a scheduled basis.

In addition to $CO_2$, the Orsat analyzer can measure $O_2$ and CO. Generally, it can be concluded from a complete Orsat analysis that high carbon dioxide means low excess air, and, therefore, low direct heat loss out the stack, and that high carbon monoxide means problems in the furnace such as a dirty burner. Measurement of oxygen is usually used to check the accuracy of the $CO_2$ measurement.

## 3.4 $CO_2$ Recorders

A $CO_2$ recorder is an apparatus for automatically determining the percentage of $CO_2$ in flue gas and recording the result of the analysis on a chart. A $CO_2$ recorder is sometimes called a combustion meter. Some modern plants are equipped with a $CO_2$ recorder. Unlike the Orsat analyzer, the $CO_2$ recorder shows actual combustion conditions during each 24-hour period. A complete analysis is made on a continuous basis, usually every two minutes. It does not require any attention from the operating personnel.

There are generally four methods of analyzing $CO_2$: chemical absorption similar to the Orsat analyzer, specific gravity, thermal conductivity and infrared. The latter method is employed in oxygen trim systems and will be further discussed in Section 4.0.

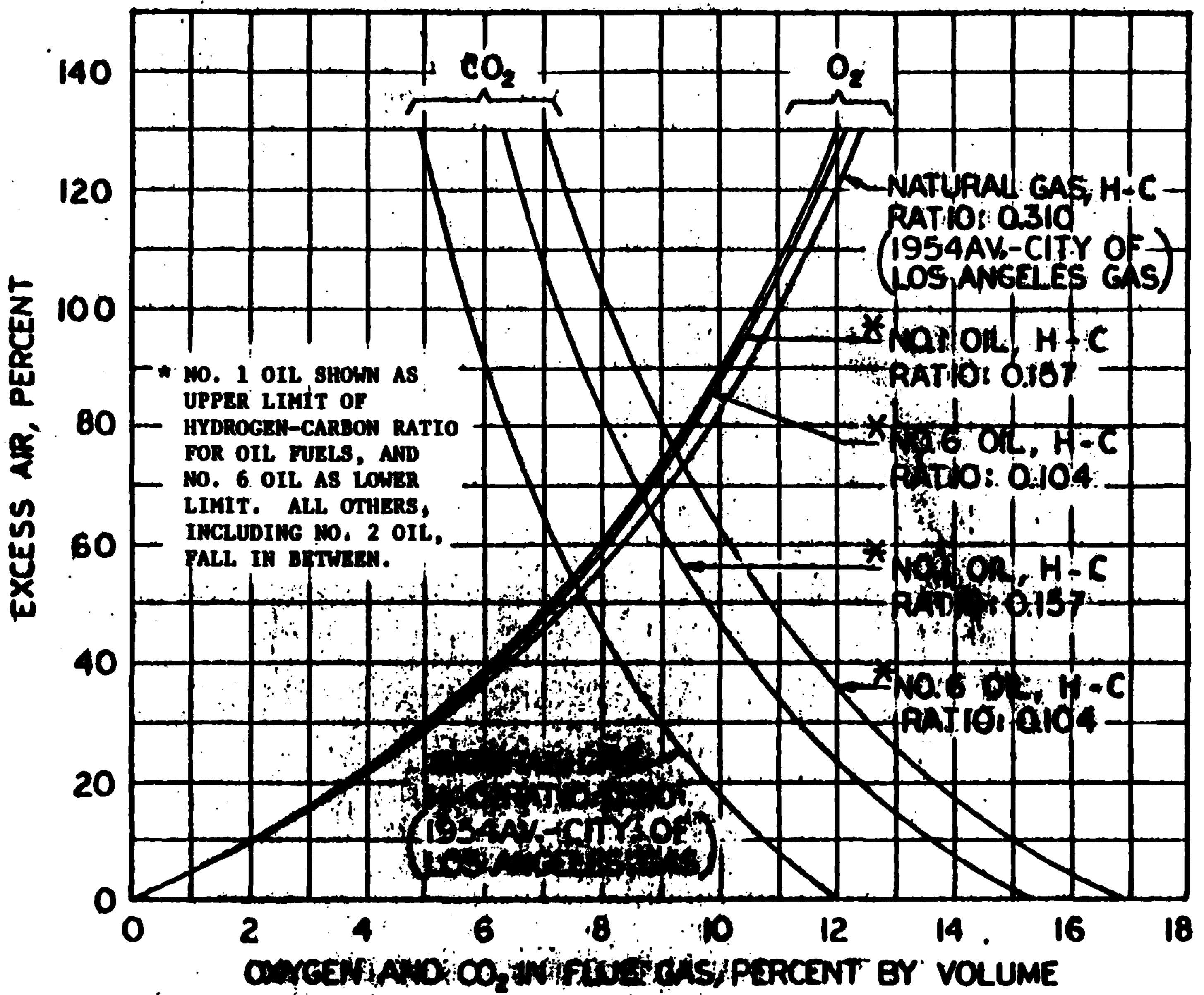


FIGURE 3-1 VARIATION OF OXYGEN AND CARBON DIOXIDE WITH NATURAL GAS/OIL AND EXCESS AIR

# 4.0 OXYGEN TRIM SYSTEMS

## 4.1 General

As was mentioned in Section 3.0, excess air must be supplied to a boiler furnace to burn the fuel completely. Too much excess air means unnecessary heat wasted out the stack, since the temperature of the "surplus" excess air must also be raised from the ambient temperature to that of the stack. On the other hand, insufficient excess air means a waste of fuel, which occurs as the result of incomplete combustion; further, this mode of operation can cause hazardous conditions in the furnace, or flue ducts; through unsafe concentration of combustibles. Eliminating the surplus excess air will increase combustion efficiency.

## 4.2 Oxygen Trim System Function

The function of an oxygen trim system is to increase combustion efficiency. Optimization of combustion efficiency sometimes requires excess air greater than that required by the minimum safe level, for example, when the CO in flue gas is controlled. Regardless of whether the excess air is reduced to the minimum safe level or to some intermediate point within the zone of excess air, the control process involves a reducing of the excess $O_2$ level in the flue gas to a practical minimum.

Auxiliary control systems that measure various flue gas constituents, such as $CO_2$, $O_2$ or CO, and provide a feedback to the combustion control system to regulate the combustion air flow accordingly are known as Oxygen Trim Systems, since they are designed to reduce the excess $O_2$ in the flue gas.

## 4.3 Application to Jackshaft, Pneumatic and Electric Systems

Maintaining the proper flow of air and fuel is the function of the combustion control system. The closeness of control, however, depends on how simple or how complex the combustion control system is made.

Most combustion control systems for industrial boilers in the 60 million BTU per hour range are relatively simple, since at the time of installation fuel costs were relatively low. By far, the vast majority of such boilers have parallel positioning control systems, since they offer quick response time and simplicity of operation; further, the firing rate of the boiler is often determined by the steam header pressure only. Therefore, it will be assumed that candidate boilers for oxygen trim are equipped with parallel positioning systems. The application of oxygen trim to series positioning control systems is similar, and application to metering control systems is the same in principle.

Figure 4-1 shows a block diagram of a simple parallel positioning control system. In a parallel positioning control system, as the name implies, the master pressure controller will generate an output signal on deviation of the steam header pressure from the set point which is sent simultaneously to fuel valve and air damper positioners. In a jackshaft control system (Figure 4-2, 4-3, and 4-4) the output signal from the master pressure controller is merely sent to the jackshaft control drive, or master positioner. In pneumatic parallel positioning systems (Figure 4-5 and 4-6) the master pressure controller output signal is sent simultaneously to the fuel valve positioner and the air-fuel ratio controller which will then transmit an output signal to the air damper positioner. In electric parallel positioning systems (Figures 4-7 and 4-8) the sequence of the control operation in basically the same as that of a pneumatic parallel positioning system, except that electric current is used to transmit control signals instead of compressed air.

A parallel positioning control system is a very simple but somewhat crude system, in that the control of the individual fuel and air positioners is open-loop. Oxygen trim systems provide a small bias or fine tuning adjustment to the air-fuel ratio controller or, in the case of jackshaft systems, to the air damper positioner. This bias helps the parallel positioning system to overcome control difficulties due to calibration, variations in fuel heating value, load changes. etc.

Oxygen trim systems are basically comprised of an analyzer portion which measures a particular constituent (or constituents) of the flue gas, and a controller which provides a fine tuning to the combustion control system. Figure 4-9 is a block diagram of parallel positioning system with oxygen trim, where tuning signal is sent to the air damper positioner. Figures 4-10 and 4-11 are schematic diagrams showing different damper trim positioners that use an adjustable link mechanism.

Analyzers systems may be of the extractive sampling type or in-situ (in-position) type. Oxygen trim systems use $CO_2$, $O_2$, and CO as control parameters, singly or in combination. The various analyzers and methods of analyses follow.

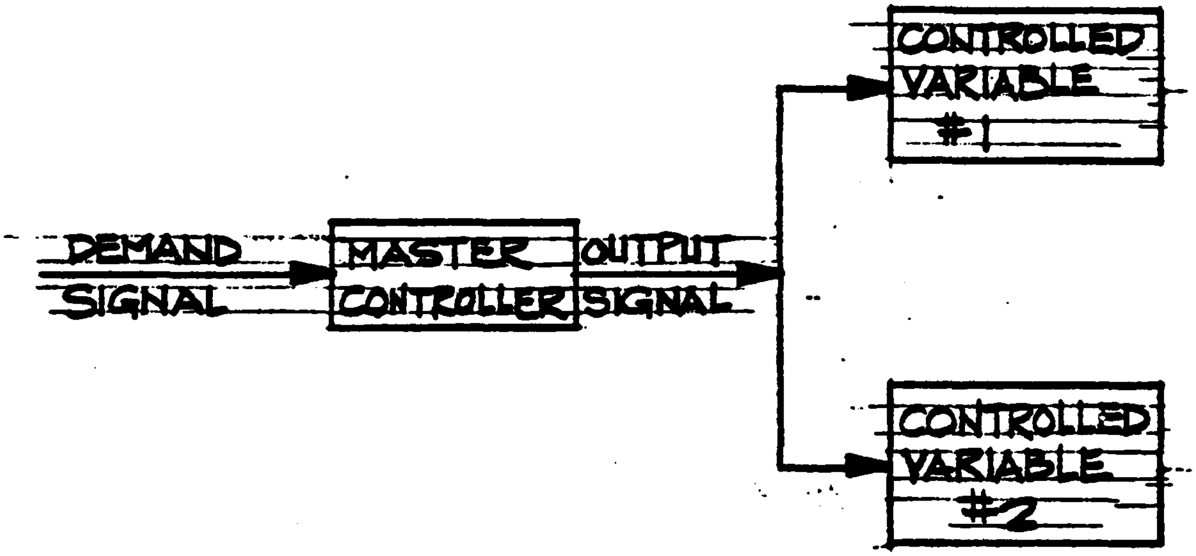


FIGURE 4.1 BLOCK DIAGRAM - SIMPLE PARALLEL POSITIONING SYSTEM

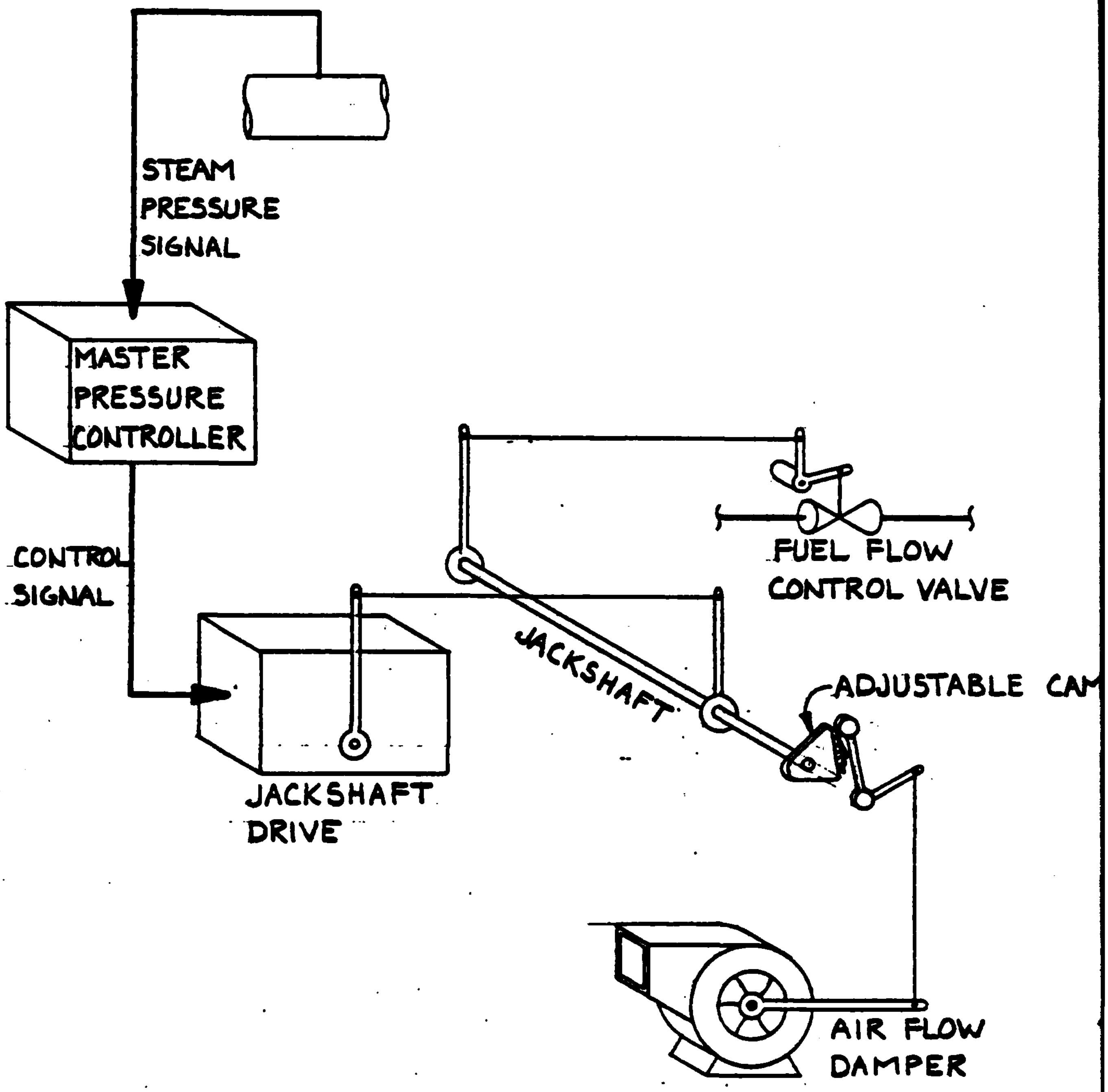


FIGURE 4-2 JACKSHAFT BURNER CONTROL SYSTEM

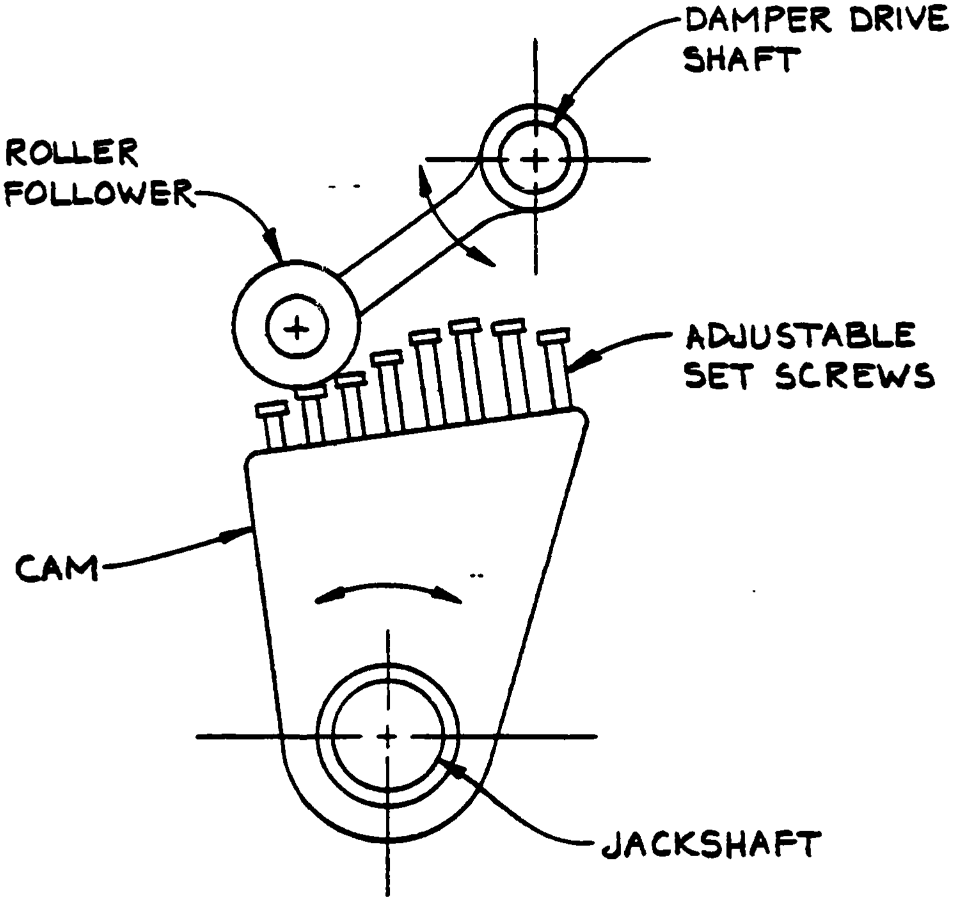


FIGURE 4-3 ADJUSTABLE JACKSHAFT CAM MECHANISM

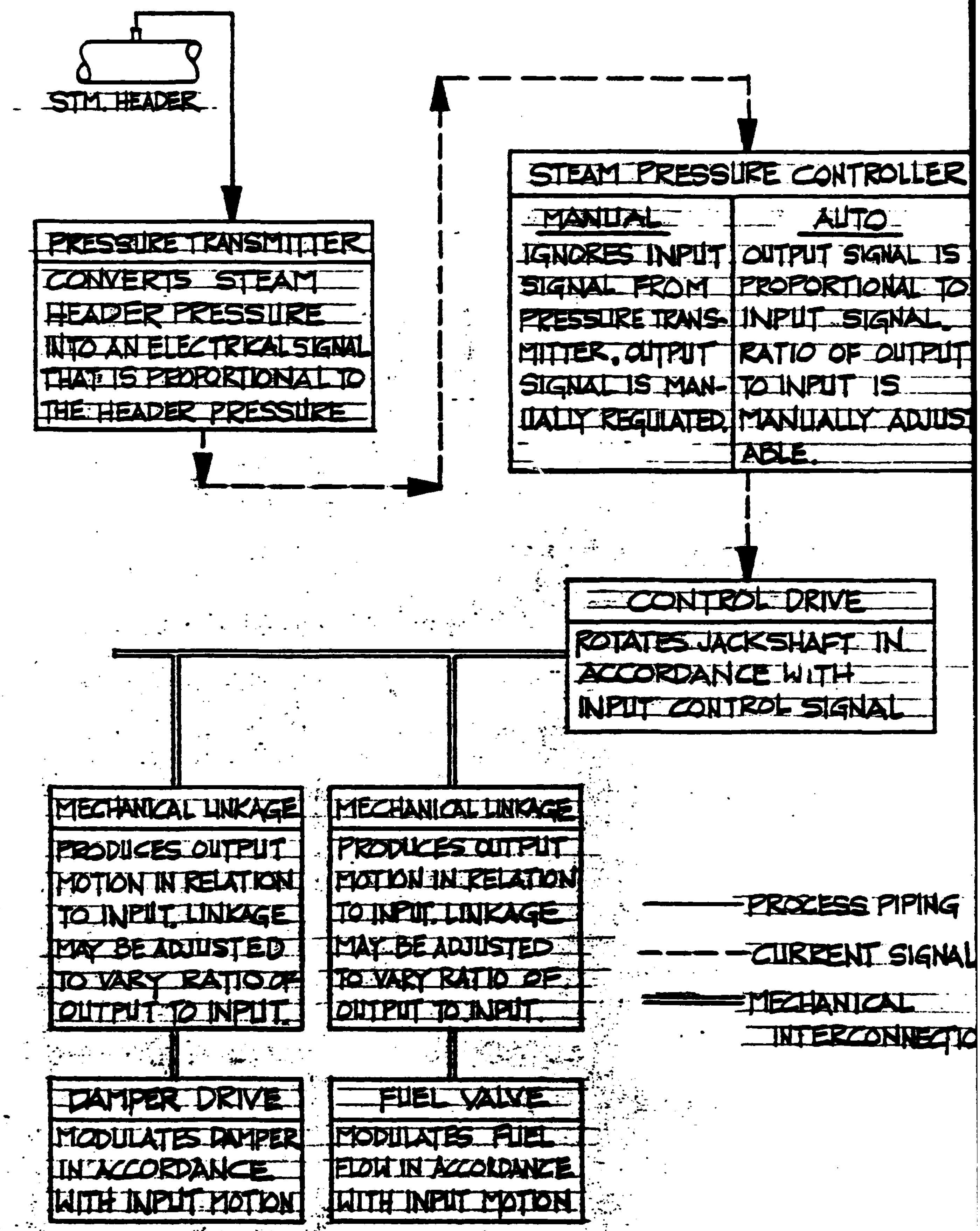


FIGURE 4.4 FUNCTIONAL SCHEMATIC DIAGRAM JACKSHAFT SYSTEM

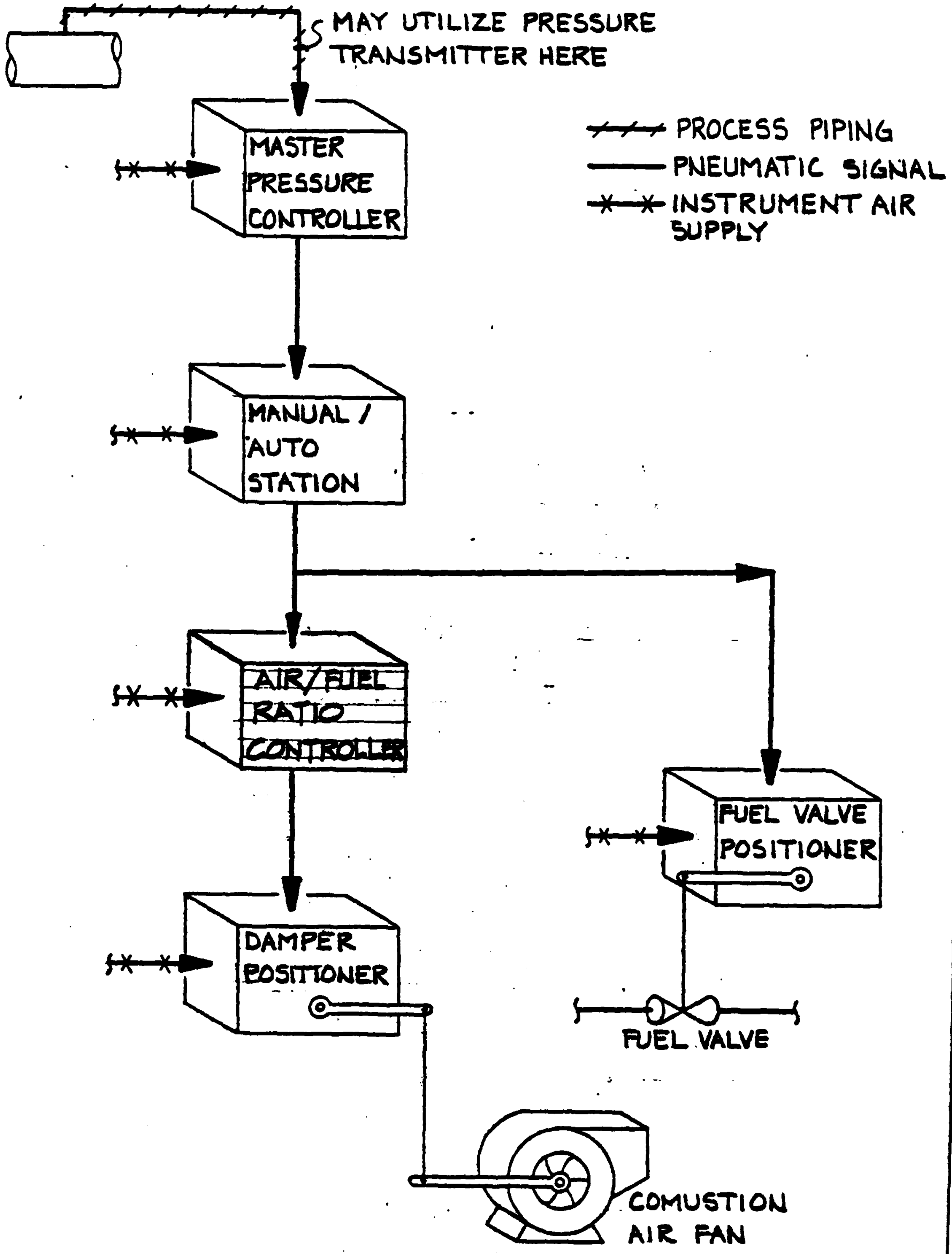
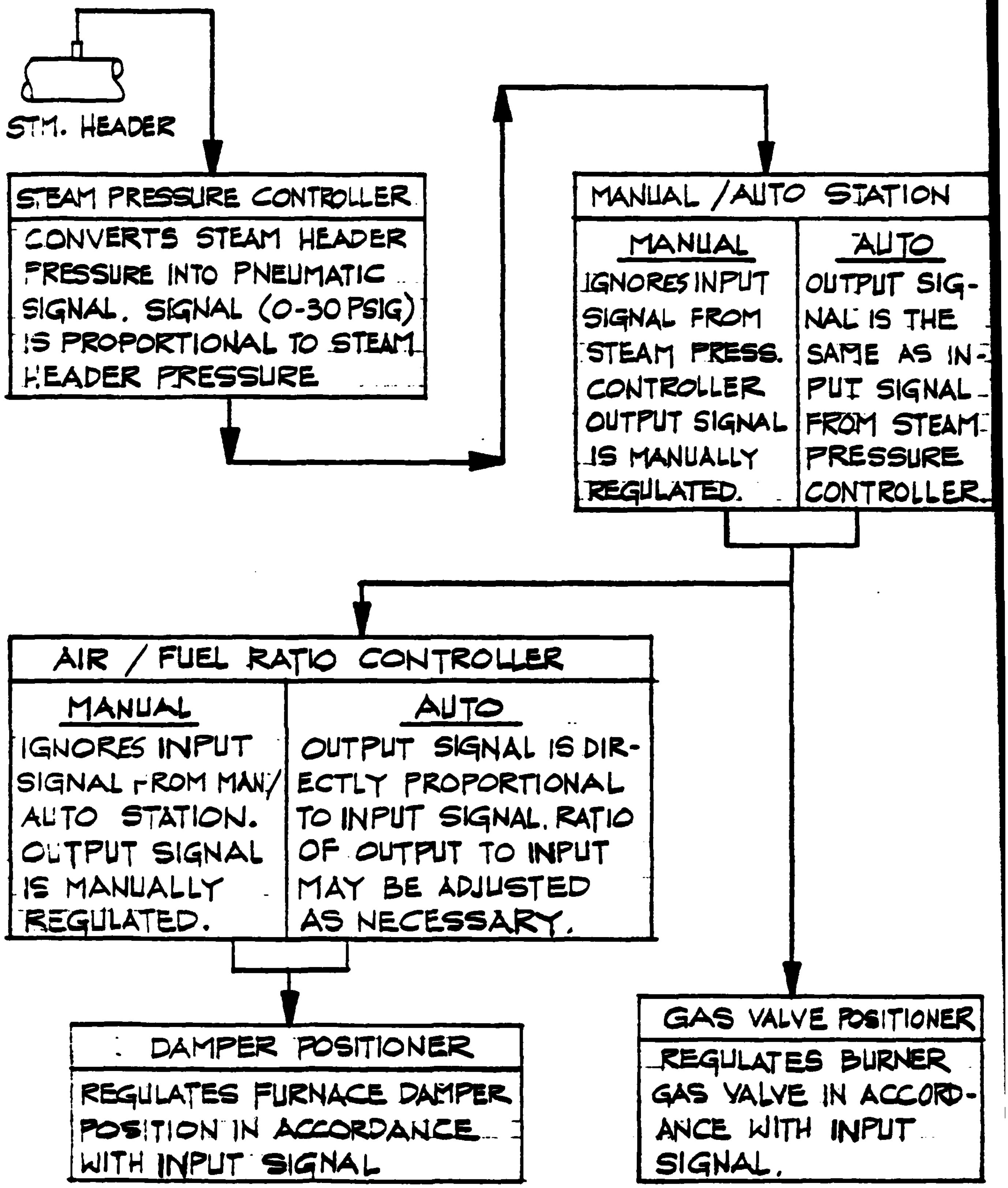


FIGURE 4-5 PARALLEL POSITIONING CONTROL SYSTEM (PNEUMATIC)



**STEAM PRESSURE CONTROLLER**

CONVERTS STEAM HEADER PRESSURE INTO PNEUMATIC SIGNAL. SIGNAL (0-30 PSIG) IS PROPORTIONAL TO STEAM HEADER PRESSURE

**MANUAL /AUTO STATION**

MANUAL: IGNORES INPUT SIGNAL FROM STEAM PRESS. CONTROLLER OUTPUT SIGNAL IS MANUALLY REGULATED.

AUTO: OUTPUT SIGNAL IS THE SAME AS INPUT SIGNAL FROM STEAM PRESSURE CONTROLLER

**AIR / FUEL RATIO CONTROLLER**

MANUAL: IGNORES INPUT SIGNAL FROM MAN/AUTO STATION. OUTPUT SIGNAL IS MANUALLY REGULATED.

AUTO: OUTPUT SIGNAL IS DIRECTLY PROPORTIONAL TO INPUT SIGNAL, RATIO OF OUTPUT TO INPUT MAY BE ADJUSTED AS NECESSARY.

**DAMPER POSITIONER**

REGULATES FURNACE DAMPER POSITION IN ACCORDANCE WITH INPUT SIGNAL

**GAS VALVE POSITIONER**

REGULATES BURNER GAS VALVE IN ACCORDANCE WITH INPUT SIGNAL.

FIGURE 4-6 FUNCTIONAL SCHEMATIC DIAGRAM PARALLEL POSITIONING SYSTEM (PNEUMATIC)

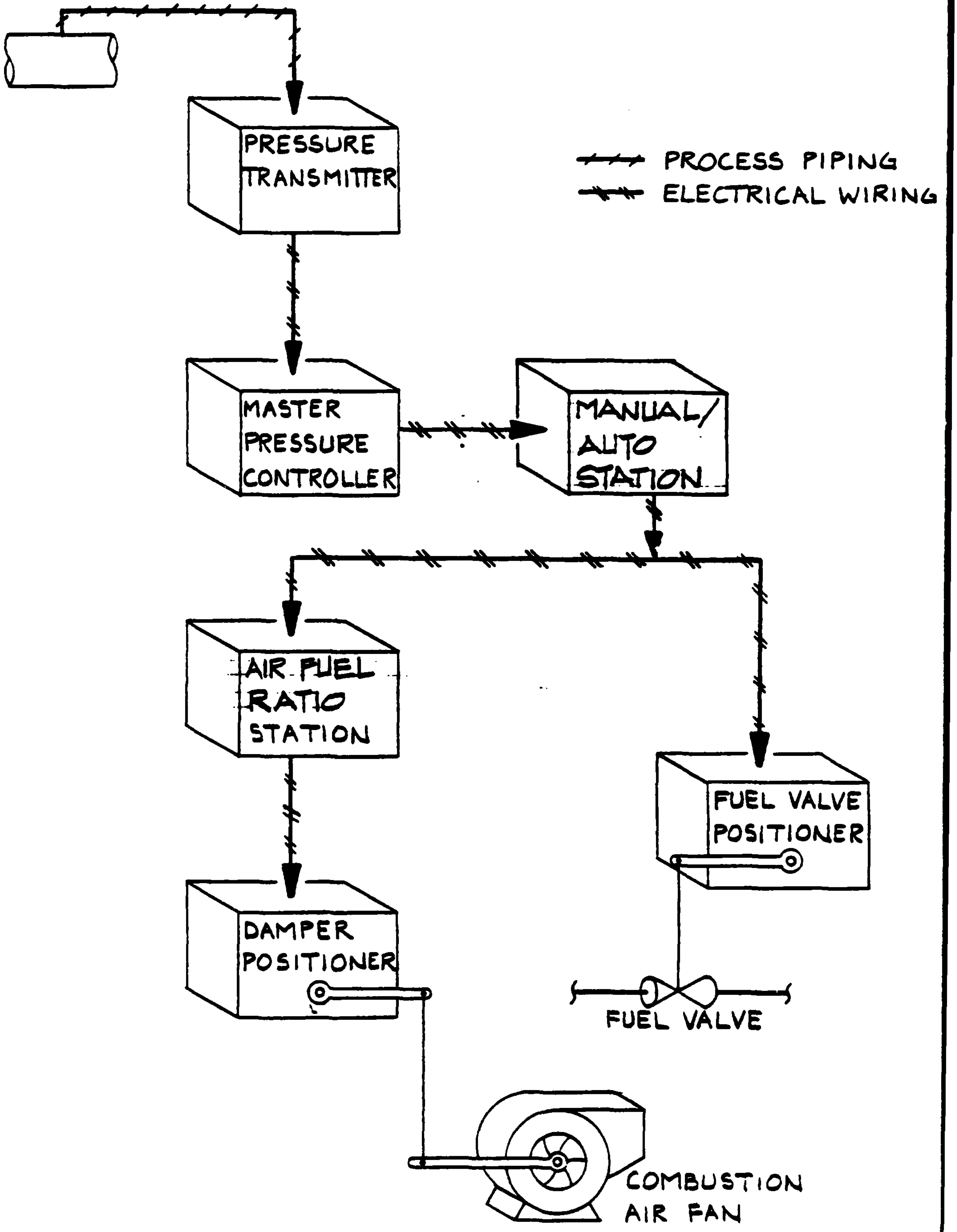
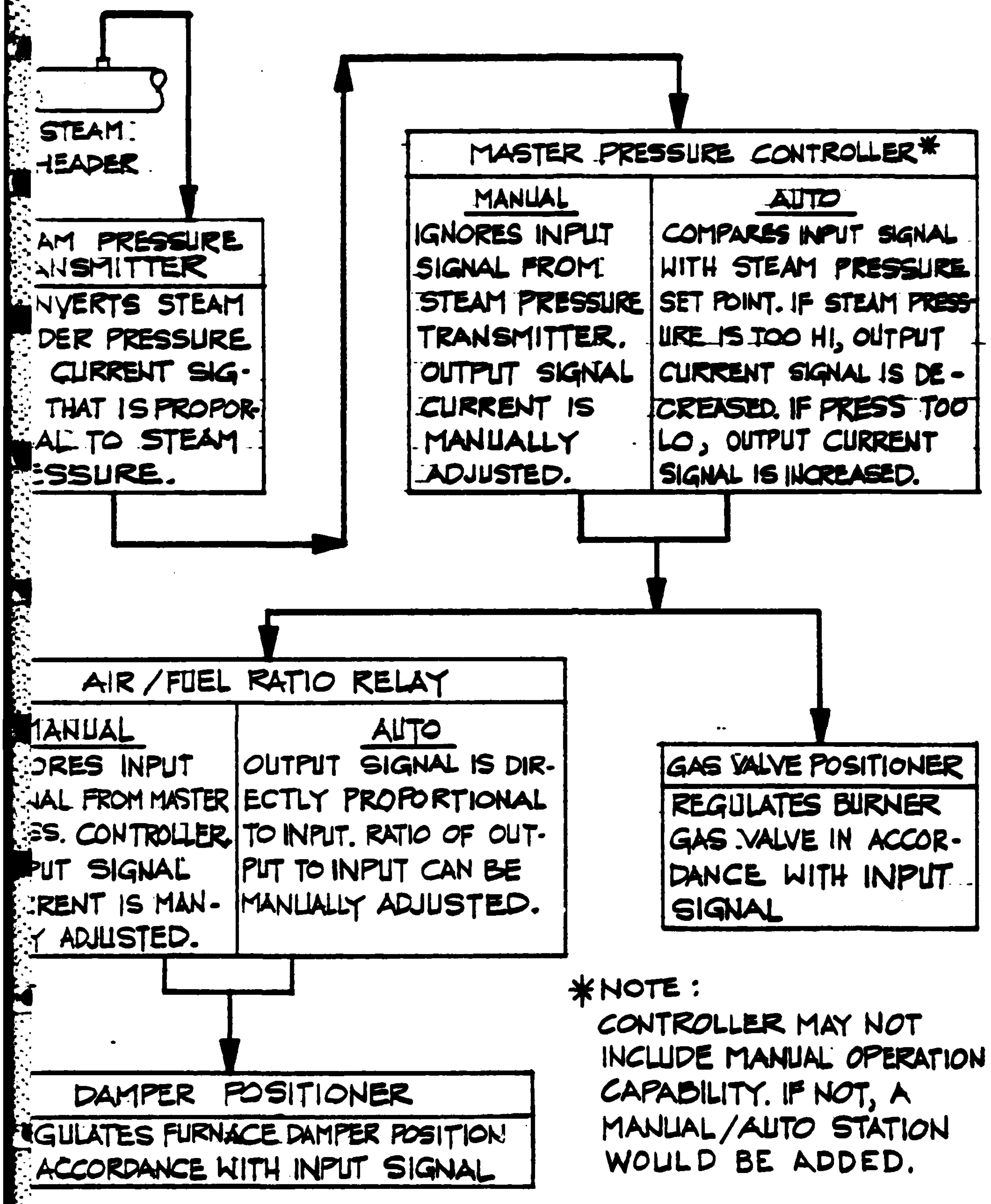


FIGURE 4-7 PARALLEL POSITIONING CONTROL SYSTEM (ELECTRIC)



*NOTE:
CONTROLLER MAY NOT INCLUDE MANUAL OPERATION CAPABILITY. IF NOT, A MANUAL/AUTO STATION WOULD BE ADDED.

URE 4.8 FUNCTIONAL SCHEMATIC DIAGRAM
PARALLEL POSITIONING SYSTEM
(ELECTRIC)

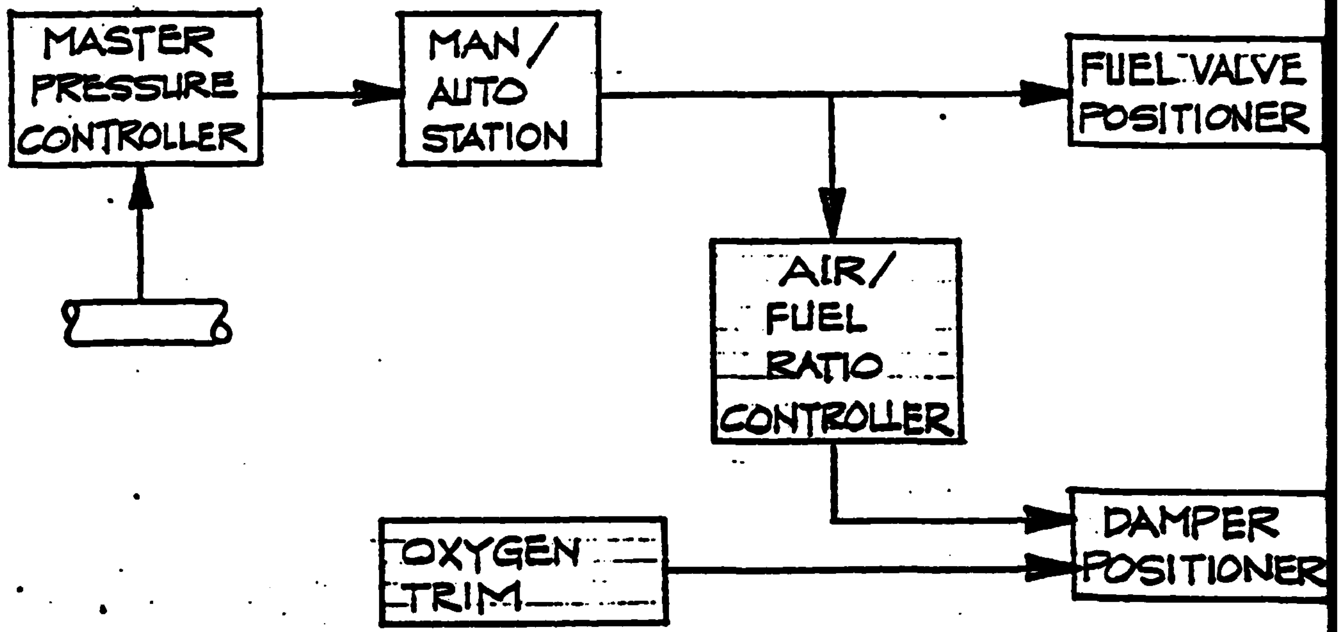


FIGURE 4-9 PARALLEL POSITIONING SYSTEM WITH OXYGEN TRIM

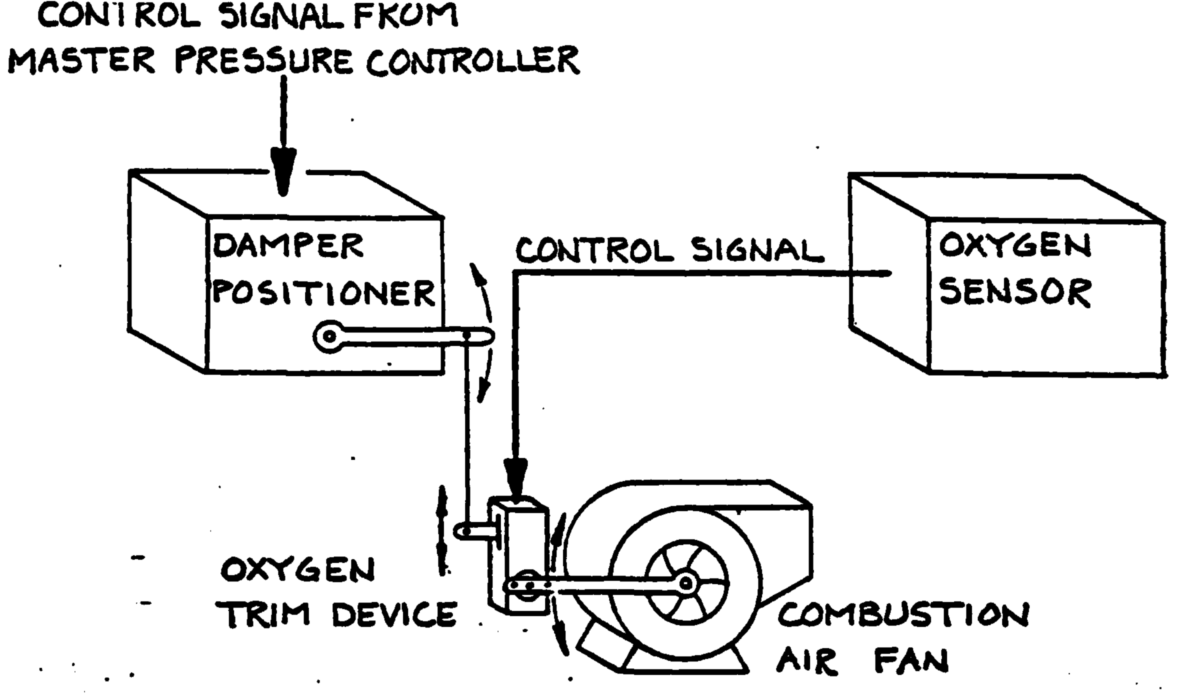


FIGURE 4-10 OXYGEN TRIM SYSTEM WITH DAMPER MOUNTED TRIM DEVICE

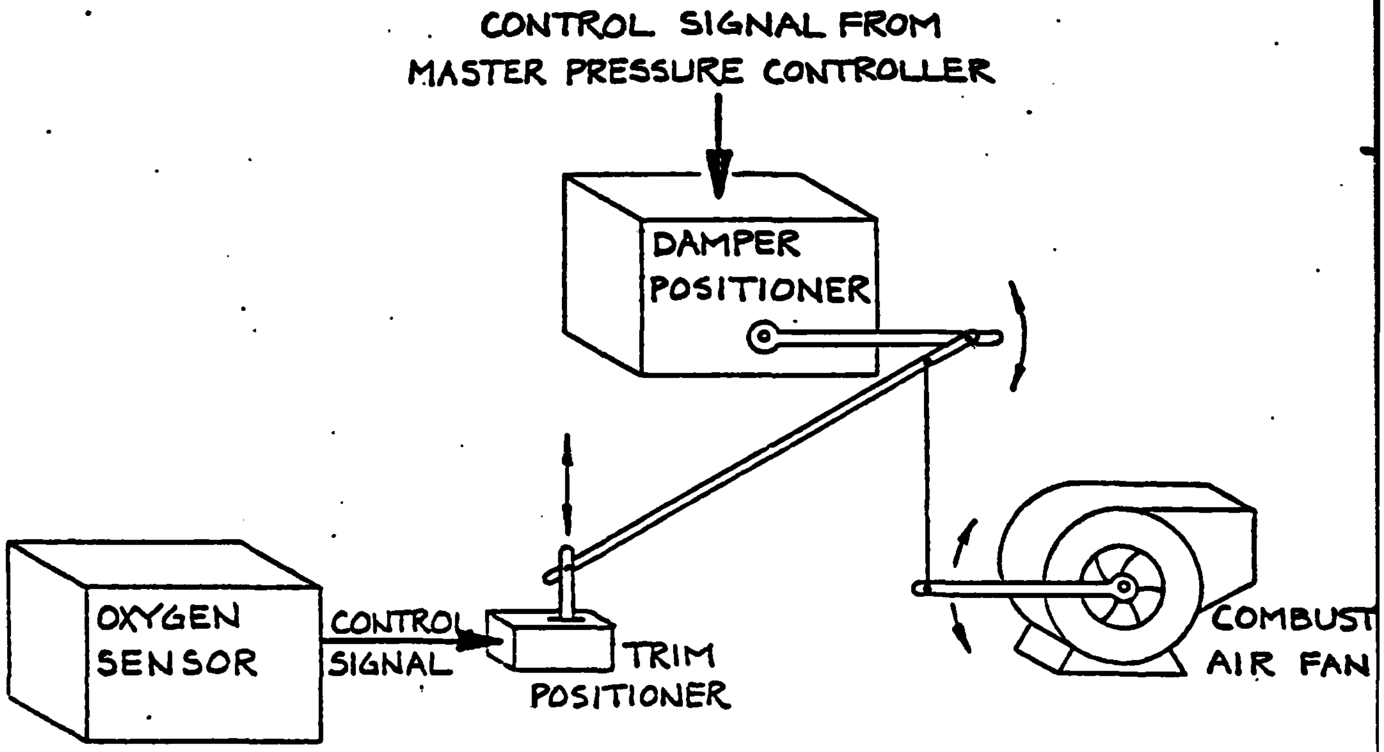


FIGURE 4-11 OXYGEN TRIM SYSTEM WITH TORY LINK TRIM POSITIONER

## 5.0 OXYGEN TRIM ANALYZERS

### 5.1 General

Flue gas may be extracted from the stack or flue duct for analysis or may be measured in-situ, that is, measured within the stack or flue duct.

In sampling systems, probes are inserted through the stack or duct wall and gases are withdrawn, usually by means of aspirators, for analysis. For oil-fired boilers, probes should be equipped with filters to ensure that flow paths are not clogged by soot or other particles. Permanent filters require periodic cleaning. Renewable filters such as glass or wool fiber filters must be replaced periodically.

In-situ analyzers (sensors in the probe) have their sensors within the stack or flue duct. Zirconium oxide $O_2$ analyzers are often of this type, utilizing integral probe and sensor assemblies placed within the stack or flue duct. Many infrared CO and $CO_2$ analyzers also measure the respective gases in-situ, by projecting a light beam across the stack.

### 5.2 $CO_2$ Analyzers

As was mentioned in Section 3.0, there are four basic methods used in the measurement of carbon dioxide. These methods are chemical absorption, specific gravity, thermal conductivity, and infrared analysis.

Thermal conductivity and infrared analyzers for $CO_2$ are the most popular for combustion control.

### 5.2.1 Thermal Conductivity $CO_2$ Analysis

The principle behind the thermal conductivity method of analyzing $CO_2$ is that every gas has different heat transfer rate. Figure 5-1 shows the effect of passing samples of pure gases through a thermal conductivity instrument that produces a deflection of 100 percent in the positive direction for 100 percent $CO_2$ sample. Hydrogen ($H_2$), when present in the flue gas in appreciable amounts can produce an error in the control signal because it has a deflection in the opposite direction from that of $CO_2$, as can be seen from Figure 5-1. Therefore, application of thermal conductivity $CO_2$ analyzers to combustion control is questionable.

### 5.2.2 Infrared $CO_2$ Analyzers

Gas analysis by infrared absorption is based on the principle that all substances have a characteristic absorption in the infrared region of the electromagnetic spectrum. The term infrared refers to electromagnetic radiation whose wavelengths are longer than visible light and shorter than most radio waves; that is, greater than 0.7 and less than 200 micron.

When infrared passes through flue gas, appropriate wavelengths of energy, are absorbed by selected constituents of the flue gas, such as $CO_2$, CO, $SO_2$ and oxides of nitrogen ($NO_x$), in proportions to their concentrations. Hydrogen, $O_2$, $N_2$ and monoatomic gases, such as helium, neon, etc., do not absorb infrared radiation. The wavelength and the amount of radiation absorbed determine the concentration of a given constituent in the flue gas.

Most infrared analyzers for flue-gas analysis use filtered radiation from just above visible red (0.7 micron) to about 15 micron.

## 5.3 Oxygen Analyzers

Excess air control in small industrial boilers is most frequently accomplished by use of real time oxygen analyzers because their output does not vary with fuel type, while $CO_2$ recorders in conjunction with charts or Orsat analyzers are often used to check the accuracy of oxygen analyzers.

### 5.3.1 Paramagnetic $O_2$ Analyzers

Analyzers of this type operate on the unique paramagnetic (attraction to a magnetic field) properties of oxygen. Oxygen is highly paramagnetic compared to the other gases in the products of combustion. This can readily be seen from Figure 5-2, which shows the deflection caused by passing pure samples of various gases through equipment calibrated to produce 100 percent deflection for a sample containing pure oxygen.

Despite their accuracy, paramagnetic analyzers cannot compete with modern zirconium oxide analyzers, because of their higher cost and slower response time.

### 5.3.2 Zirconium Oxide $O_2$ Analyzers

These analyzers use the electrochemical method of analysis. They operate on the fuel cell principle, (a fuel cell is a device that converts chemical energy directly into electrical energy). The equipment generally consists of a probe which is inserted in the stack or duct, an electrochemical cell, and an electronics enclosure.

The electrochemical cel usually contains a disc or cup shaped piece of zirconium oxide ($ZrO_2$, the electrolyte portion of the fuel cell) coated on both surfaces with porous metal electrodes. Platinum is often added to the cell to act as a catalyst. Heaters are provided to keep the cell at an elevated and consistent temperature.

A desirable characteristic of these analyzers is that they provide high sensitivity at low oxygen concentrations, since the output signal increases exponentially in magnitude as the oxygen concentration of the flue gas decreases.

These are basically two types of zirconium oxide $O_2$ analyzers. In one type, the analyzer is housed outside of the stack and only the probe is inserted in the stack. In the other, the zirconium sensor is housed within the probe assembly and is mounted in the stack or duct. Because oxygen trim control systems suitable for use in small industrial boilers utilize both designs and because each type has advantages and disadvantages, a detailed description of both outside-the-stack and inside-the-stack analyzers follows.

### 5.3.2.1 Outside-the-Stack $ZrO_2$ Oxygen Analyzer

The analyzer consists of a probe or probes placed in the stack, an attached analyzer enclosure which houses the zirconium oxide $O_2$ sensor assembly and a connected electronics enclosure (Figure 5-3).

Figure 5-4 shows the sampling system flow diagram for this analyzer. The analyzer enclosure is a combination hot sample system and $ZrO_2$ sensor bolted directly to the stack or duct wall. The probe is equipped with a non-clogging filter for oil-fired boilers.

The sample of flue gas is drawn through the analyzer by an aspirator which uses compressed air as the pumping fluid. The flue gases and aspirator air are discharged back into the stack. The components of the sample system, including all gas passages, are contained in a stainless steel block and are maintained at a temperature above the dew point temperature of the products of combustion to prevent condensation. In this manner, the gas passages are not subject to cooling in the event the enclosure door is left open for long periods during inspection.

Referring to Figure 5-4, the aspirator A is used to create a vacuum and thus draw a sample of gas through the sample probe B located in the stack or duct. The porous metal filter generally is not necessary for boilers firing natural gas only. The sample drawn through the probe is passed into a heated block assembly D which contains passageways E that preheat the compressed air used as pumping fluid for the aspirator. Oxygen analysis of the sample is performed after the sample enters the heated block and before it enters the aspirator. The sample is divided at this point between the analyzer G and a partial bypass (drop tube) H that reduces the systems transportation lag by taking about 80 percent of the sample flow.

The air supply to the aspirator is heated in several narrow passageways contained in the bottom of the heated manifold block. Heating of the pumping fluid, compressed air, to the aspirator counteracts the cooling effect of air expansion in a functioning aspirator nozzle which could otherwise lower air temperature below the dew point and cause plugging of the passageways.

The gas sample (now mixed with the aspirator air) is returned to the stack or duct.

### 5.3.2.2 Inside the Stack $ZrO_2$ Oxygen Analyzer

This type of analyzer measures the excess oxygen in-situ. It consists basically of a probe assembly which houses the zirconium oxide cell, and an electronics enclosure which houses the probe temperature controller, power supply and amplifier, as shown schematically in Figure 5-5.

The probe incorporating a zirconium oxide sensor may be placed directly in the stack or duct, or fitted into the furnace when using a high temperature analyzer that withstands temperatures as high as 2800°F. The probe unit is equipped with a ceramic filter and heat shield.

The electronics enclosure contains the probe temperature controller which controls the temperature of the oxygen sensing cell at a constant 1550°F. The amplifier accepts the millivolt dc signal generated by the zirconium oxide cell in the probe and produces a linearized standard 4-20 ma current output signal.

## 5.4 Carbon Monoxide Analyzers

These analyzers generally use the infrared method of analysis and measure the CO content of the flue gas within the stack or duct. The infrared method of analysis was described in detail under paragraph 5.2, $CO_2$ analyzers. The range of measurement for combustion control applications is from 0-1000 ppm (parts per million). An infrared carbon monoxide analyzer is shown schematically in Figure 5-6.

A beam of infrared light is transmitted across the stack from a light source on one side to a detector on the opposite side of the stack, as shown in Figure 5-6. In front of the detector is a narrow band filter that allows only the passage of that portion of the infrared spectrum that is sensitive to carbon monoxide. The analyzer only "sees", then, the residual infrared that has not been absorbed by the CO is in the stack. This residual infrared is a measure of the CO level in the stack.

In the source light compartment, an infrared source emits an infrared beam which is mechanically chopped and then directed to a focusing mirror. The beam is then transmitted through a saphire window interface and across the stack through a duplicate saphire window and onto a collecting mirror. The collecting mirror directs the beam into the wavelength discrimination module which employs gas cell correlation techniques for CO measurements.

The wavelength discrimination module includes a rotating wheel which receives the polychromatic light beam from the collecting mirror. The wheel contains three sealed gas cells. One cell contains 100 percent nitrogen, the second contains a known concentration of CO for calibration, and the third contains 100 percent CO. Note that infrared radiation is not absorbed by diatomic gases such as N2, as was explained under paragraph 5.2 above. After the light is passed through the sealed cells, it is directed into a filter which eliminates all wavelengths except the one of interest. This wavelength is passed through a detector which alternately reads each of the three sealed cells. These signals are amplified and transmitted to the controller in the control room.

The signals are again amplified and fed into an analog/digital converter. The resulting digital signal is passed into a microprocessor which is programmed to measure the difference between the signal from the nitrogen cell and the signal level from the 100 percent CO cell. This ratio is the indication of carbon monoxide in the flue gas.

## 5.5 CO and $O_2$ Dual Analyzers

A new CO sensor has been developed by Bailey that can be incorporated within their proven $O_2$ analyser to give a combination analyses which promises to have excellent boiler trim application characteristics if it proves to be as reliable and accurate as early tests indicate. This patented sensor is comprised of multiple thermocouple junctions having alternate junctions coated with a proprietary Pt oxidation catalyst and an inactive coating. The output is a function of the temperature differential between the catalytic and measuring portions of the device. Initial field testing of 5 months duration in an oil-fired boiler has indicated excellent stability and durability.

## 5.6 CO and $CO_2$ Combination Analyzers

Combination CO/$CO_2$ analyzers are offered by some manufacturers of infrared analyzers. Figure 5-7 is a diagramatic representation of such an analyzer.

The instrument and operates on the principles described in paragraph 5.4 above with the addition of filter cels for $CO_2$ analysis.

However, the cost of this scheme is high relative to the zirconium oxide type oxygen analysers.

## 5.7 Smoke Analyzers

Before discussing smoke analyzers, it is necessary to discuss smoke formation and prevention. This will provide insight in the application of smoke analyzers. Smoke and soot are produced from unburned free carbon in natural gas and fuel oils. There is, however, a special condition under which smoke is not producible. This condition is when a gas-fired boiler utilizes a premix burner in which case the absence of smoke does not imply too much excess air, neither is it an indication of complete combustion.

Assuming that the furnace design incorporates ample combustion space, smoke generally can be prevented by sufficient excess air, thorough mixing of combustibles with oxygen in the combustion air, and maintaining adequate furnace temperature to drop below the ignition temperature of the combustible gases. Implementation of these conditions, of course, implies complete combustion. This is why a lack of smoke is usually associated with good combustion.

Figure 5-8 is a diagram of a smoke analyzer (opacimeter) that may be employed in conjunction with an oxygen trim control system. Opacity monitoring is limited to the visible portion of the color spectrum. The detectors are designed to match the spectral response of the human eye. Less sophisticated models are also available. Generally, however, a well designed and well applied oxygen trim system for combustion control of small industrial boilers makes incorporation of a smoke control loop unnecessary.

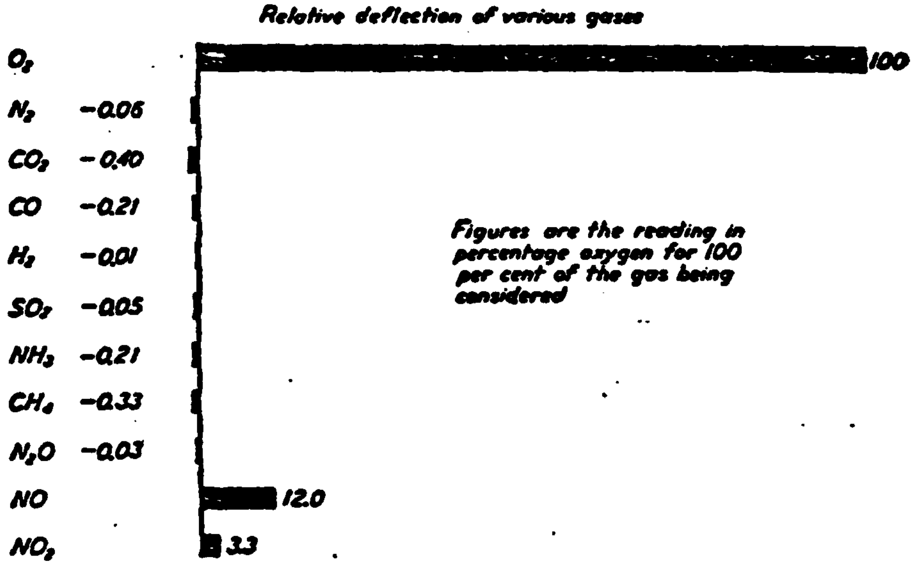


FIGURE 5-1 Effect of Passing Different Gas Samples Through Thermal Conductivity Instrument

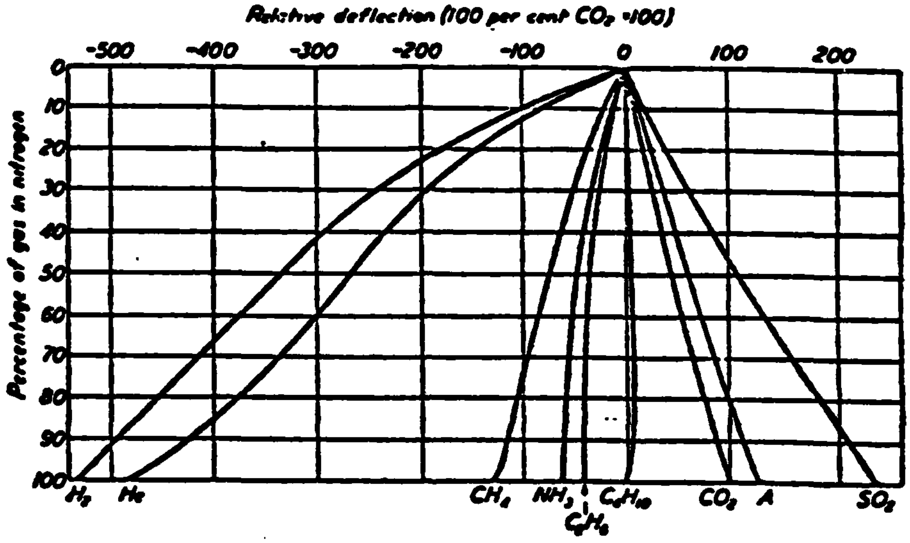


FIGURE 5-2 Paramagnetic Susceptibility of Common Gases

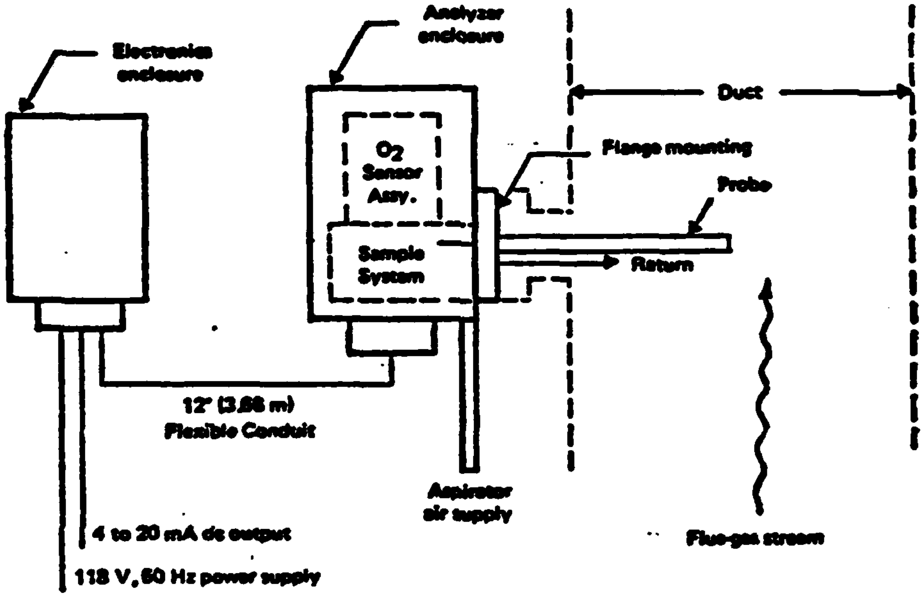


FIGURE 5-3 Zirconium Oxide $O_2$ Analyzer Block Diagram (B&W - Bailey)

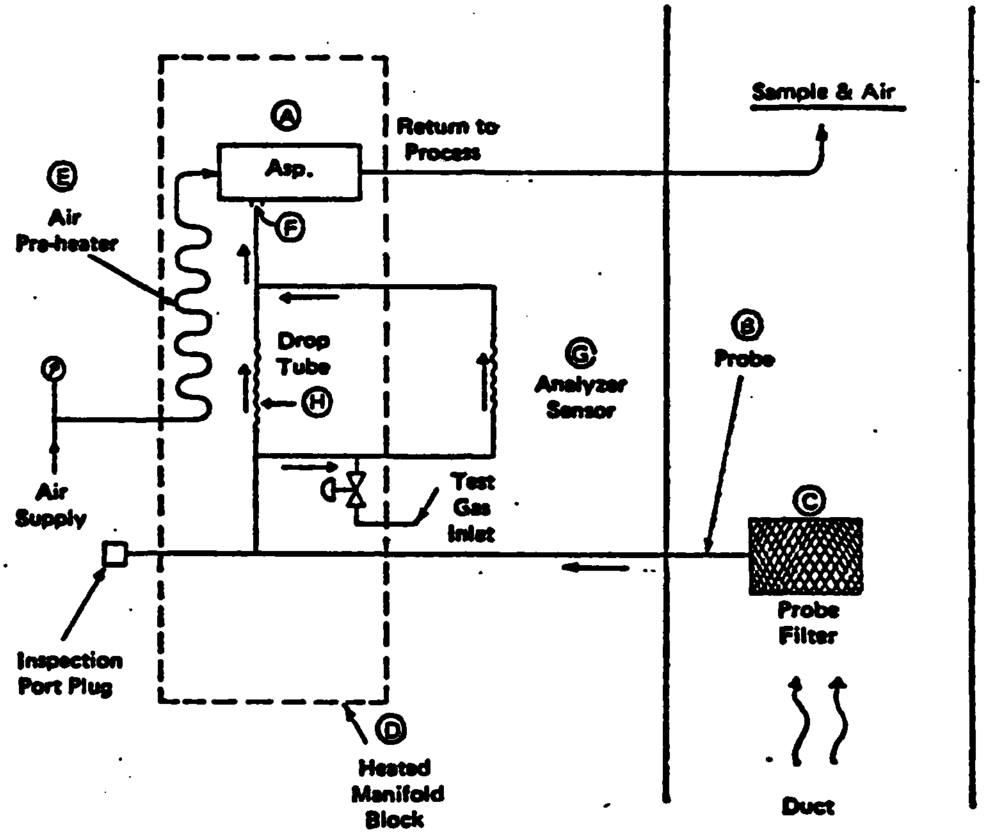


FIGURE 5-4 Zirconium Oxide $O_2$ Analyzer Sample Flow Diagram (B&W - Bailey)

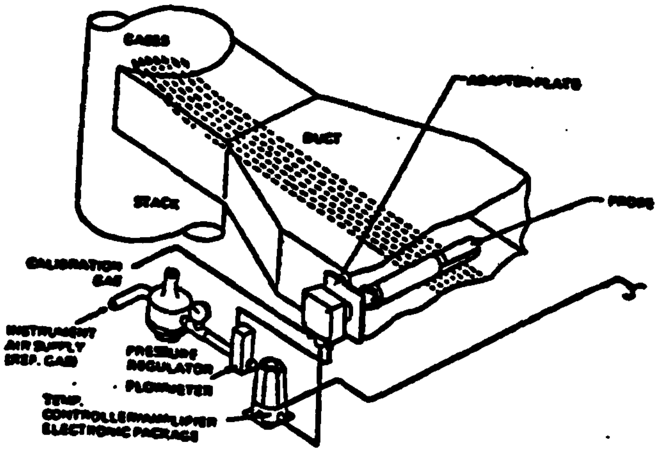


FIGURE 5-5 Schematic Arrangement of Zirconium Oxide $O_2$ Analyzer (Westinghouse-Hagan)

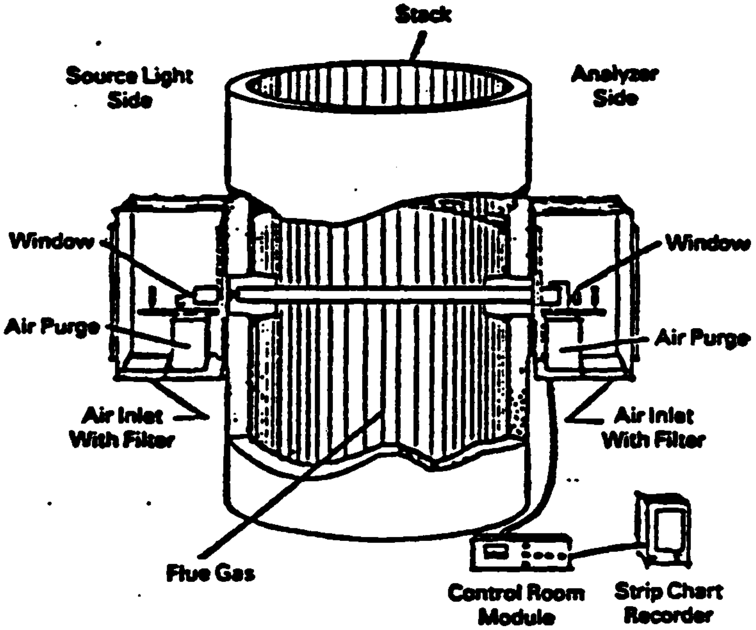


FIGURE 5-6 Schematic Arrangement of Infrared Carbon Monoxide Analyzer (Westinghouse-Hagan)

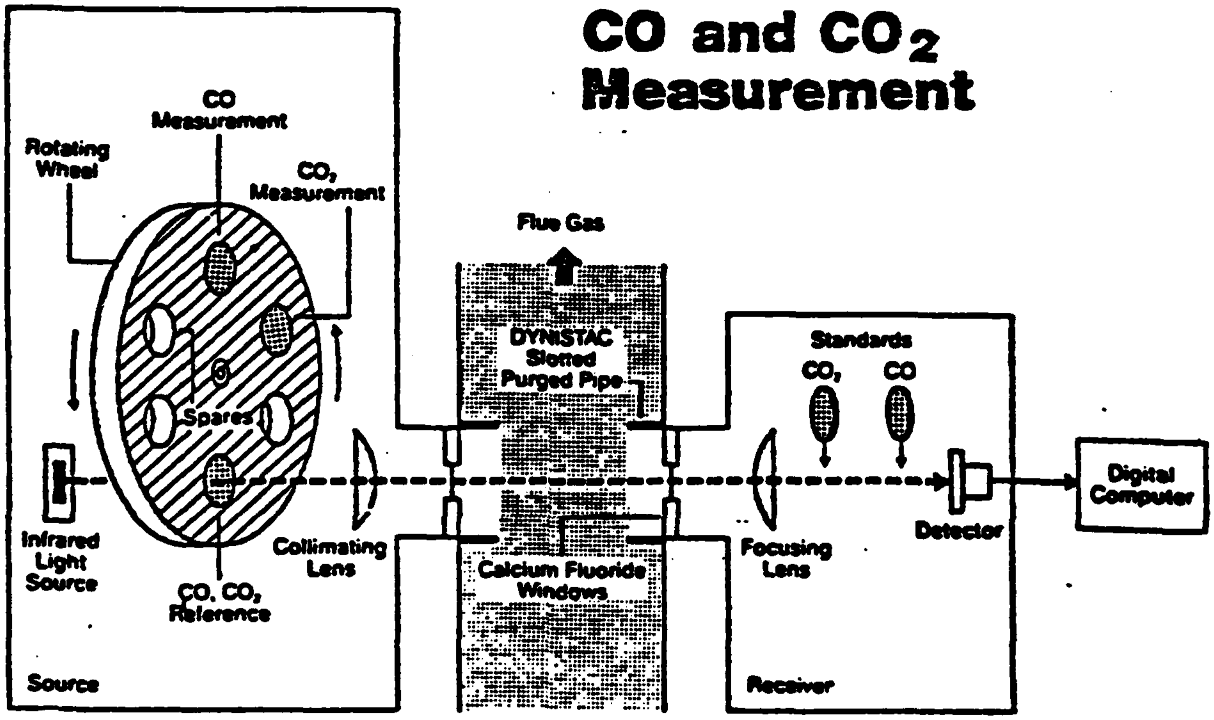


FIGURE 5-7 Diagrammatic Arrangement of Infrared Carbon Monoxide Analyzer (Measurex)

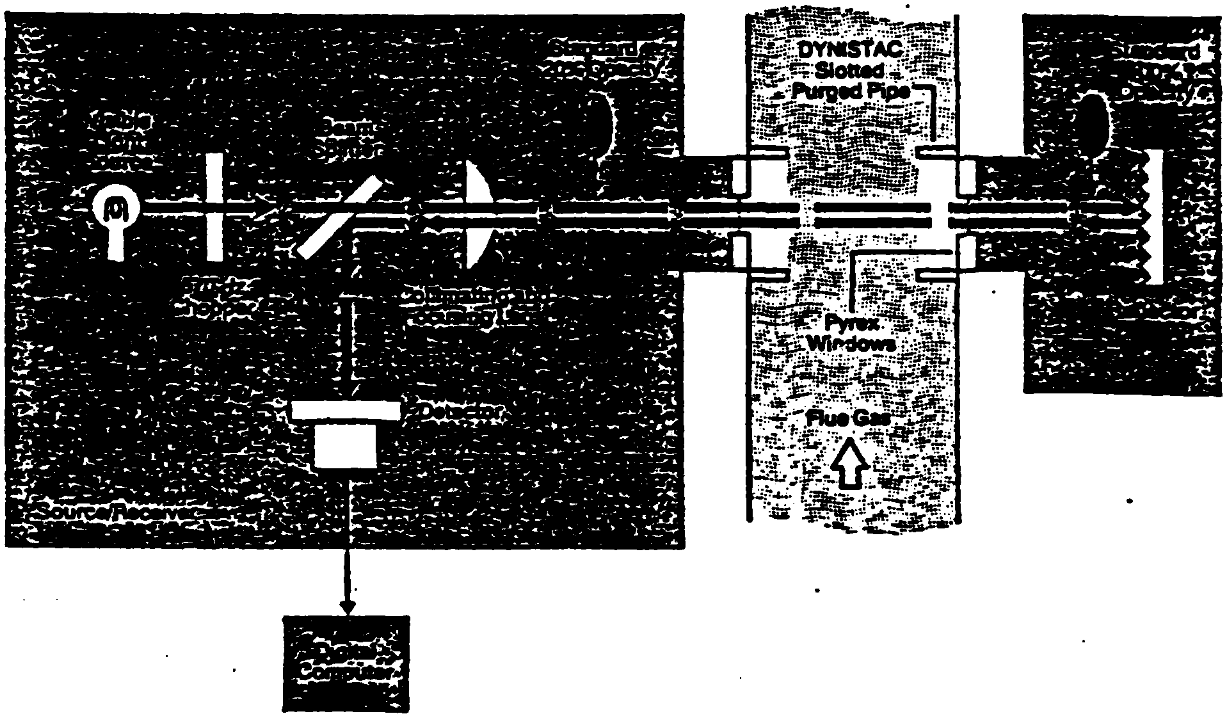


FIGURE 5-8 Diagrammatic Arrangement of Smoke (Opacity) Analyzer (Measurex)

## 6.0 OXYGEN TRIM SYSTEMS EVALUATION

### 6.1 $CO_2$ Based Trim System

$CO_2$ based trim systems are effective when one type of fuel only is burned at all times. This limitation indicates $CO_2$ as a control parameter does not offer the desired flexibility.

$CO_2$ based trim systems usually use the infrared method of analysis. The cost of these units for combustion control of small industrial boilers generally cannot be justified.

### 6.2 CO Based Trim Systems

CO based trim systems have the advantage of continuously monitoring the CO content of the products of combustion and adjusting the air-fuel ratio by providing a feedback to the controller.

CO based trim systems bring about the most economical use of fuel. $O_2$ based trim systems normally account for 80 to 90 percent of fuel savings and the rest is due to CO based trim systems.

With a rather large cost differential between a CO based trim system and an $O_2$ based trim system, the pay back for a CO based trim system for small industrial boilers may require several years more than that for an $O_2$ based trim systems.

CO based trim systems generally are not cost effective for boilers smaller than 100 million BTU per hour output capacity. In addition, the maintenance of sophisticated infrared analyzers may prove difficult, in view of the scarcity of trained personnel familiar with this type of equipment.

The cost of a CO based trim system is significantly higher than that of an $O_2$ based trim system employing a zirconium oxide analyzer.

## 6.3 $O_2$ Based Trim Systems

$O_2$ based trim systems are well suited to the combustion control of small industrial boilers. The advantages of $O_2$ based trim systems are that $O_2$ is an excellent index of excess oxygen, a relatively low cost, and in the case of trim systems using a zirconium oxide analyzer, quick response time.

A disadvantage that an $O_2$ based trim system has is that when there is a leakage of outside air it cannot differentiate between the infiltration air and the $O_2$ in the flue gas. Therefore it is mandatory that the furnace and flues be tight especially when an induced draft fan is utilized.

Advantages and disadvantages of $O_2$ based trim systems utilizing a $ZrO_2$ analyzer that measures the excess $O_2$ in-situ will be considered next; the analyzers are described in 5.3.2.1 and 5.3.2.2 above.

The sampling system type of analyser (outside the stack) offers ready accessibility to the zirconium oxide cell and supporting elements. Cost of the sampling type analyser is slightly less than that of the in-situ type. An important advantage of the sampling type analyser is that it can accept samples from a number of locations, and give an average $O_2$ reading. This eliminates the survey to select a representative location effort needed for the in-situ analyser.

The in-situ type analyser (sensor in the probe) offers compactness and simplicity, but the initial cost is slightly higher than that of the sampling type. Also, access is more difficult, although options are available to remove the zirconium cell without removing the probe from the stack or duct. Extreme care must be exercised in the selection of a mounting location for the in-situ analyser to insure that it gives a representative analysis under all conditions of load and different fuels. A survey of several duct profiles is usually required in order to determine a suitable location.

# 7.0 PROCEDURES FOR ADDITION OF OXYGEN TRIM SYSTEMS

## 7.1 General

Procedures for adding $O_2$ based trim systems that use in-situ and sampling type zirconium oxide analyzers are similar for jackshaft, pneumatic, and electric parallel positioning combustion control systems. To avoid repetition, procedures for in-situ type only are given below. A table describing the signal functions that appear in various diagrams is given in Appendix A.

## 7.2 $O_2$ Based Trim Control with In-Situ $ZrO_2$ Analyzer

### 7.2.1 Jack Shaft System

Figure 7-1 shows a jackshaft system without trim control. Figure 7-2 shows the same system with trim control; a quick comparison reveals the difference. This scheme (Westinghouse-Hagan) employs a so-called Tory Link.

Install the Tory Link in place of forced draft fan inlet vanes lever, or damper lever, using the existing orientation on the jackshaft. Next, install the trim positioner, followed by the connecting rod between the trim positioner and the floating arm of the Tory Link, shown in Figure 7-2. Complete the installation of oxygen controller and all of the instruments, including $O_2$ manual/auto station, that are located in the boiler room. Connect wiring and provide 115V, 60 Hz power source. Finally, install analyzer in duct and the electronics package at a suitable location outside of the duct, as indicated in Figure 5-5. Provide instrument air to calibration gas and reference air connections if required, provide 115V, 60 Hz power source to the electronics package (indicated in

Figure 5-5), and connect wiring between the electronics package and Oxygen controller in the boiler room.

### 7.2.2 Pneumatic System

Figure 7-3 shows a parallel positioning system without trim control. Figure 7-4 shows the same system with trim control; a comparison of the two readily shows the difference.

Replace the air-fuel ratio controller in Figure 7-3 with the multiplier shown in Figure 7-4. Install the $O_2$ controller and all of the other additional boiler room instruments. Install necessary tubing between various instrument air connections and provide instrument air supply. Procedures for the installation of the analyzer and the electronics package will be the same as those described under the jackshaft system for these items, except that the input signal from the electronics package to the $O_2$ controller will be via a transducer to convert the signal from electric to pneumatic.

### 7.2.3 Electric System

Figures 7-3 and 7-4 also apply to electric system. Procedures for addition of trim control are the same as those stated for the pneumatic system, except that wiring will be required instead of tubing and a 115V, 60 Hz power source instead of instrument air. The input signal from the electronics package to the $O_2$ controller will be direct.

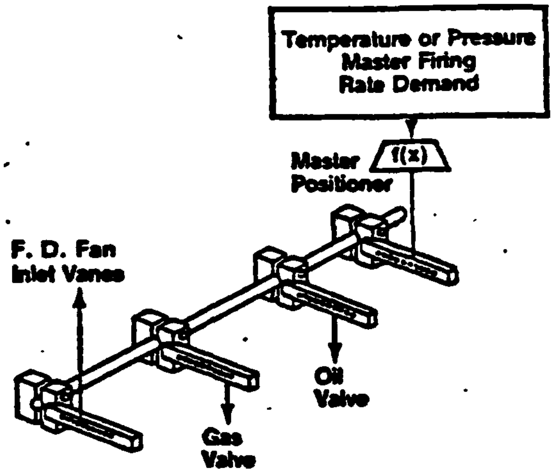


FIGURE 7-1 Jackshaft System Without $O_2$ Trim (Westinghouse-Hagan)

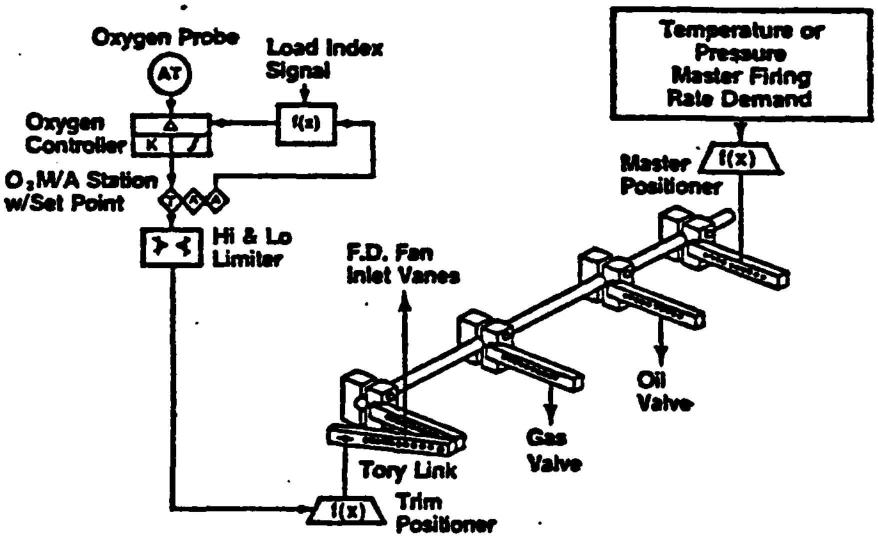


FIGURE 7-2 Jackshaft System With $O_2$ Trim (Westinghouse-Hagan)

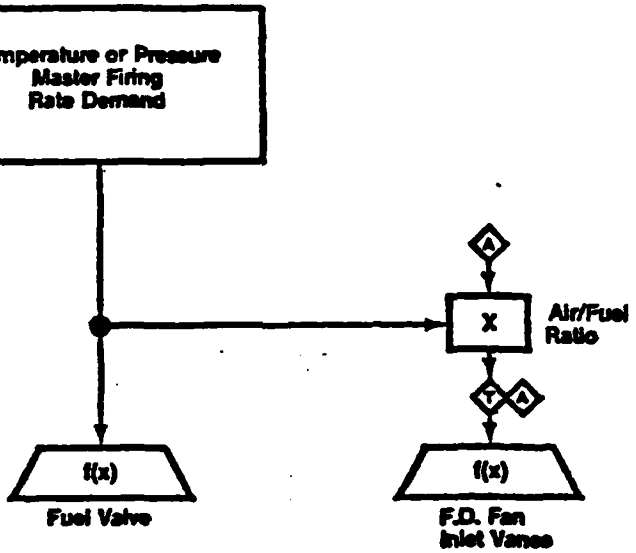


FIGURE 7-3 Parallel Positioning System Without $O_2$ Trim - Pneumatic or Electric (Westinghouse-Hagan)

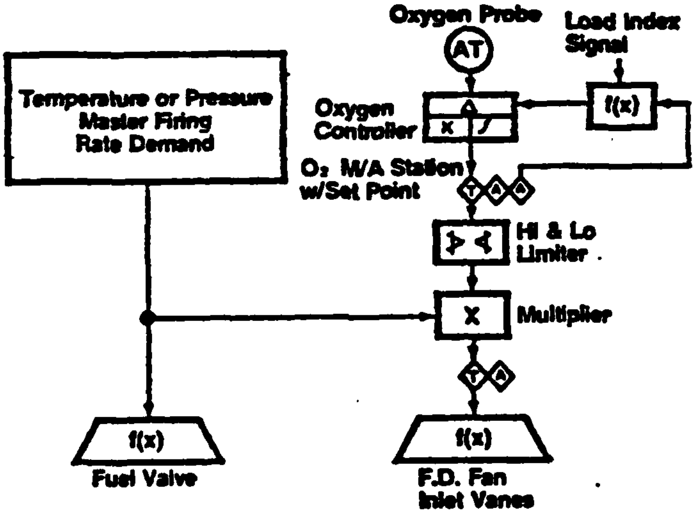


FIGURE 7-4 Parallel Positioning System With $O_2$ Trim - Pneumatic or Electric (Westinghouse-Hagan)

# 8.0 REPRESENTATIVE MANUFACTURERS OFFERINGS

A brief description of the $O_2$ trim offerings of the major manufacturers of $O_2$ trim systems is presented. This is not a complete listing, as there are a great many other systems available, but it represents the major companies that combine proven $O_2$ trim systems with extensive boiler control experience. No ranking is implied by the order of presentation.

## A. Westinghouse-Hagan

Westinghouse-Hagan offers a selection of in-situ $ZrO_2$ oxygen trim systems ranging from the Model 132 Mini Probe for flue gas temperatures up to 1,000°F through the heavy duty industrial Model 218 (1,400°F) and 225 (1,000°F) to the Model 450 high temperature oxygen analyser (2,800°F). The Model 450 can be inserted directly into the furnace or adjacent convective section of many small heating boilers. A complete $O_2$ trim system utilizing the Mini Probe can be purchased for about $5,000 while the costs for the other systems mentioned can range up to about $15,000.

## B. Bailey Controls Company

The $O_2$ trim systems offered by the Bailey Controls Company are of the sampling probe type with the $ZrO_2$ sensor outside the stack. They also offer a combined $O_2$ and CO analyser (see Section 5.5) and prefer to sell the $O_2$ trim as part of the "Conserver I" or "Conserver III" boiler control systems. The cost of the $O_2$ trim analyser for application to an existing boiler control system can run as low as about $4,000 while the complete "Conserver" systems including $O_2$ trim can range in cost up to $25,000. The addition of the CO analyser and recorder adds less than $3,000 to the above costs.

### C. Hague International

The OxSen oxygen trim analyser offered by Hague is an in-situ type probe with a $ZrO_2$ sensor. It is offered in both low (1100°F) and high (2800°F) temperature versions. A feature of this unit is that it can be check calibrated in about 1½ minutes with air. Also, a PID (proportional-integral-derivitive) controller is included in the analyser. The cost of this unit, including an automatic purge and the parts needed to adapt it to an existing boiler control system, is about $7,000 for the low (1100°F) temperature system and $8,500 for the high temperature (2800°F) system.

### D. Milton Roy Company

The Milton Roy Company has taken over the business of Hays, Republic, and Hays-Republic. Consequently, there are several different $O_2$ trim offerings available from this source and a brief listing follows:

1. The Oxyprobe is an in-situ $O_2$ trim analyser operating on the $ZrO_2$ cell principle.
2. The Hays-Republic $ZrO_2$ Oxygen analyser system Model 671 is an in-situ system generally performing the same functions as the Oxyprobe mentioned above.
3. The Hays Econ-$O_2$-trol system operates on the paramagnetic oxygen sensing principle. The Hays Trimlink was developed for use with this system to enable the $O_2$ trim bias to be applied mechanically to air damper actuators. The Trimlink can be used with other $O_2$ trim analysers.

## E. Measurex

The Measurex trim systems employ infrared sensing of $CO_2$ and CO and include Micro-processor controlled automatic calibration and signal processing. These analysers are not sold separately, but only as part of a complete boiler control system.

# APPENDIX A

## TERMINOLOGY AND DEFINITIONS

### Air

Air is a mixture of gases, mostly nitrogen ($N_2$) and oxygen ($O_2$), and some water vapor. On a dry basis, it has a composition of approximately 78 percent by volume nitrogen, 21 percent oxygen, and 1 percent argon. Other gases which are present in minute concentration are carbon dioxide (0.03 percent) and traces of hydrogen ($H_2$) and rare gases (helium, neon, etc.), collectively accounting for 0.01 percent.

In combustion technology, the 0.04 percent of carbon dioxide, hydrogen and rare gases are ignored. Moreover, the argon, and inert gas (does not chemically combine with any other substance), is lumped with the nitrogen for a total volume of 79 percent; this is referred to as the atmospheric nitrogen and the air assigned a composition of 79 percent by volume nitrogen and 21 percent oxygen, known as the atmospheric air. In combustion work, the terms air and atmospheric air usually are used interchangeably. The atmospheric air is approximately 77 percent by weight nitrogen and 23 percent oxygen; it has a molecular weight of 29. Note that it is the oxygen in the air that supports combustion.

### Air-Fuel Ratio

The weight of air supplied to burn a unit weight of fuel is called the air-fuel ratio.

### Carbon

Carbon (C) is a chemical element that mostly occurs in combination with other elements. These are called carbon compounds. Natural gas and fuel oils consist mostly of carbon compounds.

### Carbon Dioxide

Carbon dioxide ($CO_2$) is a carbon compound that appears in the products of combustion. $CO_2$ gas is heavier than oxygen or air.

### Carbon Monoxide

Carbon monoxide (CO) is a colorless, odorless gas that results from incomplete combustion of carbon in the presence of air or oxygen.

### Catalyst

A substance whose presence can increase the rate of a chemical reaction without itself taking part in the reaction is called a catalyst.

### Combustion

An oxidation reaction accompanied by the emission of heat and light is called combustion or burning.

### Excess Air

The air supplied to a boiler furnace, in excess of the amount required to burn the fuel completely, is called the excess air.

### Excess Oxygen

The oxygen content of excess air is referred to as the excess oxygen. In reference to flue-gas composition, the excess oxygen is often called oxygen, since the oxygen in flue gas is only excess oxygen (assuming no in-leakage).

### Flue Gas

Flue gas is the exhaust from a boiler. However, with reference to flue-gas analysis, it may include infiltration of outside air into the furnace or flue ducts, sootblowing steam, or other contamination in addition to the products of combustion.

### Hydrocarbons

Chemical compounds that contain only the elements hydrogen (H) and carbon are called hydrocarbons. The constituents in natural gas such as methane ($CH_4$), ethane ($C_2H_6$), etc., are hydrocarbon compounds. Fuel Oils are hydrocarbons of more complex structure.

### Hydrogen

Hydrogen ($H_2$) is the lightest of all gases. The element hydrogen (H) in combination with carbon and in various proportions appears in natural gas and fuel oils as the second most important combustible.

### Hydrogen-Carbon Ratio

The term hydrogen-carbon ratio (H-C) is used to indicate the relationship between the hydrogen and carbon content of the fuel. It is the ratio by weight of hydrogen to carbon in the fuel. Hence, H-C ratio of pure carbon is 0 and that of methane ($CH_4$) is 0.336. These two values are at the opposite ends of the H-C scale. The hydrogen-carbon ratio is an index of the heating value of fuel. The smaller the H-C ratio of a fuel, the greater is its heating value.

### Oxidation

Oxygen reacts (chemically combines) with chemical elements to form oxides of these elements. For example, one molecule of oxygen reacts with one "molecule" (atom) of carbon to form one molecule of carbon dioxide.

$$C + O_2 \quad CO_2 + \text{Heat}$$

Oxygen reacts also with many chemical compounds to form oxides of the elements in the compounds. For example, one molecule of methane, the main constituent in natural gas, will react (in the presence of heat) with two molecules of oxygen to form one molecule of carbon dioxide and two molecules of water.

$$CH_4 + 2O_2 \quad 2H_2O + CO_2 + \text{Heat}$$

The reactions of chemical elements with oxygen are known as oxidation reactions, and the element that combines with oxygen is said to be oxidized.

It is noted that not all oxidation reactions are accompanied by emission of heat. For example, nitric oxide (NO) reacts with oxygen to form nitrogen dioxide ($NO_2$), but the reaction is accompanied by the absorption of heat from the surrounding atmosphere.

$$2NO + O_2 + \text{Heat} \quad 2NO_2$$

A special case of oxidation in which the reaction is accompanied by the emission of heat and light is called combustion. It, therefore, can be concluded that every combustion reaction is an oxidation reaction, but not every oxidation reaction is a combustion reaction.

In combustion terminology, often an element in the fuel, such as carbon or hydrogen, is said to be oxidized, which means it is burned.

## Products of Combustion

Complete combustion of a fuel forms carbon dioxide, water vapor, and sulfur dioxide ($SO_2$), if sulfur is present in the fuel. In addition gases leaving the combustion chamber of the furnace contain nitrogen, oxygen, and carbon monoxide (CO). The nitrogen comes from the total air supplied, and the oxygen from the excess air. Carbon monoxide forms in the combustion chamber if all of the carbon in the fuel does not burn completely. The gases and other compounds that leave the combustion zone of the furnace are collectively called the products of combustion (POC).

### Smoke

Incomplete combustion of fuel often produces smoke, containing particles smaller than 10 micron (1 micron=0.001 millimeter). When these particles gather into clusters, they form soot. Note that when natural gas is fired in a premix type burner, no smoke is produced.

### Stoichiometric Air

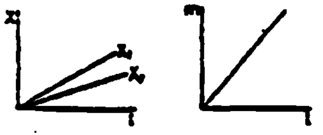
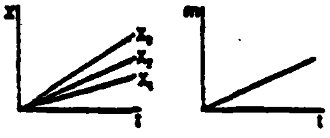
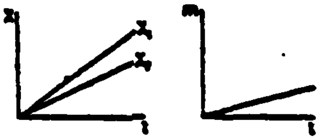
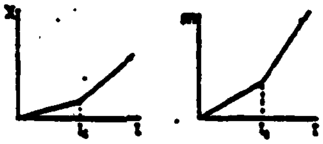
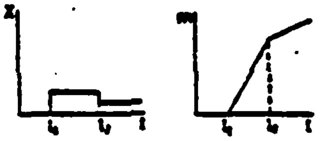
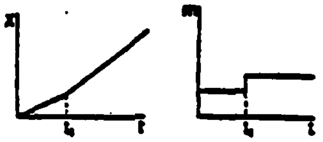
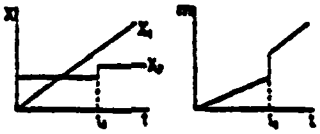
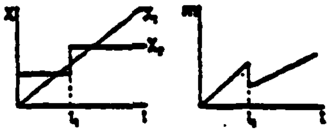
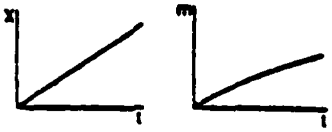
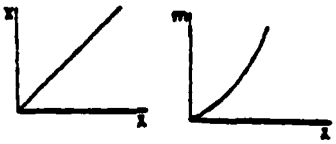
Stoichiometric air, sometimes called theoretical air, is the exact amount of air required to burn a fuel completely.

### Total Air

The sum of the stoichiometric air and the excess air is referred to as the total air.

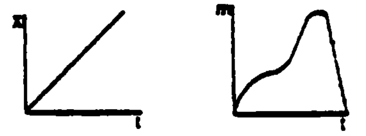
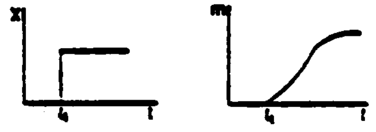
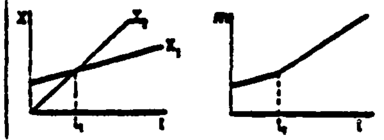
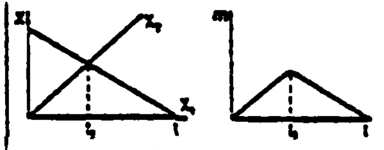
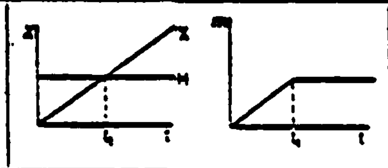
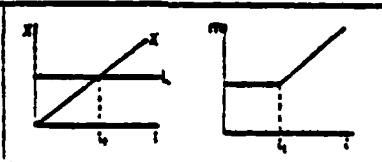
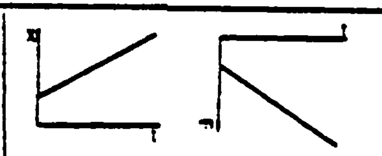
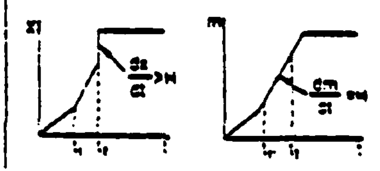
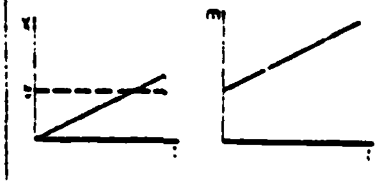
# APPENDIX B

## SIGNAL PROCESSING FUNCTIONS

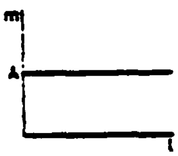
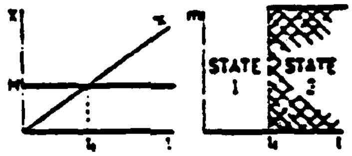
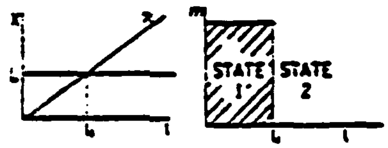
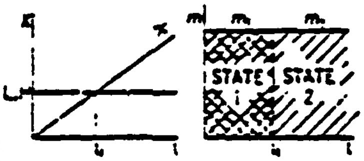
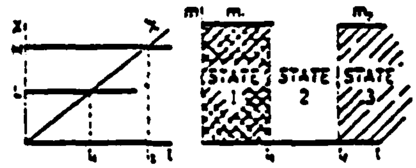
| Function & Symbol * | Math Equation | Graphic Representation | Definition |
|---|---|---|---|
| **SUMMING**<br>Σ | $m = x_1 + x_2 + \ldots + x_n$ |  | The output equals the algebraic sum of the inputs. |
| **AVERAGING**<br>Σ/n | $m = \frac{x_1 + x_2 + \ldots + x_n}{n}$ |  | The output equals the algebraic sum of the inputs divided by the number of inputs. |
| **DIFFERENCE**<br>Δ | $m = x_1 - x_2$ |  | The output equals the algebraic difference between the two inputs. |
| **PROPORTIONAL**<br>K | $m = Kx$ |  | The output is directly proportional to the input. |
| **INTEGRAL**<br>∫ | $m = \frac{1}{T_I} \int x\,dt$ |  | The output varies in accordance with both magnitude and duration of the input. The output is proportional to the time integral of the input. |
| **DERIVATIVE**<br>d/dt | $m = T_D \frac{dx}{dt}$ |  | The output is proportional to the rate of change (derivative) of the input. |
| **MULTIPLYING**<br>X | $m = x_1 x_2$ |  | The output equals the product of the two inputs. |
| **DIVIDING**<br>÷ | $m = \frac{x_1}{x_2}$ |  | The output equals the quotient of the two inputs. |
| **ROOT EXTRACTION**<br>√ | $m = \sqrt{x}$ |  | The output equals the root (i.e., square root, fourth root, 3/2 root, etc.) of the input. |
| **EXPONENTIAL**<br>$x^n$ | $m = x^n$ |  | The output equals the input raised to a power (i.e., second, third, fourth, etc.) |

*IN ACCORDANCE WITH THE SCIENTIFIC APPARATUS MAKERS ASSOCIATION (SAMA)

## SIGNAL PROCESSING FUNCTIONS (CONT.)

| Function & Symbol | Math Equation | Graphic Representation | Definition |
|---|---|---|---|
| NONLINEAR OR UNSPECIFIED FUNCTION<br>f (x) | $m = f(x)$ |  | The output equals some nonlinear function of the input. |
| TIME FUNCTION<br>f(t) | $m = x\,f(t)$<br>$m = f(t)$ |  | The output equals the input times some function of time or equals some function of time alone. |
| HIGH SELECTING<br>> | $m = \begin{cases} x_1 \text{ FOR } x_1 \geq x_2 \\ x_2 \text{ FOR } x_1 \leq x_2 \end{cases}$ |  | The output is equal to that input which is the greatest of the inputs. |
| LOW SELECTING<br>< | $m = \begin{cases} x_2 \text{ FOR } x_1 \geq x_2 \\ x_1 \text{ FOR } x_1 \leq x_2 \end{cases}$ |  | The output is equal to that input which is the least of the inputs. |
| HIGH LIMITING<br>≯ | $m = \begin{cases} x \text{ FOR } x \leq H \\ H \text{ FOR } x \geq H \end{cases}$ |  | The output equals the input or the high limit value whichever is lower. |
| LOW LIMITING<br>≮ | $m = \begin{cases} x \text{ FOR } x > L \\ L \text{ FOR } x \leq L \end{cases}$ |  | The output equals the input or the low limit value whichever is higher. |
| REVERSE PROPORTIONAL<br>—K | $m = -Kx$ |  | The output is reversely proportional to the input. |
| VELOCITY LIMITING<br>V≯ | $\frac{dm}{dt} = \frac{dx}{dt} \begin{cases} \frac{dx}{dt} \leq H \text{ and} \\ m = x \end{cases}$<br>$\frac{dm}{dt} = H \begin{cases} \frac{dx}{dt} \geq H \text{ OR} \\ m \neq x \end{cases}$ |  | The output equals the input as long as the rate of change of the input does not exceed a limit value. The output will change at the rate established by this limit until the output again equals the input. |
| BIAS<br>+, —, or ± | $m = x \pm b$ |  | The output equals the input plus (or minus) some arbitrary value (bias). |

## SIGNAL PROCESSING FUNCTIONS (CONT.)

| Function & Symbol | Math Equation | Graphic Representation | Definition |
|---|---|---|---|
| **ANALOG SIGNAL GENERATOR**<br>**A** | $m = A$ | DOES NOT APPLY  | The output is an analog signal developed within the generator. |
| **TRANSFER**<br>**T** | $m = \begin{cases} x_1 \text{ FOR STATE 1} \\ x_2 \text{ FOR STATE 2} \end{cases}$ |  | The output equals the input which has been selected by transfer. The state of the transfer is established by external means. |
| **SIGNAL MONITOR**<br>**H/** | STATE 1 $x \leq H$<br>STATE 2 (ENERGIZED OR ALARM STATE) $x > H$ |  | The output has discrete states which are dependent on the value of the input. When the input exceeds (or becomes less than) an arbitrary limit value the output changes state. |
| **/L** | STATE 1 (ENERGIZED OR ALARM STATE) $x < L$<br>STATE 2 $x \geq L$ |  | |
| **H/L** | STATE 1 (FIRST OUTPUT $m_1$ ENERGIZED OR ALARM STATE) $x < H, L$<br>STATE 2 (SECOND OUTPUT $m_2$ ENERGIZED OR ALARM STATE) $x > H, L$ |  | |
| **H//L** | STATE 1 (FIRST OUTPUT $m_1$ ENERGIZED OR ALARM STATE) $x < L$<br>STATE 2 (BOTH OUTPUTS INACTIVE OR DE-ENERGIZED) $L \leq x \leq H$<br>STATE 3 (SECOND OUTPUT $m_2$ ENERGIZED OR ALARM STATE) $x > H$ |  | |

The variables used in the table are:

A — An arbitrary analog signal
b — Analog bias value
$\frac{d}{dt}$ — Derivative with respect to time
H — An arbitrary analog high limit value
$\frac{1}{T_1}$ — Integrating rate

L — An arbitrary analog low limit value
m — Analog output variable
n — Number of analog inputs or value of exponent
t — Time
$T_D$ — Derivative time
x — Analog input variable
$x_1, x_2, x_3, \ldots, x_n$ — Analog input variable (1 to n in number)