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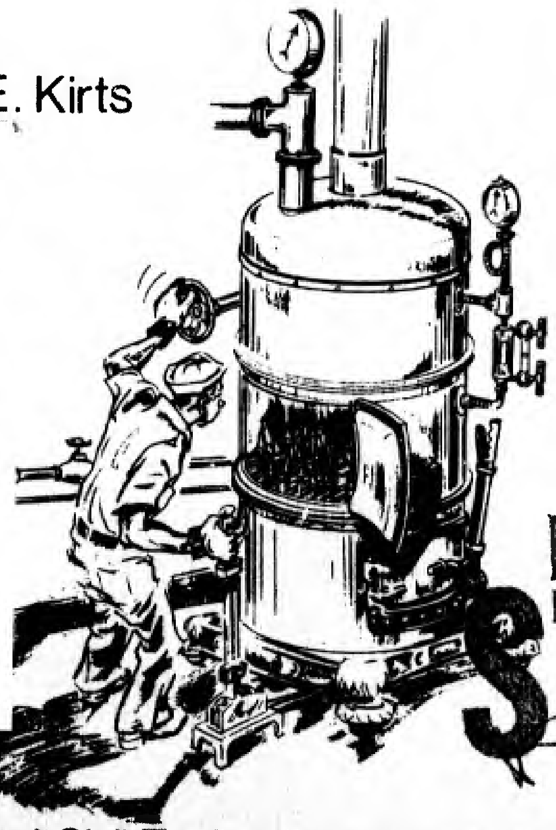
USER'S GUIDE TO AUTOMATIC BOILER CONTROLS

by R. E. Kirts



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1.0 BASIC BOILER CONTROL

1.1 Combustion Control

The purpose of a boiler control system is to regulate the boiler so as to produce the desired steam flow with safety and efficiency. To accomplish this, the control system must provide the boiler with the correct amounts of air and fuel as the demand for steam changes. Also, the control system must safely shut the boiler off should abnormal conditions, such as excessive steam pressure, ~~or~~ loss of flame, or explosions, occur.

There are several methods of controlling steam flow in the small* boilers found at most Naval facilities, but the most common method uses the steam pressure to generate a master control signal. This master control signal is usually utilized in one of two types of control methods: parallel control positioning or series control positioning. Parallel positioning control is probably the most common control scheme for small industrial boilers. With this type of control, the signal from the steam pressure sensor goes simultaneously to the fuel flow and airflow regulating devices. The position of these regulating devices is thus determined by the magnitude of the signal from the steam pressure sensor. Parallel positioning systems offer the advantages of fast response and simplicity of operation, and have been found

step 7

*"Small" boilers are defined as those having capacities less than 50,000 lbs/hr.

to be very reliable. Individual components can be adjusted independently, so control system tuning is facilitated. Parallel positioning control does have a shortcoming, however. Although the control system as a whole operates in a closed-loop (i.e., with feedback), the control of the individual air and fuel regulators is basically without feedback (i.e., open-loop). Thus, there is no assurance that the fuel/air ratio is within the desired range (other than the initial calibration of the system).

Parallel positioning control can be implemented in any of the most common control hardware types: mechanical, pneumatic, or electronic. Implementation of parallel positioning control in a typical mechanical system is illustrated in Figure 1.

In a series positioning boiler control system, the control signal from the steam pressure sensor is not simultaneously sent to the fuel and air regulating devices, Rather, the signal but instead is sent to only one of the regulating devices. The displacement of this first device is then measured and used to control the position of the second device. By using the actual displacement of one regulating device to control the other, series positioning control provides a margin of safety that is not available with parallel positioning control. For example, if the damper positioner is the first controlled device, then the fuel flow cannot increase unless the air damper actually opens. This prevents a hazardous condition from occurring should the damper drive fail to operate correctly. Control of the air and fuel regulators in a series positioning system is open-loop, just as in a parallel positioning system. Furthermore, with a series positioning system there can develop a temporary upset in the fuel/air ratio during rapid load changes. This upset can be corrected by adding "cross-limiting" or "lead-lag" to the control scheme. Cross-limiting control requires that the airflow increase first on an increasing boiler load, and that the fuel flow decrease first on a decreasing boiler load. Cross-limiting is accomplished by a system of control interlocks that will not allow the fuel valve to open until the air damper has started to open and will not allow the air damper to close until the fuel valve has started to close.

Implementation of a simple series positioning control system with pneumatic devices is illustrated in Figure 2.

Metering control systems overcome the short-comings of parallel and series positioning control, but the added cost and complexity of metered control has generally restricted their use to large boilers. With metering control, the control of the fuel and air regulators is closed loop. The steam pressure is measured and feedback is provided to a master controller which adjusts the fuel and airflows. The fuel and airflows are also measured and feedback is provided to their control devices to ensure they are in accord with the master controller. A typical metered control system is illustrated in Figure 3.

Detailed information on these basic boiler combustion control types can be found in Reference 1.

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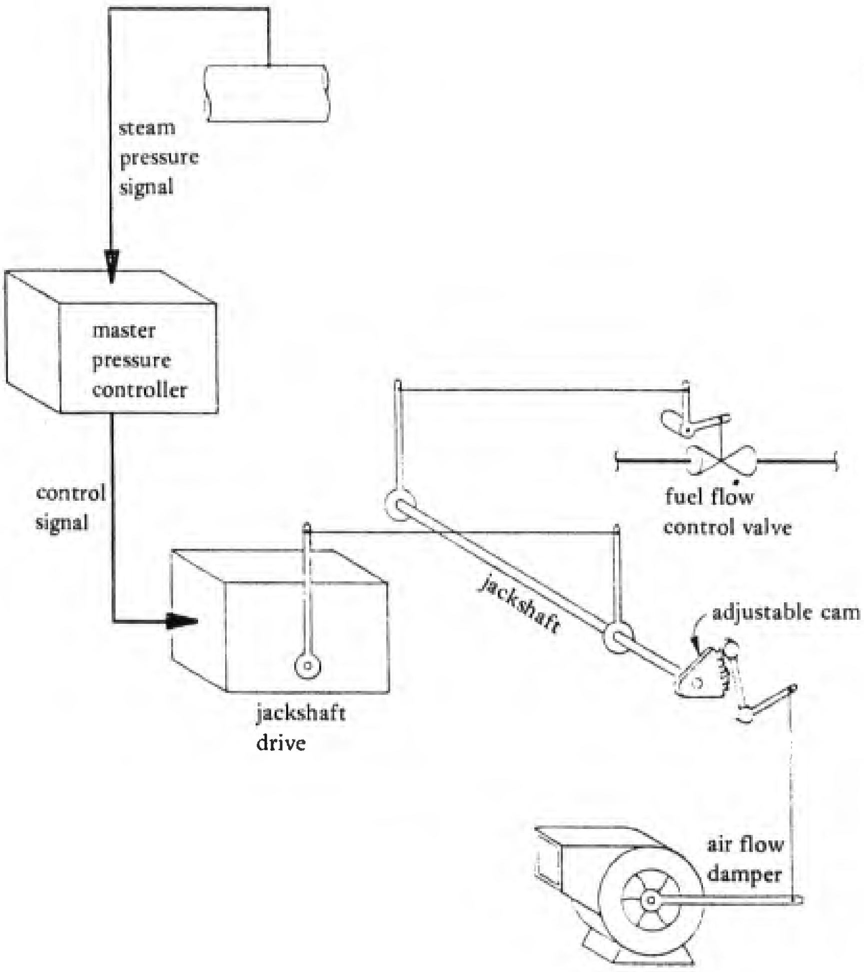

Figure 1. Jackshaft burner control system.

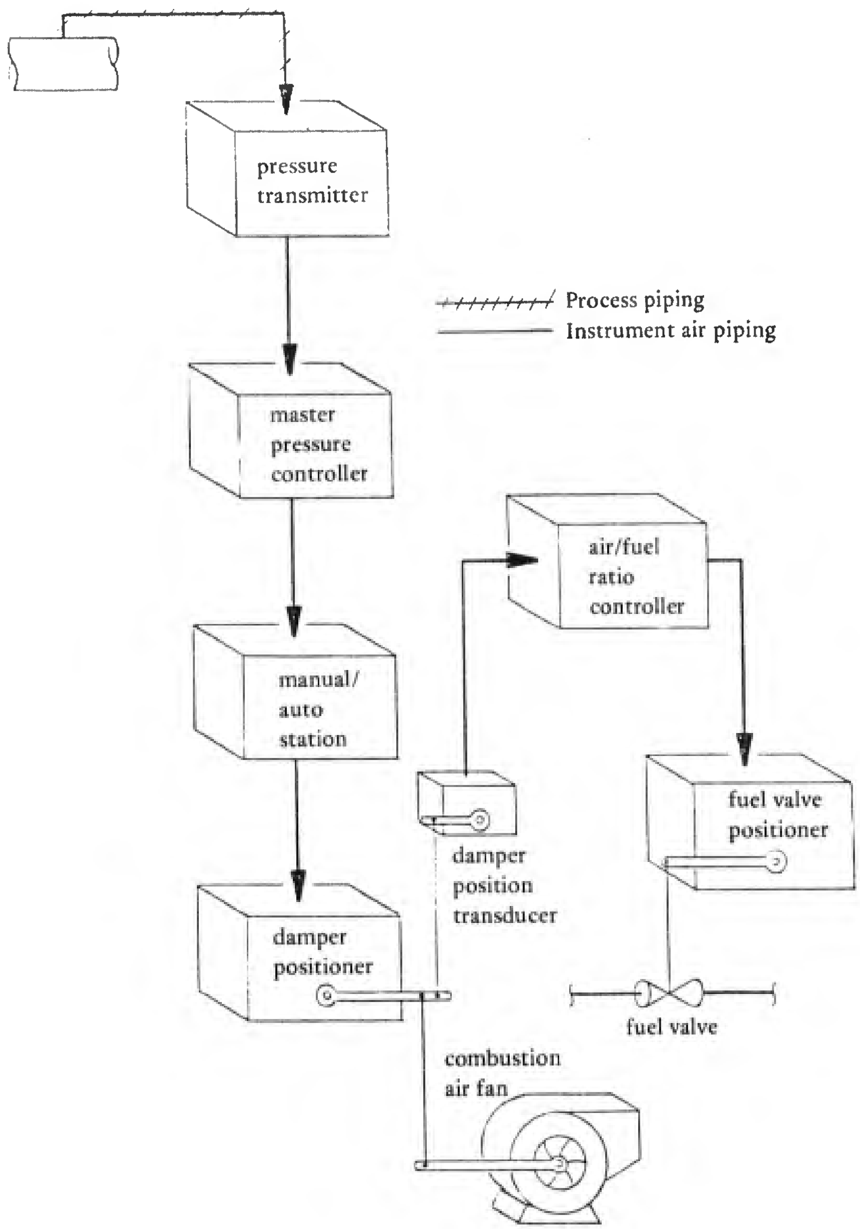

Figure 2. Series positioning control system (air leading fuel).

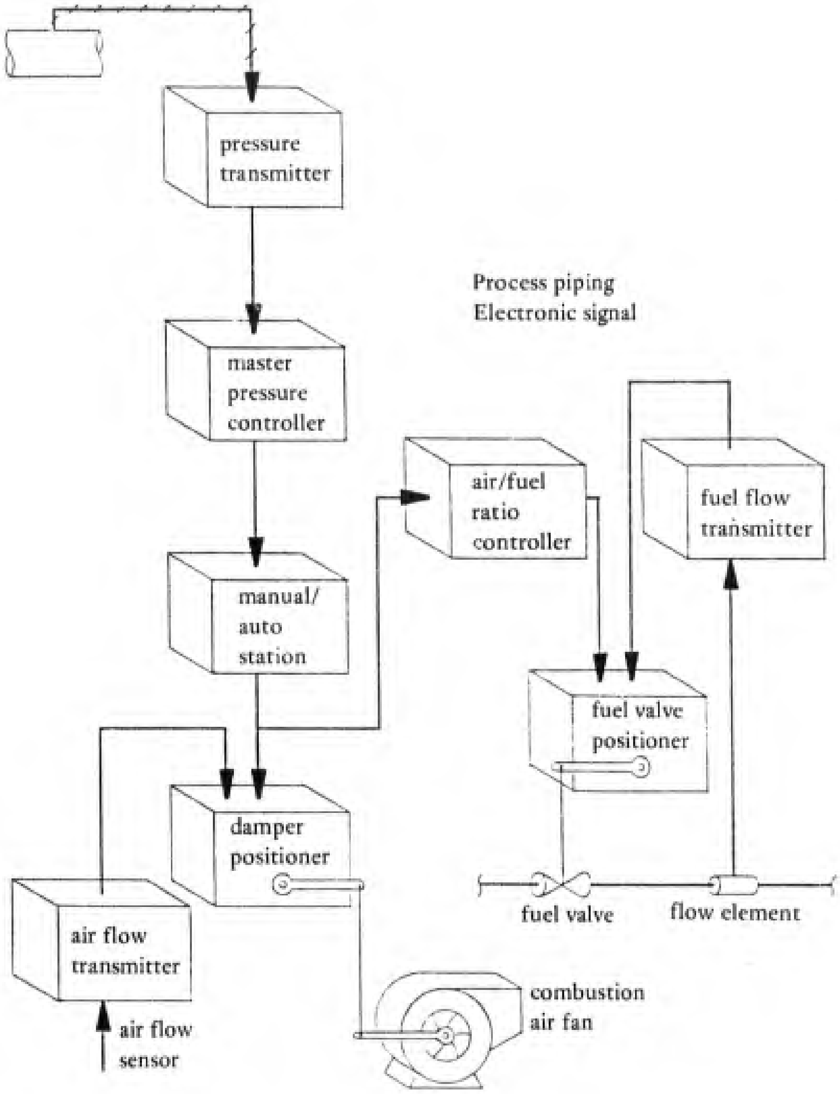

Figure 3. Metering control system.

1.2 Feedwater Control

Other controls, in addition to combustion control, are necessa~~ry for~~ proper operation of a boiler. Prominent among these are feedwater + Blowdown control systems and safety controls. The purpose of feedwater control is to maintain the correct → 49 amount of water in the boiler during all load conditions. The simplest control system uses one variable, water level, as the input to the control system (Figure 4). Controllability can be improved over that provided by single variable by adding information on steam flow and feedwater flow rate. Three-element control (Figure 5) is very precise and stable because of the closed-loop control of the feedwater valve.

Feedwater controllers are available in pneumatic, analog electronic, and digital electronic models.

1.3 Blowdown Control

In addition to the amount of water in the boiler, the quality of water in the boiler must also be controlled. As water in the steam drum is evaporated to produce steam, the concentration of impurities in the water, such as dissolved minerals or organic compounds, is increased. Unless the concentration of these impurities is periodically reduced, severe scaling of the heat transfer surfaces will occur and impurities will be carried over into the steam distribution system. The concentration of impurities in the boiler is controlled by "blowingdown" the boiler. Blowdown is the deliberate release of hot water from the drum to a drain. Blowdown is done either intermittently or continuously. On many boilers, blowdown is performed manually after an analysis of the drum water indicates that the water contains an excessive amount of impurities. Control systems are available, however, which will automatically perform the operations necessary to blowdown a boiler. Automatic blowdown controllers use electrochemical cells to measure the concentration of minerals (by measuring electrical conductivity and pH levels). The electrical signal corresponding to the impurity level is compared to the setpoint of the controller and when the concentration of impurities exceeds the set point, blowdown is initiated. Blowdown is halted when the impurity level falls below a preset value.

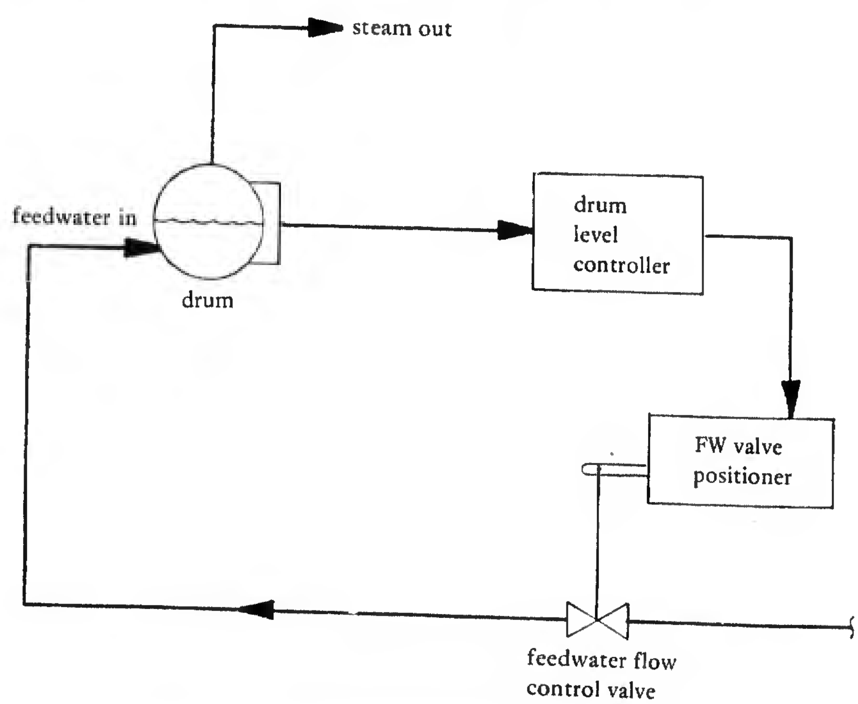

Figure 4. Single element feedwater control.

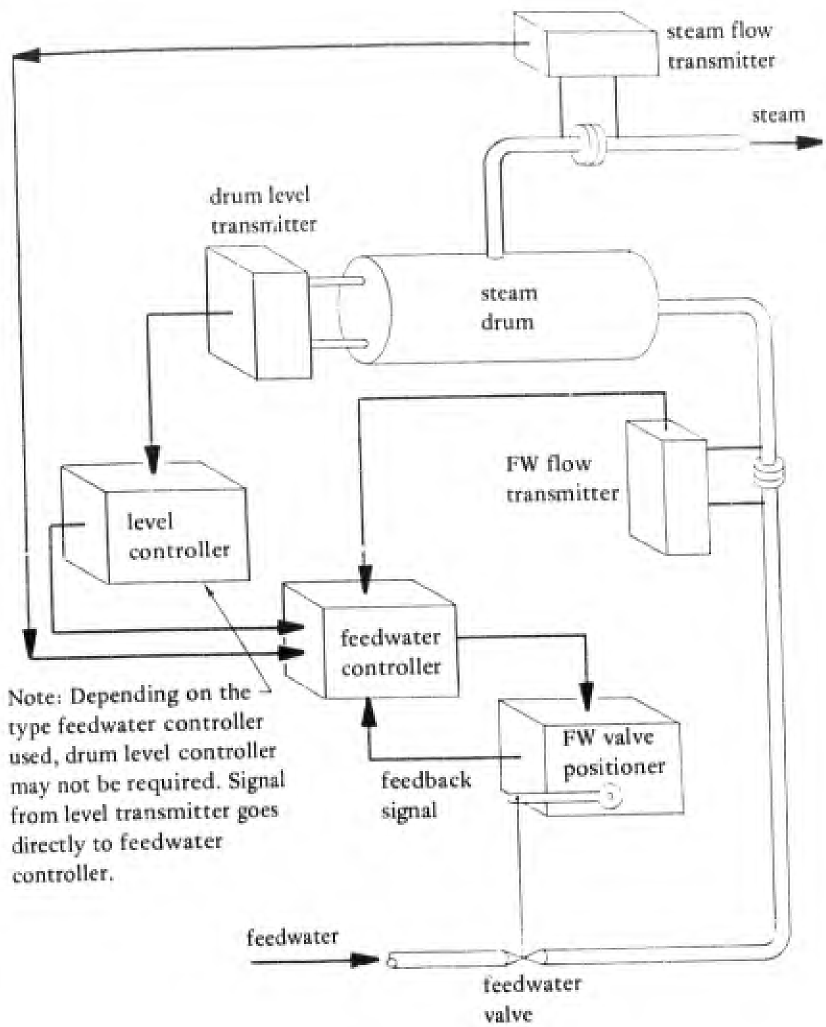

Figure 5. Three-element feedwater control.

Some boilers, especially those operated with a steady load, are equipped for continuous blowdown. Continuous blowdown means that a small amount of water is constantly being removed from the drum to keep the concentration of undesirable chemicals in the drum to a safe level.

Manual blowdown is still occasionally required however, to remove sludge from the boiler mud drum.

Boiler blowdown water is often passed through a heat exchanger to recover energy which would otherwise be wasted. Heat from boiler blowdown is usually used to heat the incoming boiler feedwater.

1.4 Soot Blowers

The efficiency of some types of boilers decreases with increased operating time due to the accumulation of soot and/or flyash on the heat transfer surfaces. Flyash accumulation is usually a problem only in coal fired boilers. Soot accumulation can occur in any boiler if combustion is incomplete. If soot is present in oil or gas fired boilers in appreciable amounts, tests should be conducted to determine if the fuel-air ratio is correct. Flyash and soot serve as insulators and restrict the transfer of heat from the hot combustion gases to the water. This layer of soot and/or flyash must be periodically removed from the boiler tubes. Usually high pressure steam lances are used to blow the soot from the heat transfer surfaces. On smaller boilers this operation is usually initiated manually, but on some large boilers the soot blowing operation has been automated. Since the thickness of the soot deposit is roughly proportional to the number of hours the boilers has been operated, automatic soot blowers are usually activated by a simple time-clock mechanism.

1.5 Safety Controls

The controls and operating procedures required for the safe operation of a boiler are presented in Volume 8 of the National Fire Codes (Ref 1). This document should be referred to for detailed descriptions of the equipment and procedures necessary for the safe operation of natural gas, oil, and coal fired boilers.

The purpose of safety controls is to prevent explosions. Generally, both pressure safety and flame safety controls are used. Pressure safety control is usually limited to an automatic pressure relief valve on small boilers. On large boilers, a signal indicating excessive steam pressure might also be used to override the main control system and shut off the flow of fuel to the boiler.

Flame safety controls are intended to prevent explosions that can occur when: (1) an ignition source is introduced into a furnace that contains air and fuel vapors in an explosive mixture, (2) fuel is discharged into the furnace during startup without proper ignition taking place, (3) the burner flame is extinguished during normal operation without the fuel supply being shut off or, (4) a major malfunction in the burner or feedwater control system occurs.

Flame safety systems are usually not discrete devices, but rather they are a number of timers, relays, limit switches and sensors which are connected to the burner control system to provide the necessary interlocks.

Startup from a cold condition presents perhaps the greatest danger from explosion. It is essential that the furnace be purged of all combustible gases before any source of ignition is introduced, and that once fuel flow is initiated, ignition take place quickly.

Purging of the furnace is generally accomplished using the combustion air fan. A purging air timer is provided that will not allow ignition until the fan has been in operation for a specific period of time. For watertube boilers the purge airflow must be sufficient for at least eight air changes to occur. For firetube boilers, the purge is conducted with wide open dampers, and four air changes are normally required. In either case, airflow is verified by providing limit switches on the dampers and a pressure switch at the fan discharge, or by providing airflow measurement devices such as differential pressure switches.

Once fuel flow has been initiated to the ignitor or main burner, flame verification is usually achieved by means of flame scanning devices. These flame scanners may be either the infrared flicker type or the ultraviolet type.

Recently manufacturers of flame safety control components have introduced integrated flame safety systems based on microcomputer technology. These units are programmed to perform the boiler startup and shutdown sequences plus perform dynamic self-checks of system inputs (sensor), output (control actions), and internal logic functions. Some of these microcomputer based devices also incorporate alarm communication, self-diagnosis of controller problems, and energy conservation features.

Additional information on feedwater controls and safety controls can be found in Reference 2.

2.0 COMBUSTION CONTROL MAINTENANCE AND ADJUSTMENT

2.1 General

This section of the User's Guide provides ~~general~~ guidelines for the establishment of an effective maintenance program for combustion controls of small industrial boilers. Many of the principles presented in this section can be directly applied to the maintenance of feedwater and safety controls also. The material in this section is excerpted from Reference 3.

This section specifically covers the maintenance of instruments and control devices, normally included in jackshaft, pneumatic, and electric parallel positioning combustion control systems using steam header pressure as the controlled variable (identified in Reference 1 as the most prevalent combustion control systems for small oil or gas fired industrial boilers). However, the maintenance guidelines given below are applicable to all boiler control systems. Maintenance of peripheral equipment such as burners, fuel storage tank, combustion air fan, furnace casing and breeching which can affect combustion control in different ways is also addressed.

It is not the intent of this section to establish a fixed set of rules and procedures for boiler combustion control maintenance. Rather, the objective is to provide general guidelines that would assist the operating personnel in developing a satisfactory maintenance program for each boiler installation. The maintenance program for combustion control must be carefully thought out and evaluated for each individual boiler installation; it should be based on boiler size, service continuity, type and complexity of control system, fuel type, and maintenance cost.

In general it is necessary to conduct an annual overhaul of the boiler control and safety systems. This will reduce the unscheduled outage time and improve the boiler's operating efficiency.

2.2 Maintenance Facilities

Several options are available for maintenance facilities. They are: on-site instrument shop, a centrally dispatched mobile unit, an instrument service contractor or a manufacturers' shop. The selection of approach for each boiler installation is dependent on economies and the criticality of the boiler operation at the particular facility.

The test equipment requirements for a local or mobile facility would be similar and are listed as follows. In general, all instruments should be high accuracy test quality.

Pressure Gauges - Ranges: 0 to 20, 0 to 60, 0 to 100, 0 to 500 psig, 0 to 30 inches mercury

Manometers Ranges: 0 to 6, 0 to 12, 0 to 30 inches water, 0 to 10 inches, 0 to 30 inches mercury

Deadweight tester - 5 to 100 psi

Pressure Regulators

Instrument air supply - 0 to 100 psig (bottled)

Thermometers

Temperature bath

Potentiometer

Megger

Multimeter: milliamperes, millivolts, volts, Ohms, etc.

Recorders, multirange electric and pneumatic with miscellaneous fittings.

In addition, instrument test stands, vises, benches, and power supply will be required. These facilities should be separated from other work areas for cleanliness and safety purposes.

2.3 Maintenance Records

A master set of drawings and instrument data sheets should be maintained for each facility. It is essential that these records are accurate and up to date. In addition, a copy of the manufacturer's service or instruction manual is required for each instrument and final drive.

Complete maintenance records not only provide a readily accessible source of information for cost control, but also provide the following functions: (1) central source of original data and specifications; (2) complete history of alterations, range changes, performance under different operating conditions, replacement and repair; (3) cross comparison between different makes and models of instruments; (4) automatic recheck and preventative maintenance schedule; and (5) basis for estimating reliability and, in part, for predicting shutdown schedules.

2.4 Guidelines for Field Checks

2.4.1 General

The field maintenance overhaul program is divided into three phases: calibration and repair, preoperation testing, and dynamic tuning. Although not specifically addressed in this guide, it is necessary to overhaul the boiler safety systems at the same time the combustion control is being checked. Many of the procedures outlined here are also applicable to the safety systems. The boiler safety system includes relief valves, high-low drum level switches, pressure switches, flame failure protection, purge protection, and other similar devices.

2.4.2 Calibration

Control system calibration is done with the boiler shut down and isolated. Each instrument or final drive is calibrated in accordance with the manufacturer's instruction book for the specific item. Instruments may be calibrated in place, however, it is frequently easier to do the work in a shop using a test stand. The general procedure is as follows:

1. Power all transmitters from system power supplies before calibration. Allow manufacturer's recommended warm-up time prior to start of calibration of device.

2. Calibrate pressure devices as follows:

    a. Use certified deadweight tester, manometer or pneumatic calibration unit as applicable.

b. Adjust zero and span.

c. Check readings or output of device at 0, 25, 50, 75 and 100% of input value.

3. Calibrate temperature devices as follows:

   a. Use water bath or oil bath as applicable and certified test thermometers.

   b. Adjust zero and span as applicable.

4. Calibrate level devices as follows:

   a. Level controllers and liquid level switches:

      1. Use water column to establish water level in float chamber.

      2. Check direction of response of controller or switch points of liquid level switches.

   b. Level transmitters or indicators:

      1. Use water column or pneumatic calibration unit, as applicable.

      2. Adjust zero and span.

      3. Check readings or output of device at 0, 25, 50, 75, and 100% of input value.

5. Calibrate switches as follows:

   a. Apply process input and adjust switch actuation points to required value.

   b. Confirm switch makes/breaks with an electrical continuity check.

c. Adjust deadband if applicable.

d. Verify repeatability of switch actuation points after adjustments are completed.

6. Calibrate receiving devices, such as recorders, indicators, etc., as follows:

   a. Apply applicable electrical or pneumatic input signals and power if required.

   b. Adjust zero and span for each range.

   c. Check readings or output of device at 0, 25, 50, 75, and 100% of input value.

7. Calibrate transmitters and signal converters as follows:

   a. Apply power, input signal, and process input, as applicable.

   b. Adjust zero and span.

   c. Calibrate as specified for the applicable process measurement.

8. Calibrate SO_2, oxygen, and other analyzers in accordance with manufacturer's instruction.

9. Attach an approved calibration label to all devices after preoperational calibration.

10. Inspect control valves, refinish seating surfaces as required, replace packing if necessary.

11. Inspect dampers and repair and adjust as required.

12. Stroke control drive and adjust the 0 to 100% and travel stops to match the input signal. Ensure all drives operate smoothly without chatter or sticking. Plot damper position versus control signal on increasing and decreasing signals to obtain hysteresis of dampers. Recondition drive and dampers when hysteresis exceeds 7 to 10%.

2.4.3 Preoperational Testing

1. Confirm that process sensing air lines are connected and in good order. Lines should be blown out, then pressurized and bubble checked for leaks. Drive cylinders should be checked for rod packing and piston cup leakage.

2. Confirm that the instrument air power sources are adjusted to the correct level. Check the air to ensure that it is clean and dry. Check the dewpoint of the instrument air to assure proper dryness.

3. Confirm electrical power sources to transmitters, control drives, etc., are properly connected and adjusted.

4. Loop checkouts should now be made with the boiler shutdown.

The control system should be powered up and signals simulating process conditions applied to the field transmitters. The final drives should be observed for correct direction of travel. For example, apply a signal to the header pressure transmitter and observe the fuel valve opening when it is less than set point and, conversely, closing when it is greater than set point. This should be done for each control sub-loop.

2.4.4 Dynamic Tuning

It is recommended that an expert in boiler control tuning supervise the dynamic testing program.

Dynamic tuning takes place with the boiler operating. The tuning should be repeated at four load levels: 25, 50, 75% and full load. Adjustments will be made to the fuel, air and feedwater controls to ensure rapid response to changes in demand without hunting or dangerously overshooting. When tuning tests are conducted, the major process variables (header pressure, fuel, air, drum level) should be observed for response time, deviation, and settling time. Although plant instrumentation may be used, high speed recorders will more clearly track the major variables. In addition, control signals may be recorded to identify the cause of control system malfunctions.

At the time boiler testing is being conducted, observers should monitor the furnace to ensure that complete combustion takes place at all times.

The boiler should be set at approximately 25% of rated load and allowed to stabilize. At this time a change in demand should be induced. This can be accomplished by changing header pressure set point or by placing equipment in service that will produce a change in steam demand.

Adjustments should be made in the proportional band and reset rate, so that the controlled variables, air and fuel, change as rapidly as possible, without hunting or significant overshoot. In addition, adjustments should be made to the fuel-air ratio based on oxygen readings or observed flame characteristics.

The testing and adjustments should be repeated at 50, 75%, and full load. Data should be taken to ensure that the boiler is operating at its design point. The data include: fuel, air, steam and feedwater flows, steam pressure, drum water level, all control signals, drive and valve positions, and flue gas oxygen. These data should be compared with results of previous tests and retained in the maintenance records.

2.5 Peripheral Equipment Maintenance

2.5.1 General

Proper maintenance of combustion control systems requires that the combustion control support systems also be maintained properly. The support systems include oil and gas burner assemblies, fuel oil system, combustion air, and the furnace system. The maintenance requirements for major components of these support systems are discussed below.

2.5.2 Oil Burners

Oil burners may be classed as vaporizing or atomizing. The vaporizing oil burners are seldom used for industrial boilers since they require distillate oils (No. 1 or 2 fuel oil); therefore, maintenance requirements for these are not discussed. Atomizing oil burners are divided into three types: steam, air, and mechanical. The mechanical type is sometimes called oil-pressure atomizing burner since the required oil pressure is high (75 to 300 psig) and usually provided by use of gear type rotary pump sets complete with heaters for industrial boiler applications.

Atomizing oil burners should be checked visually at least once every shift to ensure there is no oil blockage and that the burner gets uniform, free-flowing oil. Note that sediment in oil caused by accumulation of sludge in fuel oil storage tank and dirty strainers can clog the burner nozzles.

In rotary cup atomizing oil burners, usually used on automatically fired boilers, worn cup rims can cause poor atomization. Consequently cups with worn rims should be replaced. Cups can be protected from carbon formation on the rim by removing the cup when the burner is shut down and inserting a flame shield. Carbonized cups should also be replaced.

Mechanical atomizing nozzles are more subject to wear than other types of atomizing burners because of the high fuel oil velocity. Worn or carbonized mechanical atomizing nozzles should be cleaned at regular intervals. When cleaning a nozzle, immerse the tip in light oil or kerosene to help loosen carbon accumulated at the tip and always use a wooden scraper to protect the surfaces being cleaned.

The fuel oil preheat temperature must be correct for fuel and burner type. Good combustion requires that the preheat temperature be kept constant. Check the oil preheat temperature as part of regular maintenance program.

2.5.3 Gas Burners

Gas burners generally require only routine maintenance. The important maintenance requirement for gas burners is that the gas connection is closed tight and gas header vented when the burner is shut down, so that there are no leaks or accumulation of combustible gas.

2.5.4 Fuel Storage Tank

Fuel oil storage tank maintenance plays an important role in combustion control systems. Sludge should never be allowed to accumulate in storage tanks. Therefore, storage tanks should be cleaned on a scheduled basis; clean fuel storage tanks means relatively trouble-free burner nozzles. Also, strainers in fuel oil lines should be cleaned on a regular basis if they are not of the self-cleaning type. Water should be drained from the tanks daily.

2.5.5 Combustion Air Fan

Fans generally are of the forced draft type for small industrial boilers. They are usually motor driven through belt drives. Items that require periodic maintenance include proper belt tension, bearing lube system and lubrication requirements of the motor. The air damper on the fan outlet should also be checked periodically. Inlet filters should be cleaned on a regular basis or replaced, depending on the type of filter.

2.5.6 Furnace System

The furnace system includes the furnace casing, refractory surfaces, and stack. In forced draft systems there usually is a slight positive pressure in the furnace causing small amounts of combustion gases to leak through cracks in the furnace casing and refractory surfaces. Therefore, both the furnace casing and refractory should be checked periodically for cracks and openings. Furnace casing sections with cracks should be repaired or replaced. Any large cracks in refractory should be cleaned out and filled. Small cracks in refractory can be sealed frequently by wash coating the refractory surface. Use high temperature bonding, air dry type mortar diluted with water to the proper consistency for wash coating. Note that a telltale sign for cracks is a soot mark along the crack. Gaskets on handholes and inspection doors should be inspected periodically and changed when necessary.

The breeching and stack should be inspected periodically and cleaned if necessary. The breeching and stack should be checked carefully for in-leakage of outside air. This is especially important for sections of breeching "upstream" of any oxygen analyzers or sample lines for flue gas analysis.

2.6 Jackshaft Control System Maintenance

2.6.1 General

A jackshaft control system is shown in Figure 1 and it is usually operated electrically for small industrial boilers. A functional schematic diagram for such a system is shown in Figure 6. The maintenance of major control components shown in Figure 1 are discussed below.

2.6.2 Jackshaft

All bearings, including those at drive rod ends, should be lubricated at regular intervals, approximately once every two months.

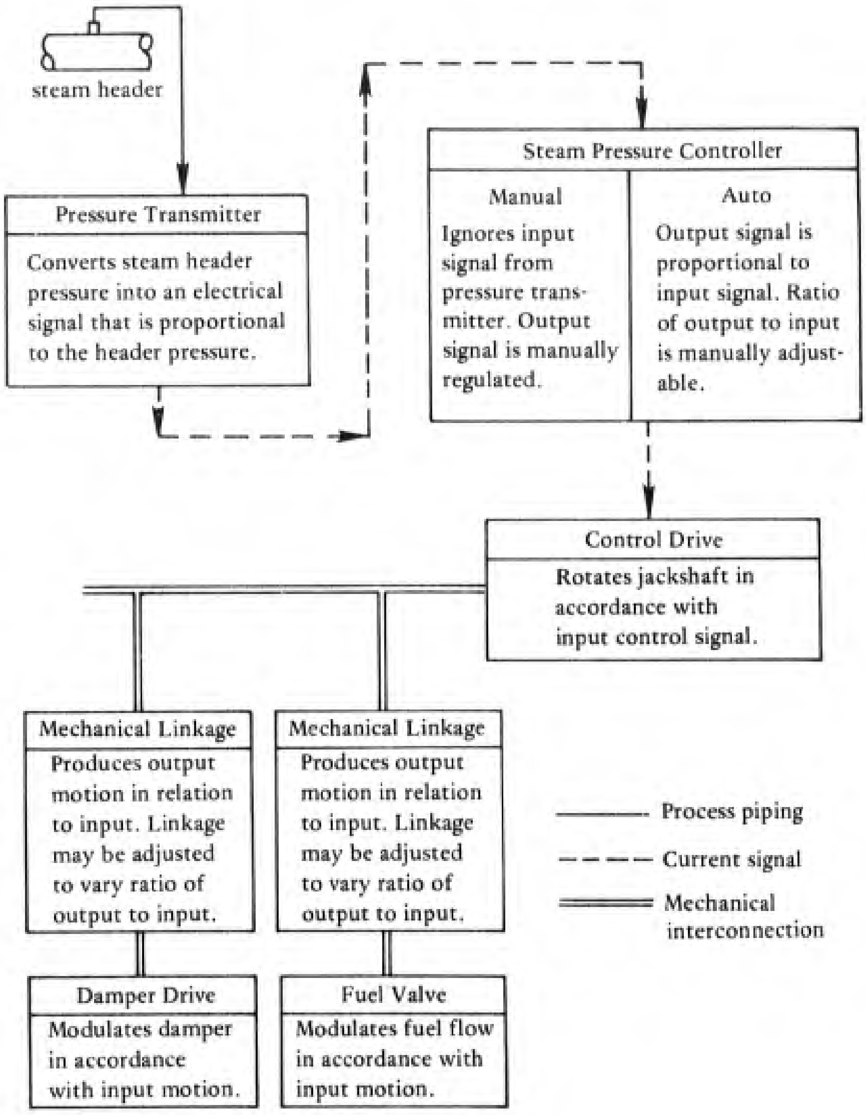

Figure 6. Functional schematic diagram of jackshaft system.

All linkage should be checked for slack on a scheduled basis. Note that linkage rods should be "wiggled" in checking for looseness. Appreciable free movement will require the replacement of worn out bearings.

Adjustable set screws on the cam mechanism, shown in Figure 7, require lubrication at regular intervals, as well as checking for proper functioning.

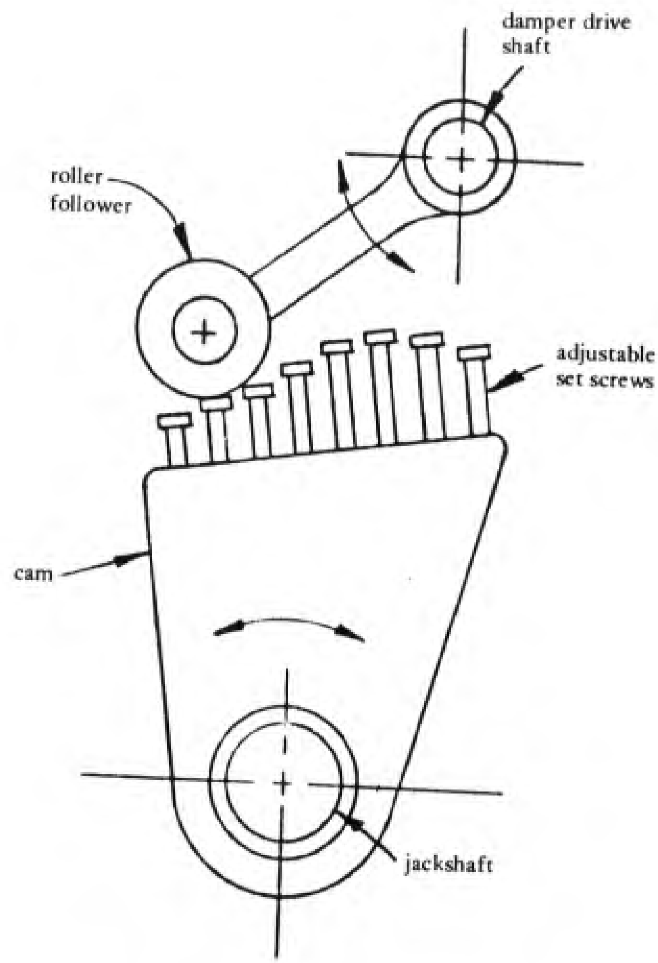

Figure 7. Adjustable jackshaft cam mechanism.

2.6.3 Other Control Components

The maintenance requirements for the mechanical components of the master pressure controller, jackshaft drive unit, fuel control valve, etc., are similar to those for the pneumatic parallel positioning (presented below). The electric devices require only minimal maintenance. Usually, repair is by replacement.

2.7 Pneumatic Parallel and Series Positioning Control Maintenance

2.7.1 General

Maintenance requirements for pneumatic parallel positioning and series positioning combustion control systems are discussed below. Figure 2 illustrates a pneumatic series positioning control system and Figure 8 illustrates a parallel positioning system. The maintenance requirements of major components, shown in Figures 2 and 8, are presented below.

2.7.2 Master Pressure Controller

Figure 9 shows a master pressure controller instrument air piping diagram. The various internal adjustments of this component depends on the particular instrument make, and the manufacturer's instructions should be followed.

Routine maintenance of the master pressure controller consists of checking the output of the device to see if it follows the steam header pressure changes. If it does not, it is probable that the steam pressure bellows in the master controller is broken. The manufacturer's instruction for bellows replacement should be followed.

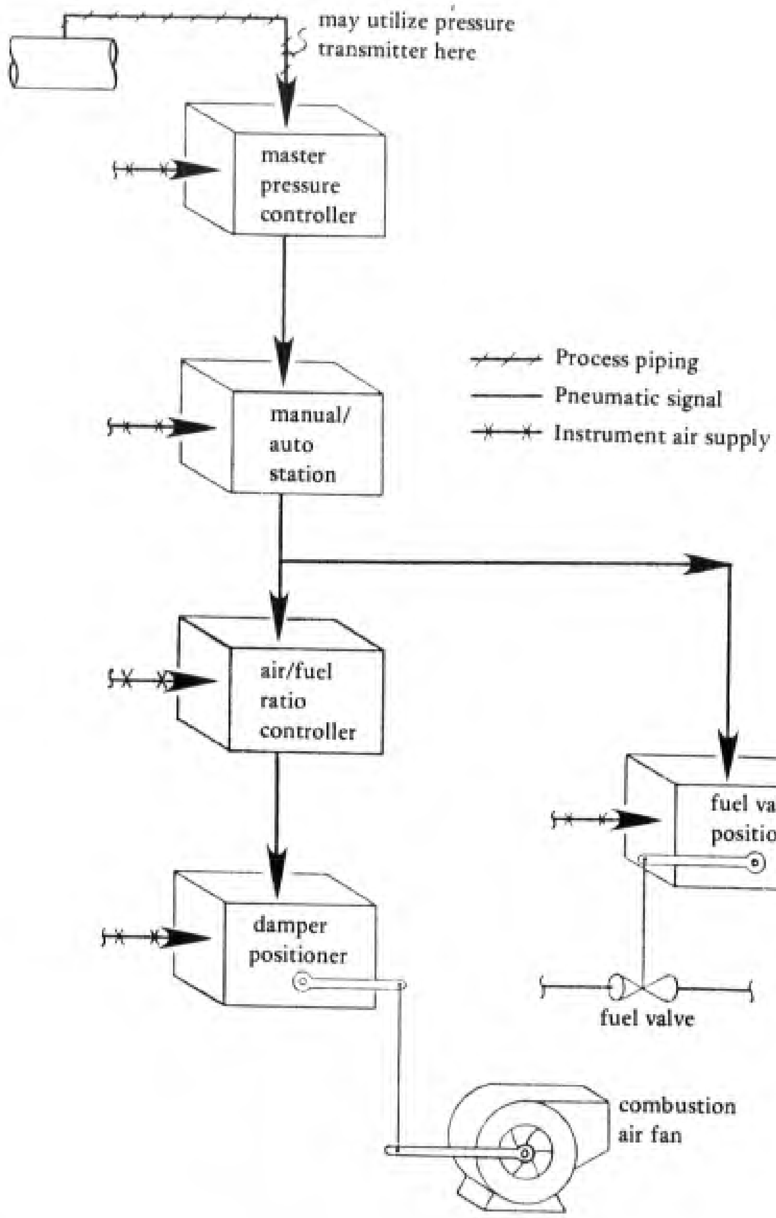

Figure 8. Parallel positioning control system (pneumatic).

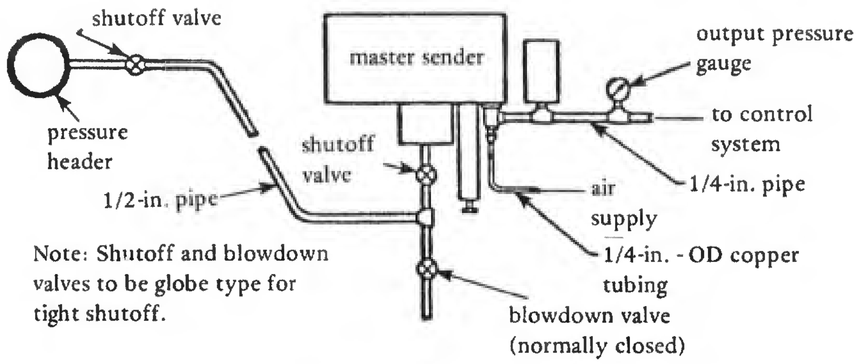

Figure 9. Master pressure controller instrument piping diagram.

2.7.3 Manual/Auto Station

The manual/automatic control station is normally located between the controller and the final control element, as shown in Figure 8. The maintenance basically involves the inspection of the poppet valve in the relay assembly for dirt or foreign matter in the inlet seat or exhaust seat. The latter is indicated by a continuous leak at the exhaust port. Cleaning and replacement of inlet or exhaust seat of the poppet valve should be in accordance with the manufacturer's instructions. The transfer valve should also be dismantled and inspected during any overhaul.

2.7.4 Air/Fuel Ratio Controller

The air/fuel ratio controller normally controls the air damper positioner, but in some installations it may control the fuel valve positioner. The basic operation is the same in either case. The routine maintenance of this component basically involves placing a few drops of light machine oil on the ball bearing fulcrum. The poppet valve should be dismantled and inspected during any overhaul.

2.7.5 Fuel Valve/Air Damper Positioner

The routine maintenance of fuel valve positioner and air damper positioner includes lubrication of the cylinder piston rod, side bars, and compensator. The lubricant should be a light machine oil. The compensator shaft should be lubricated with light grease. The pilot valve in each positioner should be inspected at regular intervals. When the piston fails to move quickly to the position required by incoming signal change, it indicates a malfunction of the pilot valve which must then be repaired or replaced, as required, in accordance with the manufacturer's instructions. The receiving diaphragm should be replaced if ruptured or deteriorated. The replacement of the receiving diaphragm should be in accordance with the manufacturer's instructions.

2.8 Electric Parallel and Series Positioning Control Maintenance

2.8.1 General

The maintenance requirements of the mechanical elements of an electric or analog electronic control system are the same as described in the preceeding paragraphs. Problems with electrical components are usually diagnosed by bench testing the suspect component to determine if the electrical output varies as anticipated with changes in the input signal. Troubleshooting and repair of electric and analog electronic control components can often be done by a qualified electronics technician, but defective components are most often repaired by replacement of part or all of the device.

3.0 CONTROLS TO IMPROVE EFFICIENCY

3.1 General

To a great extent, the efficiency of a boiler is dependent on the design of the burner, heat exchanger, and other design parameters which cannot be readily changed. However, changes in fuel composition, air temperature, pressure and humidity, boiler load, and equipment condition all introduce changes in boiler performance which can be accommodated for by improved control. In general, "improved control" means better control of the fuel-air ratio. The simple parallel positioning and series positioning systems described earlier have open-loop control of the fuel and airflows. There is no feedback into the control system which tells the system what the actual fuel and airflows are. Feedback is provided only by the steam header pressure. If the header pressure is at the control set point but the fuel/air ratio is nowhere near the desired value, the control system will take no action to correct it. For this reason, it is often desirable to modify a boiler control system to include feedback of information on the fuel/air ratio. In small boilers, this is usually done by adding an excess-air trim system to the boiler controls. The idea behind excess-air combustion control is to maximize boiler efficiency by operating at the point where the combined losses due to unburned fuel and heating excess air are minimized. This point is often called the smoke point (see Figure 10). Often, the actual boiler operating point is a fuel/air ratio slightly richer than optimum to ensure stable combustion. Table 1 presents the recommended boiler operating points for efficient operation.

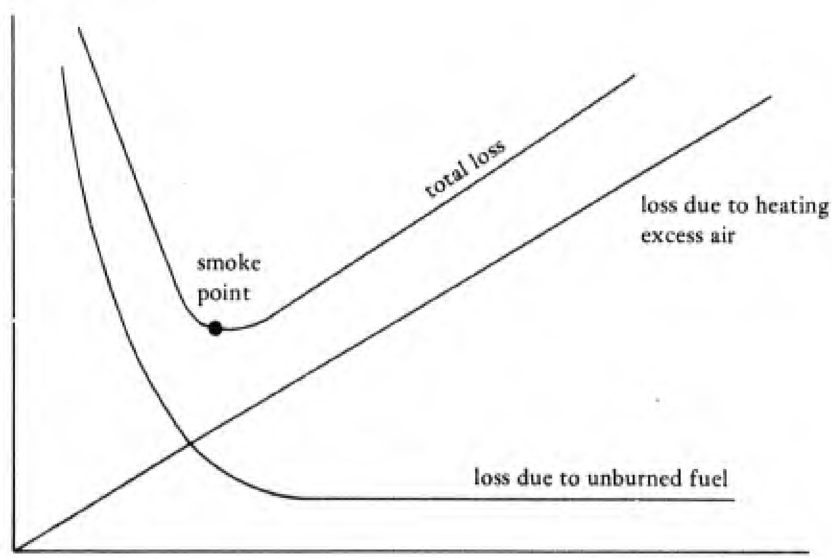

Figure 10. Boiler flue gas loss.

Table 1. Recommended Boiler Operating Points for Efficient Operation[a]

Fuel	Exhaust Gas Characteristics		
	Excess Air (%)	O_2 (%)	CO_2 (%)
Natural Gas	7	1.5	11
No. 2 Oil	10	2	14.1
No. 6 Oil	13	2.5	14.5
Coal (pulverized)	16	3	15.9
Coal (other)	23	4	15.0

[a]From Reference 4.

3.2 Oxygen Trim Systems

An oxygen trim system measures the excess oxygen in the combustion products and adjusts the airflow accordingly for peak combustion efficiency. Installation of an oxygen trim system is illustrated in Figure 11. An oxygen trim system operates as follows.

The desired fuel and airflows are initially determined by the control signal from the master pressure controller. Since the master pressure controller only receives feedback from the steam header pressure, any signal from the master pressure controller is intended only to increase or decrease the header pressure. At the same time, the oxygen trim system measures the level of oxygen in the flue gas, and makes minor adjustments to the damper positioner. If the adjustment made by the oxygen trim system causes an increase or decrease in the steam header pressure, then the master pressure controller will again adjust the fuel and airflow together. Thus, the feedback provided by the oxygen trim system may affect the fuel flow to the boiler (via the master pressure controller) even though it only adjusts the air damper positioning directly.

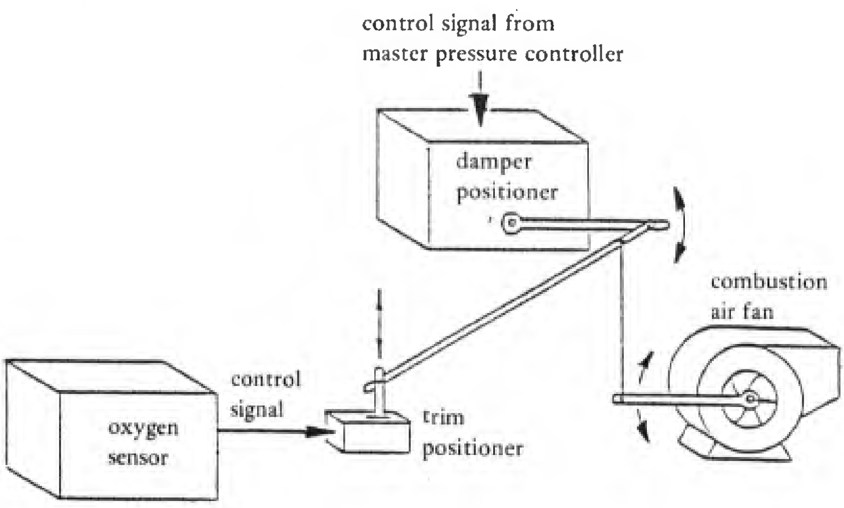

Figure 11. Oxygen trim system.

There are numerous oxygen trim systems available, but the operating principles of each are basically the same. An oxygen sensing probe measures the percentage of oxygen in the flue gas and transmits a control signal to an adjustable link mechanism. The link mechanism then alters the combustion air damper position. The trim linkage may be located anywhere between the damper drive and the damper. The damper drive moves in accordance with the signal from the master pressure controller. The trim mechanism, by changing the effective length of the connecting linkage, either adds to or subtracts from the damper drive displacement.

Modern oxygen trim systems use a zirconium oxide probe which directly measures oxygen level. Older systems use an aspirating device which draws samples from the flue gas for analysis. These aspirating-type systems are inherently slower in response and are thus becoming obsolete.

3.3 Carbon Monoxide and Carbon Dioxide Trim Systems

Carbon monoxide (CO) and carbon dioxide (CO_2) are also used as bases for excess-air trim systems. Carbon monoxide trim systems, in fact, offer several advantages over oxygen trim systems. Specifically, the measured parameter is directly related to amount of unburned fuel in the boiler and therefore can be used to control completeness of combustion better than oxygen; the control set point is independent of fuel type, and the carbon monoxide signal is unaffected by furnace air infiltration. Theoretically, no carbon monoxide will be present in the flue gases when a boiler is supplied with excess air (see Figure 12). In reality, however, a small amount (<200 ppm) of carbon monoxide is always present in the flue gas due to the incomplete mixing of fuel and air and the kinetics of chemical reactions (Figure 13). The operating point of a carbon monoxide controller is always at the knee in the carbon monoxide versus excess air curve (between 100 and 350 ppm), independent of fuel type (Figure 14). Carbon monoxide trim systems must be applied with caution, however, because carbon monoxide level is not always a measure of excess air (which should be the basic measure for low-excess air operation). A dirty burner, poor atomization, and poor fuel mixing can cause a rise in carbon monoxide level and associated increase in excess-air quantity when additional excess air is not the desired response.

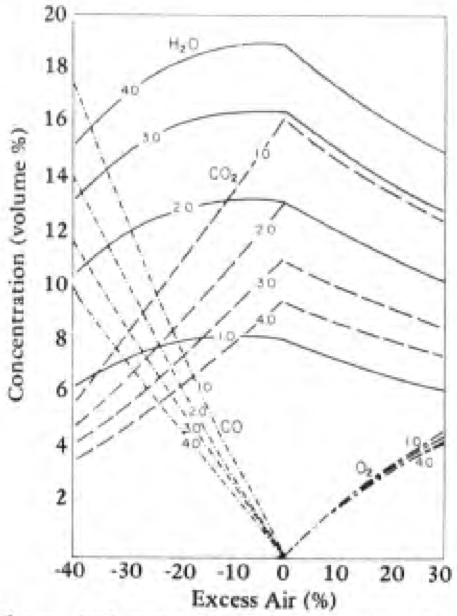

Figure 12. Theoretical composition of flue gases for several HC ratios. Hydrogen/carbon ratios: natural gas = 4, no. 2 oil = 1.7, no. 6 oil = 1.3, coal = 0.7 (from Ref 5).

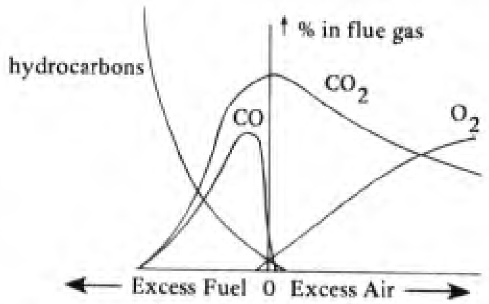

Figure 13. Variation of flue gas constituents with excess air level.

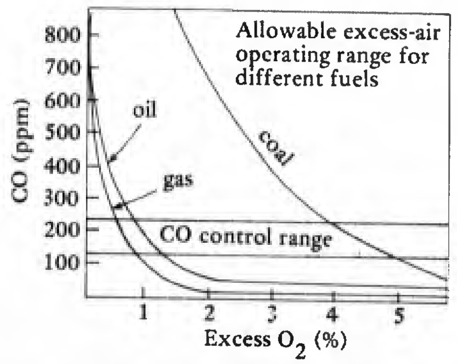

Figure 14. CO trim system operating point (from Ref 6).

In the past, the comparatively high cost (40,000 to 60,000 dollars) of carbon monoxide trim systems permitted their application only on large boilers. The high cost of carbon monoxide trim systems was due to the fact that they used relatively complex infrared absorption analysis techniques to determine the amount of carbon monoxide in the flue gases. Recent advances in catalytic chemistry, however, have permitted principles similar to those used in the ZrO_2 cell to be used to measure CO. As a consequence, many manufacturers now offer combined O_2-CO trim system for little more than the cost of an O_2 trim system.

The percent of carbon dioxide in the flue gases is a maximum when combustion is complete and excess air is minimized (Figure 13). Trim systems utilizing carbon dioxide sensors are based on this fact and operate to adjust the air dampers to either maximize carbon dioxide content in the flue gases or control the carbon dioxide content to a specified value. Carbon dioxide trim systems are based on infrared absorption technology and generally cost more than zirconium oxide cell type oxygen and oxygen/carbon monoxide trim systems.

Additional information on the various types of stack gas analysis systems can be found in Appendix A.

3.4 Procedures For Addition of Oxygen Trim Systems

3.4.1 General

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

3.4.2 Oxygen Trim Control with In-Situ Zirconium Oxide Analyzers

Jackshaft System. Figure 15 shows a jackshaft system without trim control. Figure 16 shows the same system with trim control; a quick comparison reveals the difference. This system (Westinghouse-Hagan) employs a mechanism called a "tory link".

Install the tory link in place of forced draft fan inlet vanes lever, or damper lever, using the existing orientation of 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 16. Complete the installation of oxygen controller and all of the instruments, including oxygen manual/auto station, that are located in the boiler room. Connect wiring and provide 115 volt, 60 Hertz power source. Finally, install the analyzer in the duct and the electronics package at a suitable location outside of the duct (see Figure A-5). Provide instrument air to the calibration gas and reference air connections if required. Provide 115 volt, 60 Hertz power to the electronics package and connect the wiring between the electronics package and oxygen controller in the boiler room.

Pneumatic System. Figure 17 shows a parallel positioning system without trim control. Figure 18 shows the same system with trim control; a comparison of the two readily shows the difference.

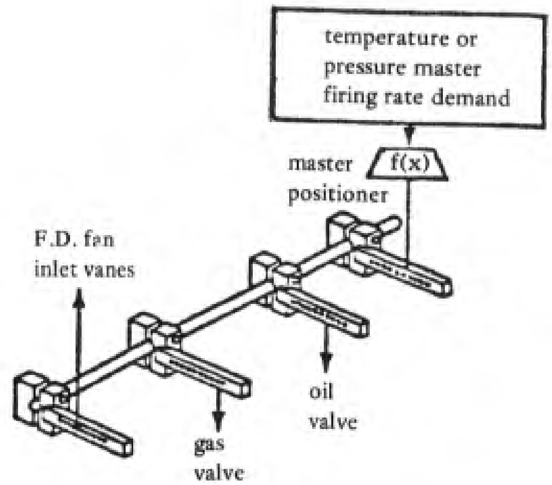

Figure 15. Jackshaft system without O_2 trim (Westinghouse-Hagan).

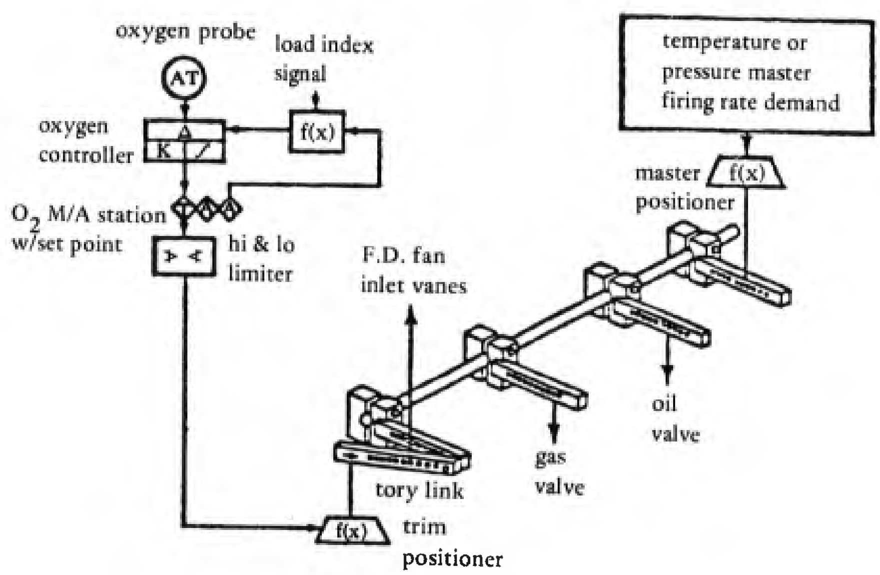

Figure 16. Jackshaft system with O_2 trim (Westinghouse-Hagan).

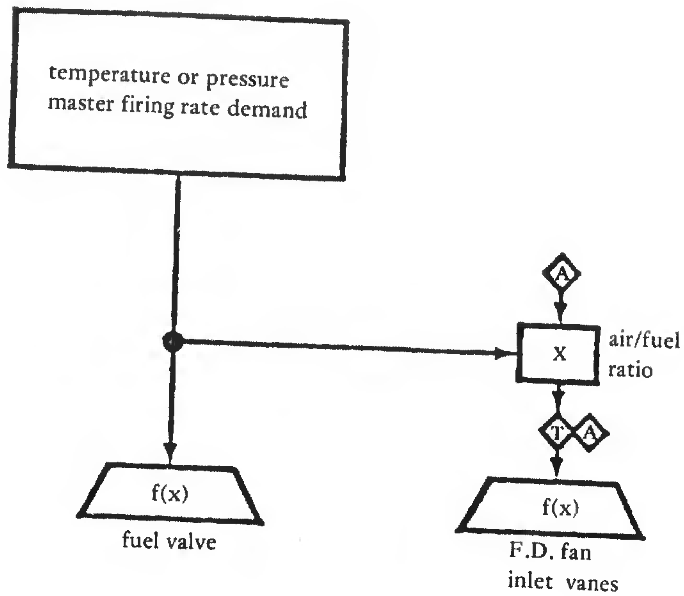

Figure 17. Parallel positioning system without O_2 trim – pneumatic or electric (Westinghouse-Hagan).

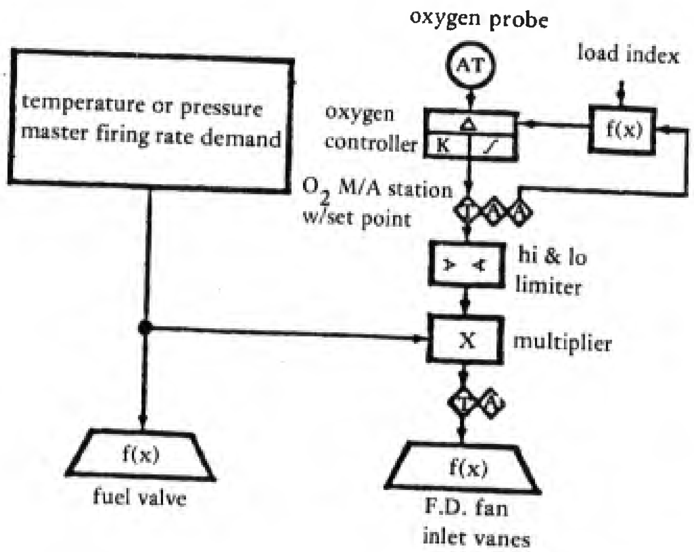

Figure 18. Parallel positioning system with O_2 trim – pneumatic or electric (Westinghouse-Hagan).

Replace the air-fuel ratio controller in Figure 17 with the multiplier shown in Figure 18. Install the oxygen controller and all of the other additional boiler room instruments. Install necessary tubing between various instrument air connections and provide an 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 elctronics package to the oxygen controller will be via a transducer to convert the signal from electric to pneumatic.

Electric System. Figures 17 and 18 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 115 volt, 60 Hertz power source instead of instrument air. The input signal from the electronics package to the oxygen controller will be direct.

3.4.3 Representative Manufacturer's Offerings

A brief description of the oxygen trim systems offered by the major manufacturers of these 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 oxygen 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 zirconium-oxide oxygen trim systems ranging from the Model 132 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 analyzer (2,800°F). The Model 450 can be inserted directly into the furnace or adjacent convective section of many small heating boilers. A complete oxygen trim system utilizing the miniprobe 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 oxygen trim systems offered by the Bailey Controls Company are of the sampling probe type with the zirconium oxygen sensor outside the stack. They also offer a combined oxygen and carbon monoxide analyzer (see Appendix A) and prefer to sell the oxygen trim as part of the "Conserver I" or "Conserver III" boiler control systems. The cost of the oxygen trim analyzer for application to an existing boiler control system can run as low as about $4,000 while the complete "Conserver" systems including oxygen trim can range in cost up to $25,000. The addition of the carbon monoxide analyzer and recorder adds less than $3,000 to the above costs.

C. Hague International. The OxSen oxygen trim analyzer offered by Hague is an in-situ type probe with a zirconium oxide sensor. It is offered in both low (1,100°F) and high (2,800°F) temperature versions. A feature of this unit is that it can be check calibrated in about 1-1/2 minutes with air. Also, a proportional-integral-derivative (PID) controller is included in the anlayzer. 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 (1,100°F) temperature system and $8,500 for the high temperature (2,800°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 oxygen trim offerings available from this source and a brief listing follows:

1. The Oxyprobe is an in-situ oxygen trim analyzer operating on the zirconium oxide cell principle.

2. The Hays-Republic zirconium oxide oxygen analyzer 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 oxygen trim bias to be applied mechanically to air damper actuators. The Trimlink can be used with other oxygen trim analyzers.

E. Measurex. The Measurex trim systems employ infrared sensing of carbon monoxide and carbon dioxide and include microprocessor controlled automatic calibration and signal processing. These analyzers are not sold separately but only as a part of a complete boiler control system.

3.4.4 Cautionary Notes

Excess-air trim systems can improve boiler efficiency by as much as 1% for every 10% reduction in excess air levels. In addition to saving fuel, they can lower pollutant emissions, provide safer operation, and reduce operator effort. However, excess-air trim controls are not applicable to every boiler facility and so the following cautionary statements should be carefully considered before investing in any type of trim system.

1. A trim system will not make an old, worn boiler control system perform like new. As a matter of fact, it may not perform any better at all with a trim system than it did without.

2. If a very careful manual adjustment of a boiler control system, using an oxygen indicator, Orsat analyzer, or similar device, does not markedly improve the performance, the addition of a trim system will not help.

3. If the "play" in a boiler control system is of a magnitude comparable to the "trim range" of a trim system, the addition of a trim system will not help.

4. The response characteristics of a trim system must be such that interplay with the primary control system does not cause hunting or control instability.

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 excusions, and possible smoke, on boiler load changes.

7. Trim systems are not very effective on boilers which operate at low loads most of the time.

8. Some excess-air trim systems control to only one set point, independent of load, and thus do not provide the optimum excess-air level required for different boiler loads.

9. Periodic adjustment of the control system will still be required after addition of a trim system. A trim system cannot compensate for any and all control system problems. Poorly adjusted primary controls may cause the trim system to reach the end of its control range before the control point is reached.

10. In-house maintenance of trim systems will require skills and test equipment which may not exist at some Navy activities.

Before investing in any type of excess-air trim system, other options for improving boiler efficiency, such as control tuning or replacement or burner tuning or replacement, should be evaluated. The services of a knowledgeable consultant may be of value in weighing the options for improving the efficiency of a boiler.

3.5 Economic Analysis

The following example illustrates a method for evaluating the cost effectiveness of an excess-air trim system at a facility. For this example the following conditions were assumed:

Boiler - gas fired, 30,000 lb/hr rating

Operation - average of 80% capacity for 500 hr/yr

Fuel cost - 55¢/therm

Life of trim system - 15 years

Annual O&M cost of trim system - $200

Discount rate - 10%

Differential fuel cost escalation rate - 7%

Differential O&M cost escalation rate - 4%

Salvage value - None

An ORSAT or similar analysis is performed on the flue gases with the following results:

Oxygen - 5-1/2%

Carbon dioxide - 9%

Measured flue gas temperature equalled 350°F.

Appendix C contains data on combustion efficiency as a function of flue gas composition for several fuels. Refer to Figure C-1 for natural gas and 350°F flue gas temperature. Figure C-1 shows that the measured conditions (oxygen equals 5-1/2%, carbon monoxide equals 9%) correspond to operation with about 30% excess air and a combustion efficiency of about 82.5%. This is quite good for a manually trimmed boiler, but the efficiency could be increased to about 83.7% with the addition of a trim system to fine tune the combustion airflow. The question is: Is the increase in efficiency worth the additional expense of the trim device?

The current rate of fuel consumption is approximately equal to

$$\frac{30{,}000 \text{ lb/hr} \times 1{,}000 \text{ Btu/lb} \times 0.80 \times 500 \text{ hr/yr}}{0.825}$$

$$= 14.54 \times 10^9 \text{ Btu/yr}$$

The fuel consumption rate after addition of a trim system is estimated to equal

$$\frac{30{,}000 \text{ lb/hr} \times 1{,}000 \text{ Btu/lb} \times 0.80 \times 500 \text{ hr/yr}}{0.837}$$

$$= 14.34 \times 10^9 \text{ Btu/yr}$$

The energy savings is, therefore,

$$14.54 \times 10^9 \text{ Btu/yr} - 14.34 \times 10^9 \text{ Btu/yr}$$

$$= 200 \times 10^6 \text{ Btu/yr}$$

$$= 2{,}000 \text{ therms/yr}$$

The value of this energy savings (in present dollars) is

$$2{,}000 \text{ therms/yr} \times 0.55 \text{ \$/therm} = 1{,}100 \text{ \$/yr}$$

The present worth of this savings is

$$\$1{,}100 \times \text{CPW (15 yr, 10\%, 7\%)}$$

$$= \$1{,}100 \times 12.278 = \$13{,}506$$

The present worth of the O&M cost is

$$\$\text{-}200 \times \text{CPW (15 yr, 10\%, 4\%)}$$

$$= \$\text{-}200 \times 10.142$$

$$= \$\text{-}2{,}028$$

CPW is the compound present worth factor. Tables of these factors can be found in Reference 7. A manufacturer of oxygen trim systems offers a complete system for $8,000 including installation and startup. Therefore, the net present worth of the proposed installation is

$$\$13{,}506 - 8{,}000 - 2{,}028 = \$3{,}478$$

so the installation would be cost effective. The savings to investment ratio equals

$$\frac{13{,}506}{8{,}000 + 2{,}028} = 1.35$$

and the pay-back period is about 9 years.

If the boiler had been running at 100% excess air, the annual fuel savings would be 8,500 therms, so the cost effectiveness of installing an oxygen trim system would be about four times greater.

The data in Appendix C shows that the control of excess air is especially important for boilers which have a high flue gas temperature. There are two causes of high flue gas temperatures: (1) a poor boiler design which has insufficient heat transfer area, and (2) fouling of the boiler tubes which reduces the effective heat transfer area. It is recommended that the trim system evaluation procedure outlined above be performed soon after the boiler has been cleaned so that good estimates of the flue gas temperature and other operating parameters are obtained. If the flue gas temperature is still high (greater than about 320°F) after the boiler has been cleaned, consideration should be given to adding an air preheater or other type of heat recovery system to utilize the excess heat that is going up the stack.

An alternative and more complete method of evaluating excess-air trim systems is presented in Reference 8.

4.0 DIRECT DIGITAL CONTROL

4.1 General

The latest developments in automatic boiler control systems have been in the technology of direct digital control (DDC) of boilers. DDC systems are based on microcomputer technology and control the boiler by means of a changeable program, or "software" rather than fixed interconnections or "hardwired logic". Digital control systems often combine the functions previously performed by separate hardware systems such as combustion control, safety controls and interlocks, and monitoring and data acquisition. In a typical DDC system, (Figure 19) input devices such as sensors, switches, and position encoders are accessed at frequent intervals and requested to transmit their data (steam pressure, on/off status, shaft position, etc.) to the controller. Modern data encoding and multiplexing techniques permit this communication to take place over a single pair of shielded wires. The controller then acts on these data according to a set of instructions, or program, which has been entered into the computer. The output or results of the program are then transmitted to the appropriate output device, such as a fuel valve positioner.

The advantages of microcomputer based control systems include: (1) the control instructions and set points can be easily changed; (2) the systems are usually easily expanded to include more control features or additional boilers; (3) low cost control redundancy; (4) boiler operation diagnostics and performance data acquisition; and (5) control system self-diagnostics.

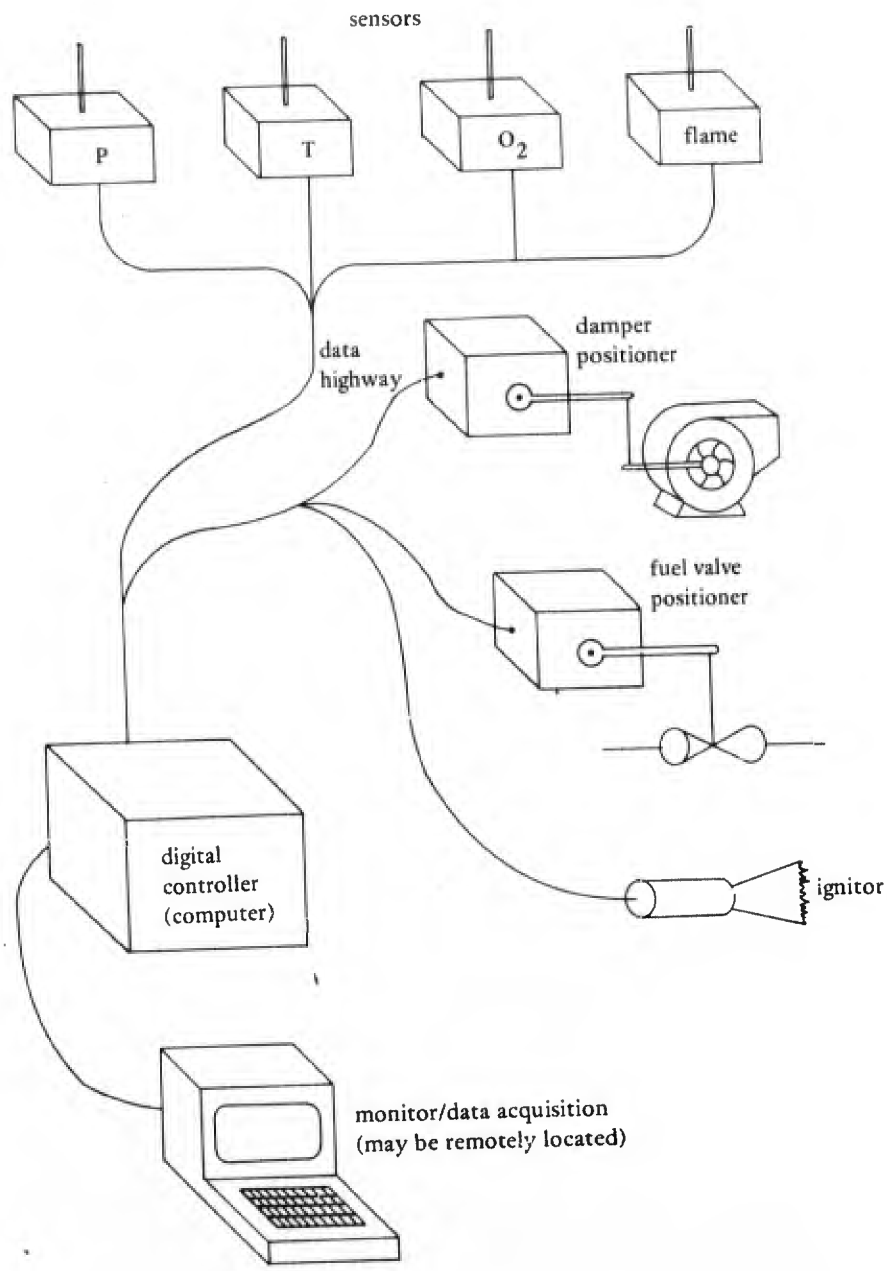

Figure 19. Digital control system.

While DDC systems do have some advantages over conventional pneumatic and analog electronic control systems, they are not presently cost effective in every installation. A simple microcomputer base boiler control system currently costs 50% to 70% more than a system based on older technology but prices for DDC systems are rapidly falling. Large boilers with more complex control schemes are presently less expensive to implement with microcomputer-based systems than with traditional control components. Table 2 compares some of the digital boiler control systems that are currently being marketed. More information on the systems listed in Table 2 can be found in Appendix D.

The following general discussion (excerpted from Reference 7) of some of the major characteristics of these control systems is presented to give an understanding of the overall considerations for the application of direct digital control to the Navy's small boilers. It was assumed that the present controls on these boilers are relatively old and generally not in good repair, and that most of the control systems include little or no flow metering.

4.2 Cost Effectiveness

The cost effectiveness of direct digital control systems is often so good compared to the control systems presumed in place that the return on investment will be very rapid on the basis of fuel cost savings alone. The reason for a fuel cost savings is of course the reduction of excess air which must be heated by burning fuel to the exhaust temperature. An older combustion control system, in poorly maintained condition, must be adjusted to have a large amount of excess air to prevent smoking, while a tight digital system can be adjusted to have a minimum of excess air with good combustion and no smoke. To this savings, the reduced requirements for the operator and lower maintenance expense must be added. It is estimated that a savings in the fuel cost of from 2 to 6% can be realized by the installation of a "tight" control system.

4.3 Reliability

Reliability is the most important characteristic of any boiler control system and this is well recognized by all of the system manufacturers listed. It is the primary reason that the "distributed system" approach is used for most of the manufacturers listed, wherein the data base memory used by each loop controller resides in that controller at all times (although it may be duplicated in other parts of the system). This means that a communication link failure, for instance, will not jeopardize the function of a controller, as would be the case if all data base memory resided in a larger central controller or computer. In addition to the distributed system architecture mentioned above, many of the following security and reliability techniques are used in conjunction to provide the utmost control and monitoring system reliability.

Error Check Codes. Each word transmitted on the communication link is checked for data integrity. A sophisticated error check code is computed by the sending device and included in the word. The error check code is then recomputed by the receiving device. Each data word transmitted is retransmitted (echoed) by the receiving device, and must compare identically. Any discrepancy in any check will cause the word to be rejected, and a notice of the rejection given. If a predetermined error threshold is exceeded, the communication link may be automatically switched to a backup link.

Redundant Communication Links. Most systems include a redundant communication link which has its cables routed separately to preclude loss of both the primary and backup link in case of an accident. Most communication links also include isolation couplings at each connected element to prevent damage to the link in case of element failure.

Diagnostic Routines. The controllers generally incorporate diagnostic routines to self test several times a second. The following items are checked: power regulator, analog/digital and digital/analog conversions at high and low limits, output, CPU errors, memory and instruction set check. Diagnostic routines are also programmed to check the communication link and all connected elements.

Redundant Memory. A backup nonvolatile RAM memory that is constantly updated during normal operation with all pertinent process data, both configured and process derived, is often included in the controller. This permits error diagnostics as well as allowing restart after a power loss or equipment failure.

Battery Backup. A battery backup system is either included or provided as an option for these systems. These battery backups are generally sized to allow at least 30 minutes of operation in which to checkout the loss of power and to permit an orderly shutdown if it is required.

Table 2. Comparison chart of direct digital boiler control systems (Ref 9).

	COMPARISON CHARACTERISTICS	A Leeds & Northrup Max 1	B Fischer & Porter DC1-4000	C Westinghouse - Hagan DCS-1700	D Rosemount Diogenes	E Beckman MV-8000	F Moore Products Mycro	G Texas Instruments PM-550	H Robertshaw DCS-1000	I Micon MDC-200	J Bristol Babcock UCS-3000	K Bailey Network 90
1.	Number of loops per controller	8	8-16	6 (4 display)	Non. Dist.	6	1 (Analog)	8/16	1/100	8	8/30	1-4
2.	Number of control algorithms	40	32	56	25+ Comb.	56	1 (Analog)	16 Claimed	10	70	27	65
3.	Track and hold on output	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
4.	Stand alone controller with display and pushbuttons	No	No	Yes	Yes	Yes	Yes	No	Yes/No	Yes	Yes	Yes
5.	Built in diagnostic program	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
6.	Configuration loading without operators station - integral	No	No	Yes	Yes	Yes	Yes	No	Yes	Yes	No	No
7.	Configuration loading without operators station - attachment	No	Yes	Yes-Tape	No	No	No	Yes	No	No	Yes	Yes
8.	Uninterrupted automatic control option	Yes	Yes	Yes	Yes, Analog	Yes	No	Yes	No	Yes	Yes	No
9.	Manual backup with indicators	Yes	Yes	Yes	Yes, Analog	Yes	Yes	Yes	Yes-Plug in ind.	Yes	Yes	Yes
10.	Is communication link (data hiway) available	Yes	Yes	Yes	No	Yes	Yes	Yes	No	Yes	Yes	Yes
11.	Is communication link (data hiway) mandatory	No	No	No	NA	No	Yes	No	No	No	No	No
12.	Number of controllers per CRT	8	4-16	16	300	64	1-3	132	16/1	8/32	1000	512
13.	Maximum distance from controller to CRT - Local	1000'	600'	50'/4000'	Local Only	5000'	12,000'	2500'	1000'	500'	400'	400'
14.	Maximum distance from controller to CRT-Comm. Link	NA	1.2 Mi.	4000'	Local Only	NA	12,000'	10,000'	NA	4 Mi.	5 Mi. Loop	1500'
15.	Storage media for display	ROM	ROM	Tape	Floppy for Graphics	Floppy for Graphics	Floppy for Graphics	Floppyfor Graphics	Floppy for Graphics	Floppy	Memory	Floppy for Graphics
	Is computer interface available	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
	Estimated cost per controller (in dollars)	$15,000	$30,000	$8,300	NA	NA	$3,000	$8,000	$2,200/ 10,000	$14,000	$23,000	$2,500
	Estimated cost per loop (in dollars)	$2,000	$3,000	$1,400	NA	NA	$3,000	$1,000	$2,200/ 10,000	$2,800	$3,000	$700/2500
[illegible]	Estimated cost for interface if required	NA	NA	NA	NA	NA	$18,000	NA	$10,000	$14,000	NA	Included in CRT
20.	Estimated cost for 1st CRT (in dollars)	$15,000	$13,000	$35,000	NA	NA	$40,000	$14,000	$7,000	$10,000	$8,000	$60,000
21.	Estimated cost for additional CRT (in dollars)	$15,000	$13,000	$10,000	$13,000	$30,000	$18,000	$4,000	$17,000	$10,000	$8000	$60,000
22.	Estimated cost for 1 reference boiler control system W.O. CRT/ W. CRT (in dollars)	$/60,000	$/60,000	$13,000/ 45,000	$/70,000	$/150,000 including print	$/90,000	$16,000 75,000	$43,000	$45,000	$23,000/ 35,000	$22,000/ 82,000
23.	Estimated cost for 4 reference boiler control systems - 1 op. sta. (in dollars)	$120,000	$150,000	$65,000	$135,000	$210,000	$160,000	$95,000	$85,000	$90,000	$60,000	$115,000
24.	Year system was introduced	1980	1979	1977	1972	1981	1980	1978	1977	1979	1975	1978
25.	Number of systems installed	75	150	200	208	31	7	20,000	85	600	400	150
26.	Number of boiler systems	not known	30	150	44	8	0	1,000	12	120	12 (8 Navy)	60

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2. Comparison chart of direct digital boiler control systems (Ref 9).

D Rosemount Diogenes	E Beckman MV-8000	F Moore Products Mycro	G Texas Instruments PM-550	H Robertshaw DCS-1000	I Micon MDC-200	J Bristol Babcock UCS-3000	K Bailey Network 90	L Honeywell TDC-2000	M Foxboro Specturm	N Gould Modicon	O Measurex 2002	P Fisher PROVOX
Non. Dist.	6	1 (Analog)	8/16	1/100	8	8/30	1-4	8	1/30 (Microspec)	32	32	1/8
25+ Comb.	56	1 (Analog)	16 Claimed	10	70	27	65	28	180	50+	150	22/250
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yes	Yes	Yes	No	Yes/No	Yes	Yes	Yes	Yes	Yes	Yes	No	No
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
Yes	Yes	Yes	No	Yes	Yes	No	No	No	No	No	No	No
No	No	No	Yes	No	No	Yes	Yes	Yes	No	Yes	Console	Yes
Yes, Analog	Yes	No	Yes	No	Yes	Yes	No	Yes	Yes	Yes	No	Yes
Yes, Analog	Yes	Yes	Yes	Yes-Plug in Ind.	Yes	Yes	Yes	Yes	Yes	Yes	No	Yes
No	Yes	Yes	Yes	No	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
NA	No	Yes	No	No	No	No	No	Yes	No	No	No	Yes W/CRT
300	64	1-3	132	16/1	8/32	1000	512	288	100+	64	1	240
Local Only	5000'	12,000'	2500'	1000'	500'	400'	400'	NA	1000'	5000'	500'	200'
Local Only	NA	12,000'	10,000'	NA	4 Mi.	5 Mi. Loop	1500'	5000'	15,000'	15,000'	4000'	7500'
Floppy for Graphics	Floppy for Graphics	Floppy for Graphics	Floppyfor Graphics	Floppy for Graphics	Floppy	Memory	Floppy for Graphics	Floppy	Floppy for Graphics	Floppy for Graphics	Floppy	Core
Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes	Yes
NA	NA	$3,000	$8,000	$2,200/ 10,000	$14,000	$23,000	$2,500	$8,000	$2,500	$25,000	NA	$5520
NA	NA	$3,000	$1,000	$2,200/ 10,000	$2,800	$3,000	$700/2500	$1000	$2500	$800	NA	$1380
NA	NA	$18,000	NA	$10,000	$14,000	NA	Included in CRT	$8500	Included	NA	NA	$7000
NA	NA	$40,000	$14,000	$7,000	$10,000	$8,000	$60,000	$36,500	$50,000	$26,000	NA	$39,000
$13,000	$30,000	$18,000	$4,000	$17,000	$10,000	$8000	$60,000	$36,500	$10,000	$6000	$12,000	$13,500
$/70,000	$/150,000 including print	$/90,000	$16,000 75,000	$43,000	$45,000	$23,000/ 35,000	$22,000/ 82,000	$38,000/ 60,000	$25,000/ 75,000	$14,800/ 41,000	$80,000 w/ Pr. & CRT	$16,800/ 49,800
$135,000	$210,000	$160,000	$95,000	$85,000	$90,000	$60,000	$115,000	$101,000	$120,000	$58,000	$170,000	$71,600
1972	1981	1980	1978	1977	1979	1975	1978	1975	1972	1979	1975	1980
208	31	7	20,000	85	600	400	150	1500	700+	3000	200	126
44	8	0	1,000	12	120	12 (8 Navy)	60	150	105	150	200	16

Gradual Degradation. Programming is utilized to ensure that progressive failures will cause gradual degradation of control performance rather than a catastrophic "hard over" error. Most systems employ tracking of the process variable signal to ensure "bumpless" transfer between automatic and manual control.

Uninterrupted Automatic Control. Uninterrupted automatic control requires a spare controller which is automatically substituted for a failed controller. The foregoing takes place in less than one second, regardless of the complexity of the control strategy of the failed controller, and the operator can monitor and manipulate the same loops exactly as he did before the failure. One spare controller can serve as backup for several controllers, so the substitution is not on a one for one basis.

Another approach to uninterrupted automatic control is a system involving a completely redundant controller having full memory, configuration, diagnostics, etc., which is tracking the working controller at all times and ready to take over at any time that the diagnostic programs in the active controller indicate that it is not operating properly. It should be understood that both of the above approaches to uninterrupted automatic control are expensive options and are not necessary for reliable control in most applications.

In addition to these system considerations, reliability of the electronic components is enhanced by a "burn-in" for many hours at high temperature and high power. This serves to move them past the initial failure region of the failure history curve to where they are very reliable, especially when operated at the conservative power levels where the components of these systems are designed to operate.

4.4 Retrofit Installation

Retrofit capabilities are inherent in most DDC systems and many of them are specifically designed so that this can be effected in stages as funds become available. A hypothetical case will serve to illustrate how this might be accomplished for a boiler with old, worn out controllers but with some good transmitters (sensors) and valve/damper operators. It could be done in the following steps.

Step 1. Replace controllers with single or multi-loop digital controllers, add flow meters as required, replace bad transmitters, replace bad valve/damper operators and install pneumatic/electronic relays on good transmitters and valve operators.

Step 2. Add oxygen trim system.

Step 3. Add CRT-keyboard operators' station.

Step 4. Replace all remaining transmitters (sensors) and valve/damper operators.

Step 5. Add tie-in to supervisory computer.

Step 6. Add more boilers to system on same basis.

4.5 Interface Requirements

A typical mechanical configuration of a DDC control system has the controllers mounted in standard 19-inch relay racks. The operator's CRT keyboard is available in a rack-mounted version or a built-in desk mount for most systems.

The electrical power requirements are typically 117 volts AC ±8% 50/60 Hertz, but several systems will operate on 24 volts DC ±8% as an option. The total power required for these systems will not exceed 1,000 watts per boiler. The electrical input/output interfaces are brought out to integral termination panels.

4.6 Sensors

All DDC systems will accept digital, analog, or even pneumatic (with adapter relay) sensor inputs. Thus, they can be used with existing sensors.

4.7 Backup Controls

DDC systems "track and hold" output variable so the system can provide "bumpless" transfer to backup controls which can be either:

a. An existing control system if in good operating condition.

b. Manual backup stations with indicators.

c. Uninterrupted automatic control. This extra cost option provides transfer to a spare controller in case of component failure. It increases the cost significantly.

The practical choice for the small Navy boilers is probably "b" above.

4.8 Compatibility with Current Operations

Most DDC control systems are designed to be as compatible as possible with current operating practices so as to minimize the need for additional operator and engineer orientation and training. Often the CRT display of a single loop or group of loops simulates the face of a standard pneumatic or electric analog controller. Similarly, the keyboards have been planned with a great deal of ingenuity to make them as simple and easy for the operator to understand as possible. Even the engineering configuration of most of these control systems can be performed without computer programming knowledge but with just inputs to a "menu" which leads the boiler operator through required steps.

4.9 Integration with EMCS

All DDC boiler control systems have the capability of connection to a computer for energy monitoring and control system (EMCS) application, and in addition to this, several of the systems have the capability of performing some level of EMCS with no, or very minimal, additional equipment.

REFERENCES

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3. Boiler Combustion Control Maintenance Manual, Naval Civil Engineering Laboratory, Contract Report CR 83.022. Irvine, Calif., Ultrasystems, Inc., Mar 1983. (Contract No. N62474-81-C-9388)

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5. John B. Edwards. Combustion -- The Formation and Emission of Trace Species. Ann Arbor, Mich., Ann Arbor Science Publishers Inc., 1974.

6. Power, Sep 1982, pp S-5.

7. Economic Analysis Handbook, Naval Facilities Engineering Command, NAVFAC P-442. Alexandria, Va., 1971.

8. J. Breeding and S. Londerville, "How to Evaluate Low-Excess-Air Controls for Packaged Boilers," Power Magazine, Jul 1983, pp 99-102.

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Appendix A

FLUE GAS ANALYSIS SYSTEMS

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 oxygen analyzers are often of this type, utilizing integral probe and sensor assemblies placed within the stack or flue duct. Many infrared carbon monoxide and carbon dioxide analyzers also measure the respective gases in-situ, by projecting a light beam across the stack.

Carbon Dioxide Analyzers

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.

Thermal Conductivity CO_2 Analysis. The principle behind the thermal conductivity method of analyzing CO_2 is that every gas has a different thermal conductivity. Figure A-1 shows the effect of passing samples of pure gases through a thermal conductivity instrument that produces a deflection of 100% in the positive direction for 100% 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 very high value of thermal conductivity as can be seen from Figure A-1. Therefore, application of thermal conductivity CO_2 analyzers to combustion control is questionable.

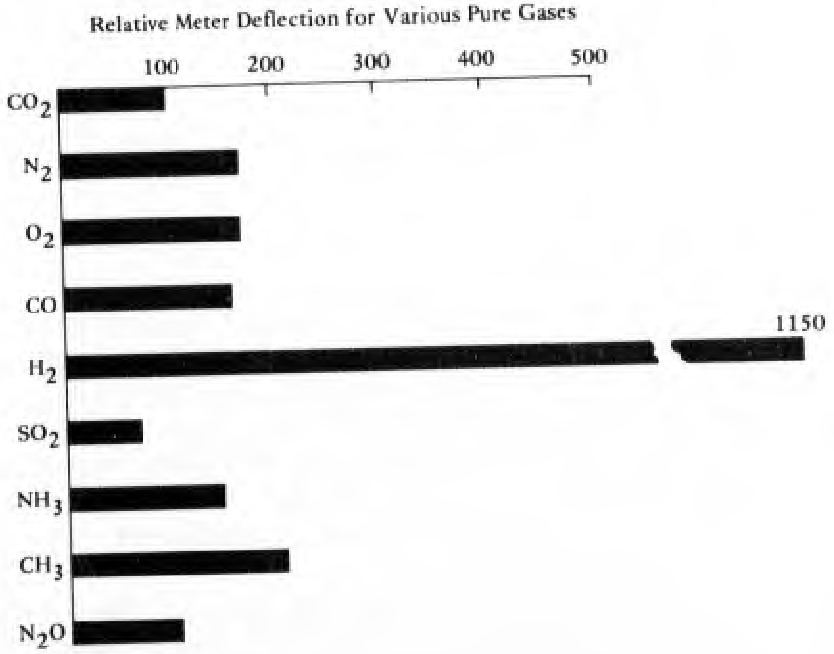


Figure A-1. Effect of passing different gas samples through thermal conductivity instrument.

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 (i.e., 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 monatomic 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.

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 carbon dioxide recorders in conjunction with charts or Orsat analyzers are often used to check the accuracy of oxygen analyzers.

Paramagnetic Oxygen 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 A-2 which shows the deflection caused by passing pure samples of various gases through equipment calibrated to produce 100% deflection from 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.

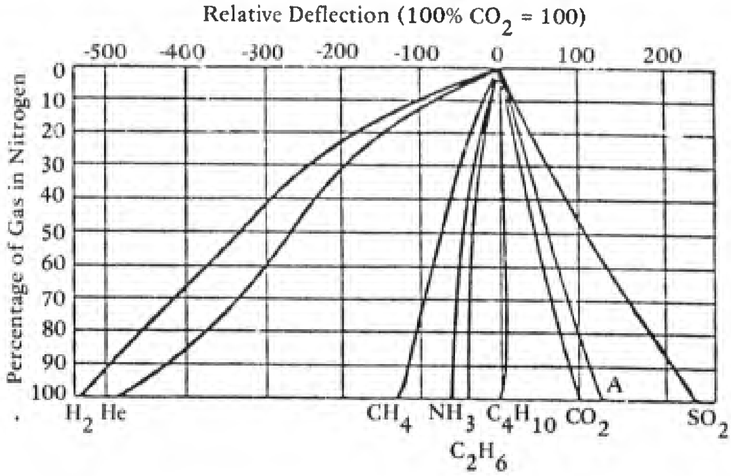


Figure A-2. Paramagnetic susceptibility of common gases.

Zirconium Oxide Oxygen 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 cell 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.

There are basically two types of zirconium oxide oxygen 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.

Outside-the-Stack Zirconium Oxide Oxygen Analyzer. The analyzer consists of a probe or probes placed in the stack, an attached analyzer enclosure which houses the zirconium oxide oxygen sensor assembly, and a connected electronics enclosure (Figure A-3).

Figure A-3 shows the sampling system flow diagram for this analyzer. The analyzer enclosure is a combination hot sample system and zirconium oxide sensor bolted directly to the stack or duct wall. The probe is equipped with a nonclogging 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 A-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 system's transportation lag by taking about 80% 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.

Inside-the-Stack Zirconium Oxide 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 A-5.

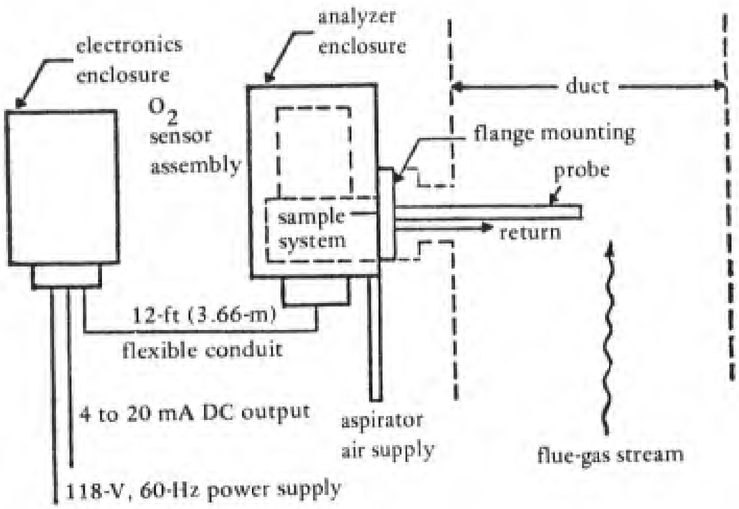


Figure A-3. Zirconium oxide O_2 analyzer block diagram (B&W – Bailey).

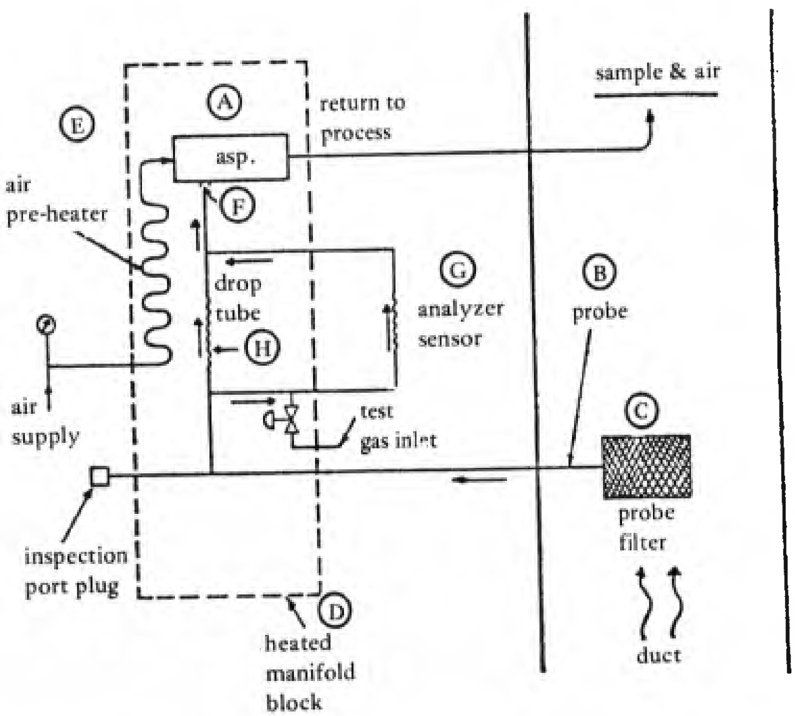


Figure A-4. Zirconium oxide O_2 analyzer sample flow diagram (B&W – Bailey).

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 2,800°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 1,500°F. The amplifier accepts the millivolt DC signal generated by the zirconium oxide cell in the probe and produces a linearlized standard 4 to 20 mA current output signal.

Carbon Monoxide Analyzers

These analyzers generally use the infrared method of analysis and measure the carbon monoxide content of the flue gas within the stack or duct. The infrared method of analysis was described in detail under carbon dioxide analyzers. The range of measurement for combustion control applications is from 0 to 1,000 ppm (parts per million). An infrared carbon monoxide analyzer is shown schematically in Figure A-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 A-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 carbon monoxide is in the stack.

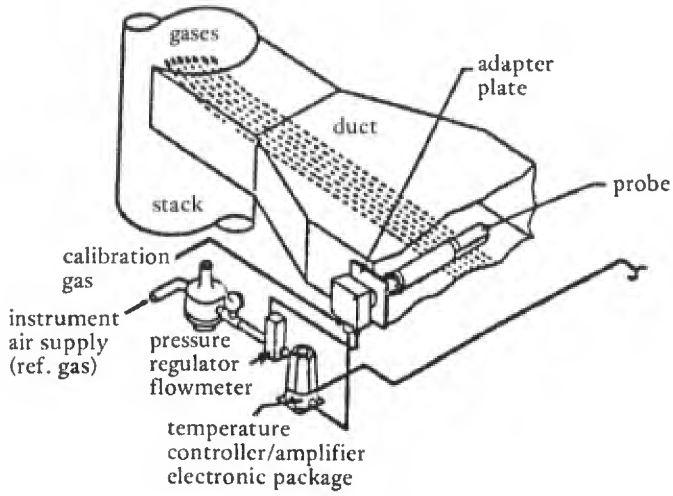


Figure A-5. Schematic arrangement of zirconium oxide O_2 analyzer (Westinghouse-Hagan).

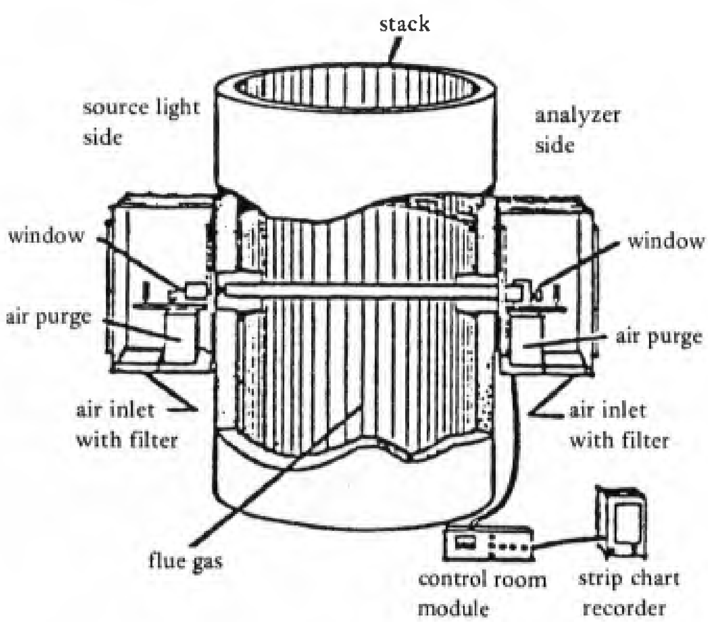


Figure A-6. Schematic arrangement of infrared carbon monoxide analyzer (Westinghouse-Hagan).

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 sapphire window interface and across the stack through a duplicate sapphire window and onto a collecting mirror. The collecting mirror directs the beam into the wavelength discrimination module which employs gas cell correlation techniques for carbon monoxide 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% nitrogen, the second contains a known concentration of carbon monoxide for calibration, and the third contains 100% carbon monoxide. Note that infrared radiation is not absorbed by diatomic gases such as N2. After the light is passed through the sealed cells, it is directed into a filter which elminates 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% carbon monoxide cell. This ratio is the indication of carbon monoxide to the flue gas.

Carbon Monoxide and Oxygen Dual Analyzers

A new carbon monoxide sensor has been developed by Bailey that can be incorporated within their proven oxygen analyzer 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 platinum 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 a oil-fired boiler has indicated excellent stability and durability.

Carbon Monoxide and Carbon Dioxide Combination Analyzers

Combination carbon monoxide/carbon dioxide analyzers are offered by some manufacturers of infrared analyzers. Figure A-7 is a diagramatic representation of such an analyzer.

The instrument operates on the principles described above with the addition of filter cells for carbon dioxide analysis. However, the cost of this scheme is high relative to the zirconium oxide type oxygen analyzers.

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.

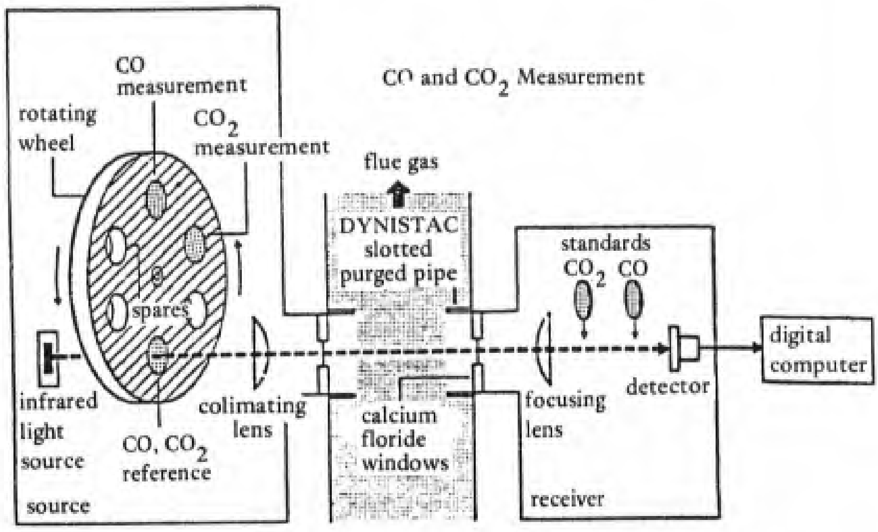


Figure A-7. Diagrammatic arrangement of infrared carbon monoxide analyzer (Measurex).

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 A-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.

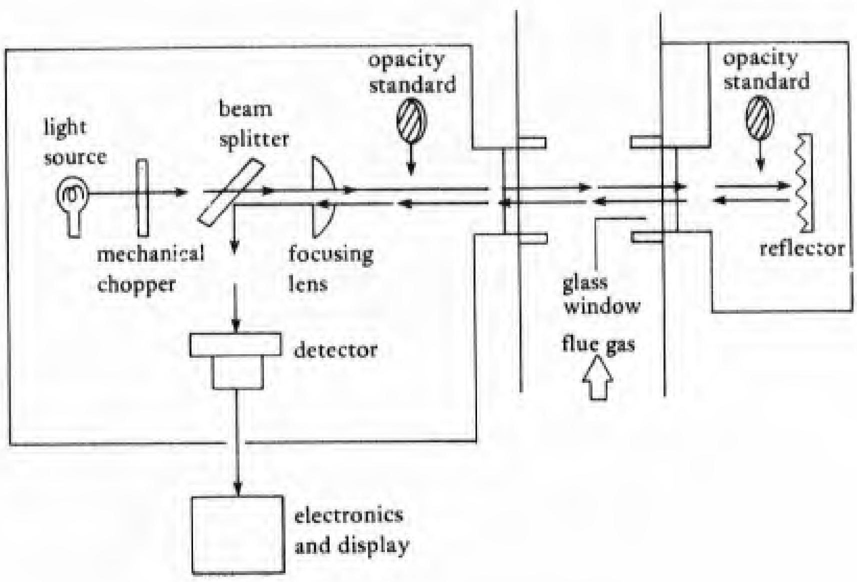
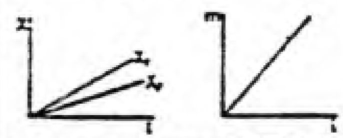
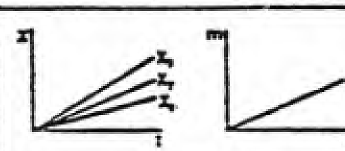
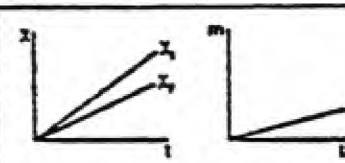
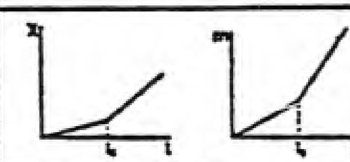
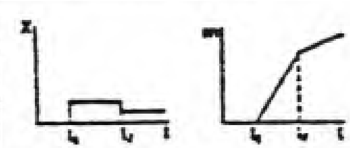
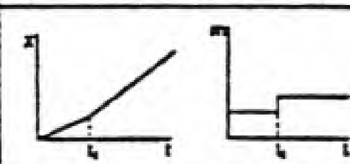
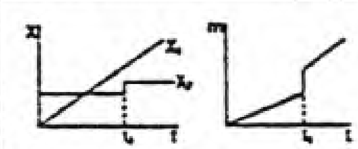
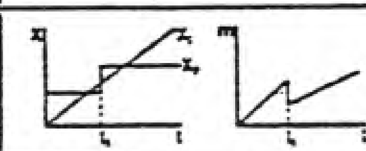


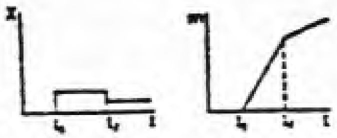
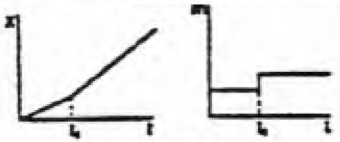
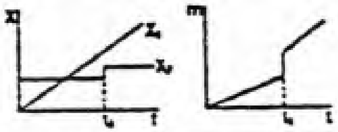
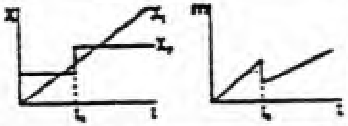
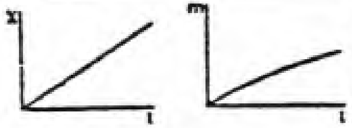
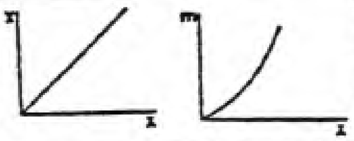
Figure A-8. Smoke (opacity) analyzer (Measurex).

Appendix B

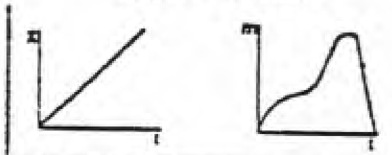
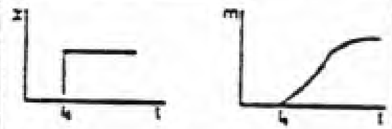
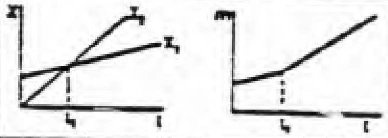
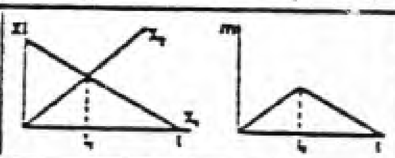
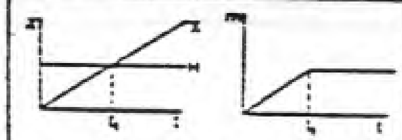
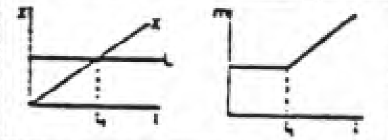
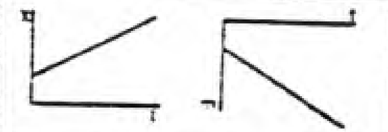
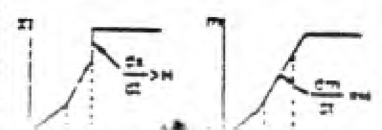
SIGNAL PROCESSING TERMINOLOGY

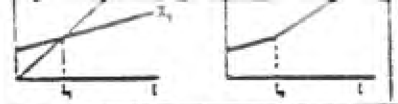
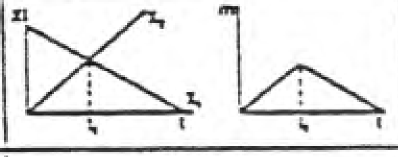
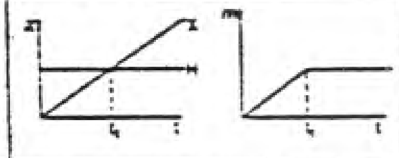
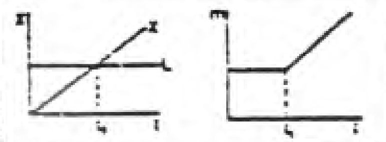
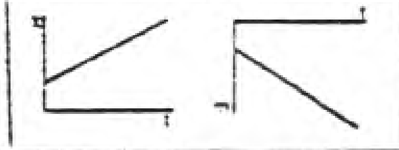
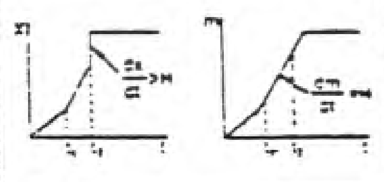
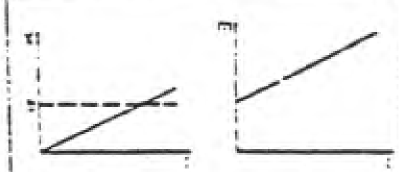
SIGNAL PROCESSING FUNCTIONS

Function & Symbol *	Math Equation	Graphic Representation	Definition
SUMMING Σ	$m = x_1 + x_2 + \ldots + x_n$		The output equals the algebraic sum of the inputs.
AVERAGING 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 Δ	$m = x_1 - x_2$		The output equals the algebraic difference between the two inputs.
PROPORTIONAL K	$m = Kx$		The output is directly proportional to the input.
INTEGRAL $\int$	$m = \frac{1}{T_i} \int x\,dt$		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 d/dt	$m = T_D \frac{dx}{dt}$		The output is proportional to the rate of change (derivative) of the input.
MULTIPLYING X	$m = x_1 x_2$		The output equals the product of the two inputs.
DIVIDING $\div$	$m = \frac{x_1}{x_2}$		The output equals the quotient of the two inputs.

PROPORTIONAL K	$m = Kx$		The output is directly proportional to the input.
INTEGRAL $\int$	$m = \frac{1}{T_I} \int x\,dt$		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 d/dt	$m = T_D \frac{dx}{dt}$		The output is proportional to the rate of change (derivative) of the input.
MULTIPLYING X	$m = x_1 x_2$		The output equals the product of the two inputs.
DIVIDING ÷	$m = \frac{x_1}{x_2}$		The output equals the quotient of the two inputs.
ROOT EXTRACTION $\sqrt{}$	$m = \sqrt{x}$		The output equals the root (i.e., square root, fourth root, 3/2 root, etc.) of the input.
EXPONENTIAL x^n	$m = x^n$		The output equals the input raised to a power (i.e., second, third, fourth, etc.)

SIGNAL PROCESSING FUNCTIONS (CONT.)

Function & Symbol	Math Equation	Graphic Representation	Definition
NONLINEAR OR UNSPECIFIED FUNCTION $f(x)$	$m = f(x)$		The output equals some nonlinear function of the input.
TIME FUNCTION $f(t)$	$m = x\, f(t)$ $m = f(t)$		The output equals the input times some function of time or equals some function of time alone.
HIGH SELECTING $>$	$m = \begin{cases} x_1 \text{ FOR } x_1 \geq x_2 \\ x_2 \text{ FOR } x_1 \leq x_2 \end{cases}$		The output is equal to that input which is the greatest of the inputs.
LOW SELECTING $<$	$m = \begin{cases} x_2 \text{ FOR } x_1 \geq x_2 \\ x_1 \text{ FOR } x_1 \leq x_2 \end{cases}$		The output is equal to that input which is the least of the inputs.
HIGH LIMITING $\not>$	$m = \begin{cases} x \text{ FOR } x \leq H \\ H \text{ FOR } x \geq H \end{cases}$		The output equals the input or the high limit value whichever is lower.
LOW LIMITING $\not<$	$m = \begin{cases} x \text{ FOR } x > L \\ L \text{ FOR } x \leq L \end{cases}$		The output equals the input or the low limit value whichever is higher.
REVERSE PROPORTIONAL $-K$	$m = -Kx$		The output is reversely proportional to the input.
VELOCITY LIMITING $V\not>$	$\frac{dm}{dt} = \frac{dx}{dt} \begin{cases} \frac{dx}{dt} \leq H \text{ and} \\ m = x \end{cases}$ $\frac{dm}{dt} = H \begin{cases} \frac{dx}{dt} > H \text{ OR} \end{cases}$		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

HIGH SELECTING $>$	$m = \begin{cases} x_1 \text{ FOR } x_1 \geq x_2 \\ x_2 \text{ FOR } x_1 \leq x_2 \end{cases}$		The output is equal to that input which is the greatest of the inputs.
LOW SELECTING $<$	$m = \begin{cases} x_2 \text{ FOR } x_1 \geq x_2 \\ x_1 \text{ FOR } x_1 \leq x_2 \end{cases}$		The output is equal to that input which is the least of the inputs.
HIGH LIMITING $\not>$	$m = \begin{cases} x \text{ FOR } x \leq H \\ H \text{ FOR } x \geq H \end{cases}$		The output equals the input or the high limit value whichever is lower.
LOW LIMITING $\not<$	$m = \begin{cases} x \text{ FOR } x > L \\ L \text{ FOR } x \leq L \end{cases}$		The output equals the input or the low limit value whichever is higher.
REVERSE PROPORTIONAL $-K$	$m = -Kx$		The output is reversely proportional to the input.
VELOCITY LIMITING $V\not>$	$\frac{dm}{dt} = \frac{dx}{dt} \begin{cases} \frac{dx}{dt} \leq H \text{ and} \\ m = x \end{cases}$ $\frac{dm}{dt} = H \begin{cases} \frac{dx}{dt} \geq H \text{ OR} \\ m = x \end{cases}$		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 $+$, $-$, or $\pm$	$m = x \pm b$		The output equals the input plus (or minus) some arbitrary value (bias).

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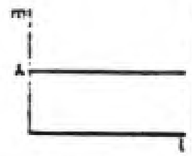
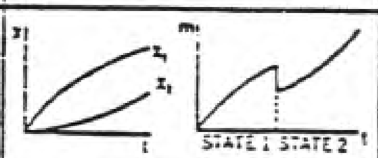
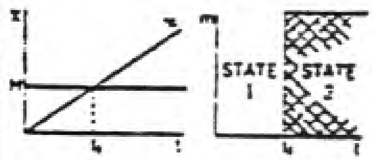
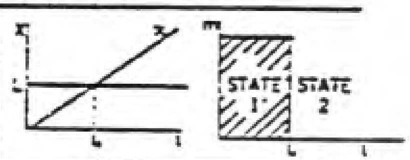
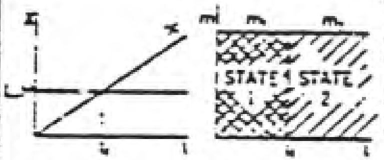
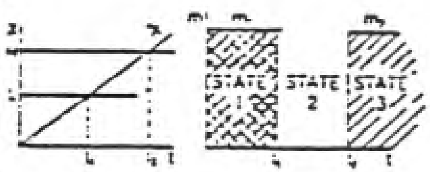
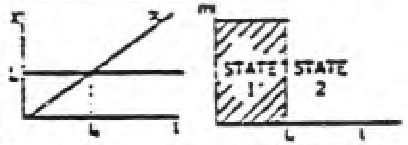
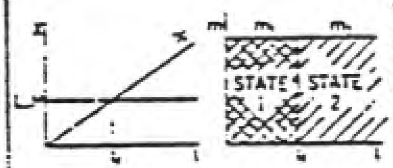
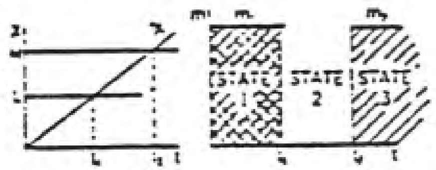
SIGNAL PROCESSING FUNCTIONS (CONT.)

Function & Symbol	Math Equation	Graphic Representation	Definition
ANALOG SIGNAL GENERATOR A	$m = A$	DOES NOT APPLY 	The output is an analog signal developed within the generator.
TRANSFER 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 H/	STATE 1 $x \leq H$ 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) $x < L$ STATE 2 $x \geq L$		
H/L	STATE 1 (FIRST OUTPUT m_1 ENERGIZED OR ALARM STATE) $x < H, L$ 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) $x < L$ STATE 2 (BOTH OUTPUTS INACTIVE OR DE-ENERGIZED) $L \leq x \leq H$ STATE 3 (SECOND OUTPUT m_2 ENERGIZED OR ALARM STATE) $x > H$		

	ALARM STATE		
/L	STATE 1 (ENERGIZED OR ALARM STATE) $x < L$ STATE 2 $x \geq L$		
H/L	STATE 1 (FIRST OUTPUT m_1 ENERGIZED OR ALARM STATE) $x < H, L$ STATE 2 (SECOND OUTPUT m_2 ENERGIZED OR ALARM STATE) $x > H, L$		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.
H//L	STATE 1 (FIRST OUTPUT m_1 ENERGIZED OR ALARM STATE) $x < L$ STATE 2 (BOTH OUTPUTS INACTIVE OR DE-ENERGIZED) $L \leq x \leq H$ 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)

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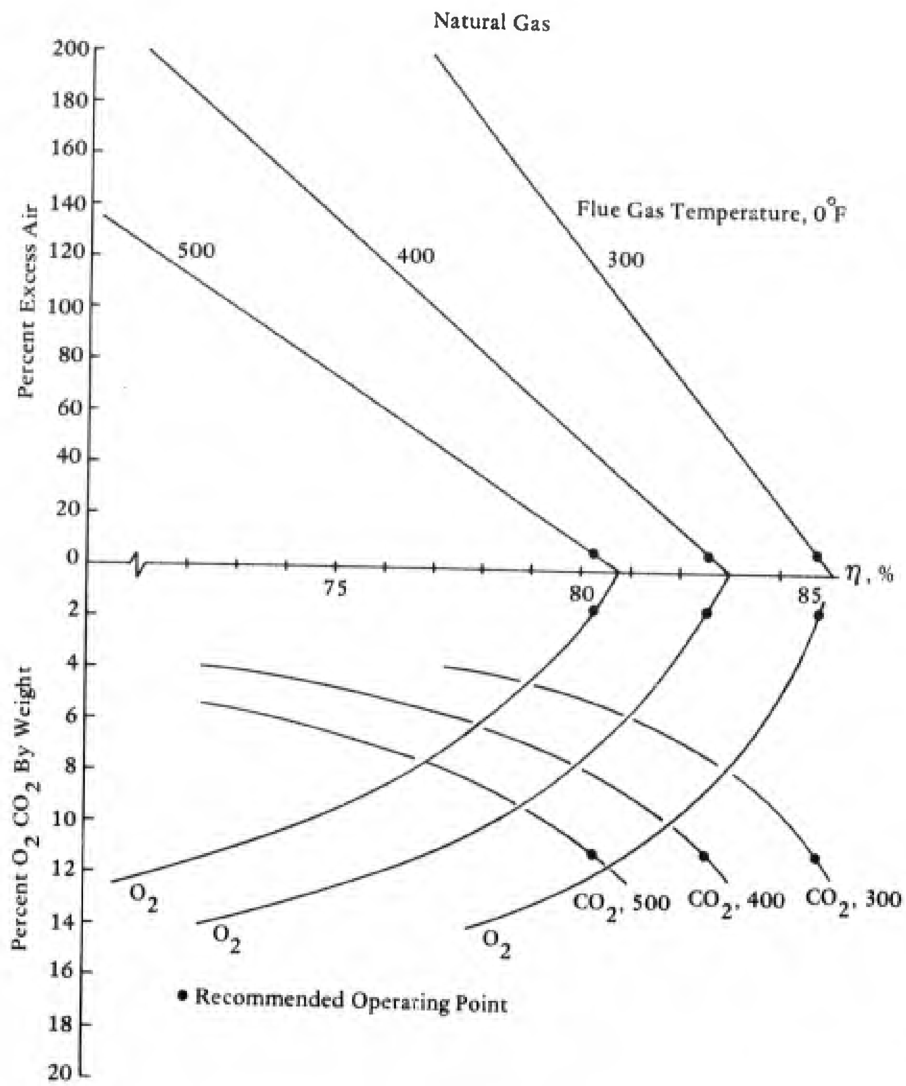
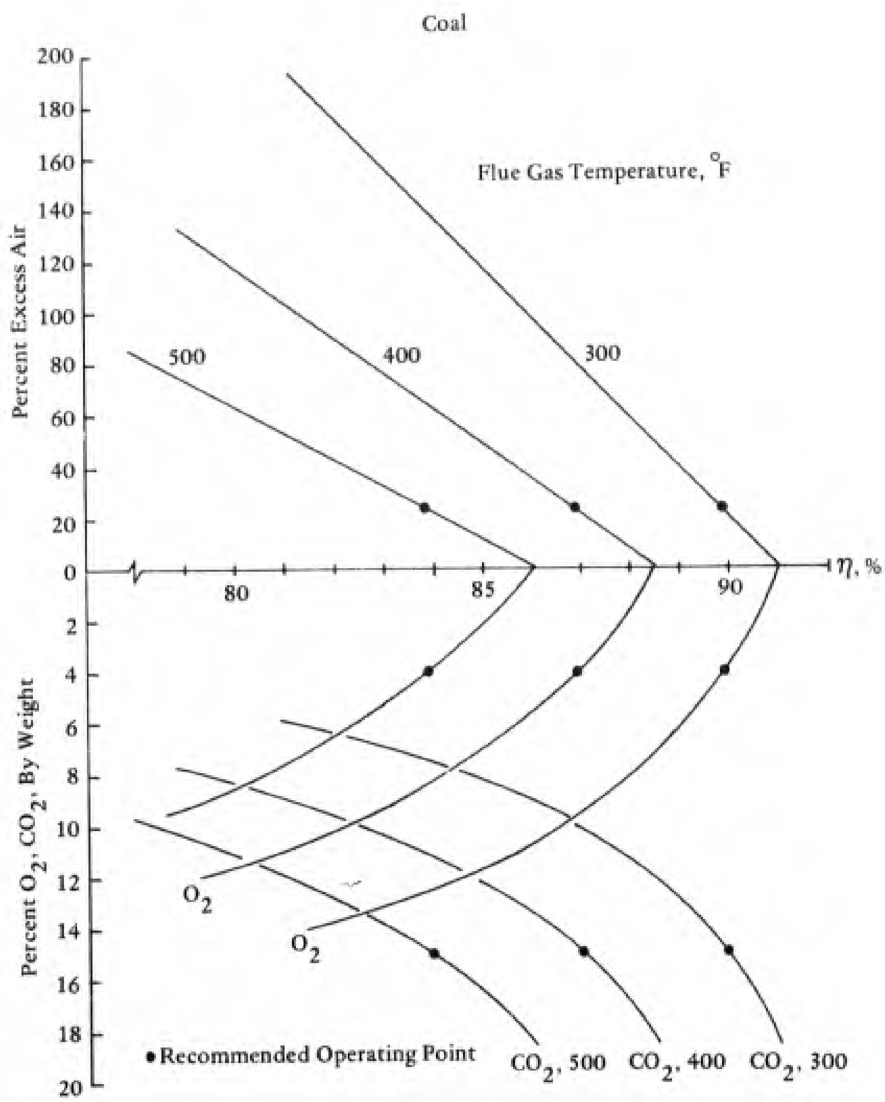
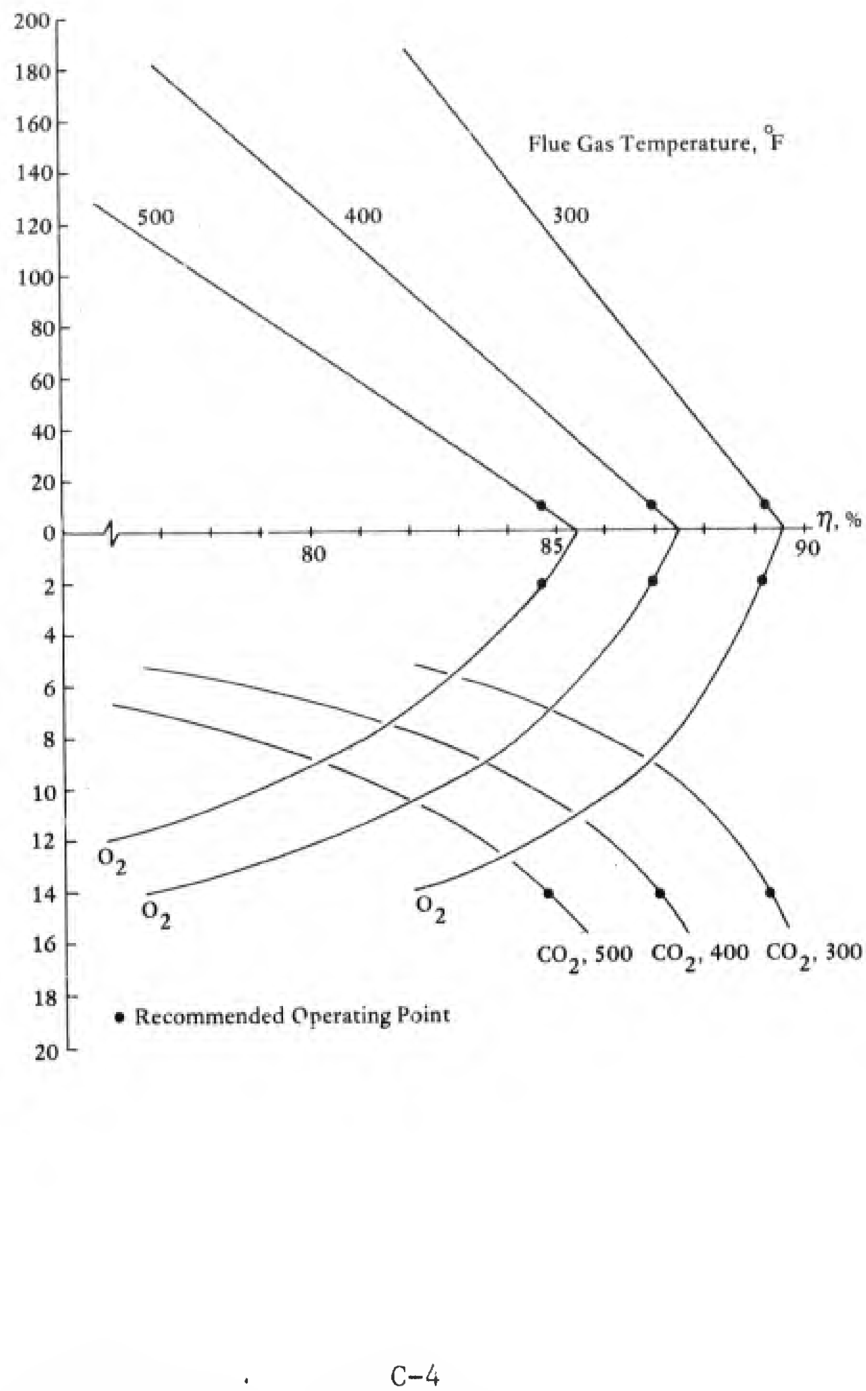
Appendix C

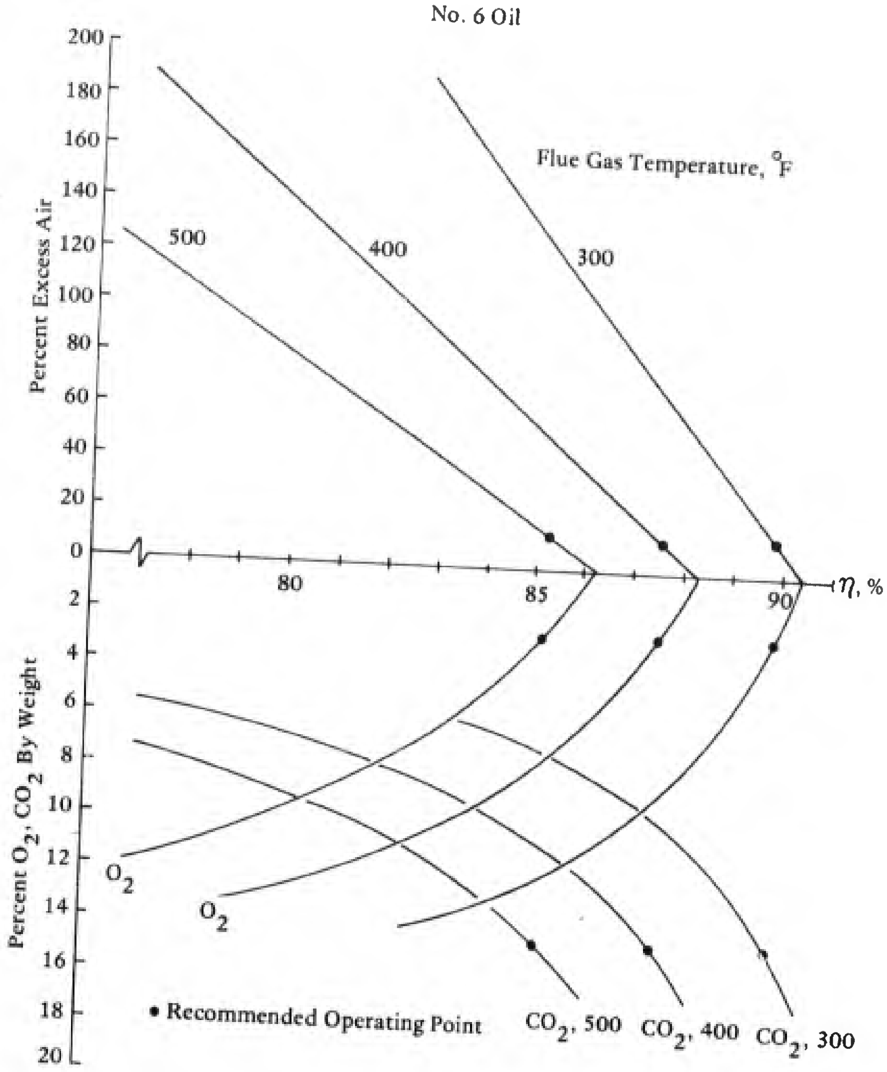
COMBUSTION EFFICIENCY PARAMETERS


Natural Gas
Percent Excess Air
200
180
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
20
Percent O2 CO2 By Weight
Flue Gas Temperature, 0°F
500
400
300
75
80
85
η, %
O2
O2
O2
CO2, 500
CO2, 400
CO2, 300
• Recommended Operating Point


Coal
Flue Gas Temperature, °F
Percent Excess Air
500
400
300
η, %
80
85
90
Percent O_2, CO_2, By Weight
O_2
O_2
• Recommended Operating Point
CO_2, 500
CO_2, 400
CO_2, 300

No. 2 Oil


Flue Gas Temperature, °F
500
400
300
η, %
80
85
90
200
180
160
140
120
100
80
60
40
20
0
2
4
6
8
10
12
14
16
18
20
O_2
O_2
O_2
CO_2, 500
CO_2, 400
CO_2, 300
• Recommended Operating Point



No. 6 Oil
Flue Gas Temperature, °F
Percent Excess Air
200
180
160
140
120
100
80
60
40
20
0
500
400
300
80
85
90
η, %
Percent O2, CO2 By Weight
2
4
6
8
10
12
14
16
18
20
O2
O2
• Recommended Operating Point
CO2, 500
CO2, 400
CO2, 300

Appendix D

DESCRIPTIONS OF DDC BOILER CONTROL SYSTEMS

Leeds & Northrup -- MAX 1

The MAX 1 is a radially connected direct digital distributed control system having eight loops per controller. A long range communication link (data highway) is available for this system, but is probably not required for the Navy application to small boiler systems. Color CRT displays are available as well as printers, tape configuration recorders or a floppy disc for custom graphics displays.

This system can be configured to give boiler efficiency directly, or can be connected to a plant computer for more extensive energy monitoring and control. The provisions for reliability incorporated into this system have been thoroughly considered and incorporate self diagnostics, uninterrupted automatic control, and redundant power supplies and data transmission. Forty control algorithms are available for this sytsem including a selection of three different function generators. The price for this system is competitive for both a single boiler system or multiple boilers.

Fischer & Porter DCI-4000

The DCI-4000 system is a direct digital distributed control system with a great deal of flexibility in its concept and implementation. In a simple basic configuration for controlling a single small heating boiler it would consist of an eight-loop controller connected to a single CRT station with control keyboard. Programming of the software can be done by a teletype, other standard terminals, or a portable

The controller also includes a special calibrating function for an oxygen trim probe. A possible shortcoming of this system is the relatively small number of data input and output channels.

Rosemount -- Diogenes

The Diogenes control system is a direct digital control system that employs a central computer for control and display operation. It has been used on a significant number of boiler control applications with very good results. The use of a central computer allows some integral energy optimization to be performed. Even though this system is not a distributed system, the backup control in the event of a primary control fault is by means of an independent analog controller whose memory is updated once per second. Since this system has been sold for 10 years, the operator interface, the displays (including custom graphics) and the engineering configuration procedures are very well worked out and convenient.

This system has the inherent capability to monitor and alarm a large number of inputs and output a large number of digital outputs in addition to the continuous loop control functions. The cost figures for a single reference boiler control are a little above many of the systems analyzed but for multi-boiler installations, the cost for the Diogenes systems is very competitive.

Beckman -- MV-8000

The MV-8000 control system from Beckman is a "high end" system which utilizes a redundant communication link (data highway or Beckman bus) which allows spacing of up to 5,000 feet between system elements. The single loop controllers unit which Fischer & Porter makes. There are ample control algorithms available including a six segment function generator.

The operator's keyboard of this system is exceptionally well planned and one of its features is that the loop selection keys are arranged directly below the CRT screen so that it is an almost automatic reflex to select the loop you want further information or trend data on. A communication link is also available for serving greater distances and more complex systems, but it would probably not be justified for the small boiler application unless there were multiple boilers which were widely separated geographically.

The DCI-4000 system can provide uninterrupted automatic control by using a constantly tracking backup controller which automatically takes over on fault detection in the primary controller.

This system has excellent growth potential in both the software and hardware. It is intermediate in cost between the small special purpose units and the large system in which a communication link is mandatory.

Westinghouse-Hagan DCS-1700

The DCS-1700 system is an outstanding system for the control of boilers. As examination of the comparison chart shows, the DCS-1700 has over twice as high a percentage of boiler applications as any of the other systems analyzed. Configuration programming can be done locally or from the CRT keyboard, and a keyswitch is provided on each to prevent unauthorized modifications.

The local loop includes track and hold, bumpless transfer, uninterrupted automatic control (optional) and 55 control algorithms.

used with this system are hybrid analog-digital controllers, but all multi-loop controllers are fully digital and incorporate complete functional redundancy for inherent uninterrupted automatic control.

The control algorithms available for this system include a six segment function generator and a mode transfer code which allows transfers between analog control and digital control as often as required to implement the desired control functions. The operator station is very well designed with a color CRT, keyboard, and separate alarm annunciator panel. In addition to the keyboard, a light pen is included for the operator to directly call up detailed displays from the CRT without using the keyboard. All data are transferred using ASCII/RS232C format, so the use of computers, analyzers, or printers by Beckman or others is readily effected.

The cost of this system is high for a single small boiler application, but may be feasible for multiple boiler control from a single operator station.

Moore Products -- Mycro System

The Mycro distributed control system is included even though the present controllers offered are electronic analog type, because Moore Products has a full digital controller in development. The operator's station and displays are very well thought out for operator and configuration engineer convenience, and this system includes a graphic pad option for custom graphic's display generation. This option is not offered by any of the other control system manufacturers and it appears to simplify the preparation of custom graphic displays. A redundant communication link is included as well as thorough internal diagnostics. Location of malfunctions is facilitated by an automatic functional diagnostic routine backed up by a more intensive off-line routine which can be initiated by the operator if further problems are suspected.

The cost estimates for this system placed it in an intermediate position for both single and multi-boiler applications.

Texas Instruments -- PM 550

The Program Master (PM 550) control system is capable of controlling a minimum of eight loops per control module, and the operator interface can be either a pushbutton station with digital display of the process variable, set point, output and tuning parameters or a CRT keyboard station. Programming of control algorithms is done by a simple keyboard and digital display unit or the CRT keyboard station. Sixteen control algorithms are included and they can be "chained" together to perform desired control or data manipulation functions. Mathematical operations on the data can be easily programmed, and this unit will accept BCD data inputs.

The estimated price for this system is among the lowest of the systems examined and more units of this system have been sold than any of the other control systems examined, although this may be misleading as most of the units sold were for use as programmable controllers and not for continuous control.

Robertshaw -- DCS-1000

The DCS-1000 is a flexible distributed control system based on single loop stand-alone intelligent controller modules. These modules include a manual backup station which can be used when the digital unit is removed for service or replacement.

The display options available for the CRT monitor include custom graphics, and an arrangement of so-called "virtual firmware" (software) which allows the creation of nondistributed digital control loops within the CRT electronics for the control of noncritical loops where lower reliability can be accepted. These "virtual firmware" elements include ramps, timers, boolean logic and computational units which may be used alone or linked together.

The DCS-1000 system is in the intermediate price category between the "high end" systems and the least expensive systems. It offers the flexibility of being implemented in a progressive manner, starting with the single loop stand-alone controllers on a single boiler, and then adding a CRT operating station when more boilers are added.

Micon -- MDC-200

The MDC-200 control system is a distributed digital control system based on the Micon P-200 controller, which may be used as a stand-alone controller for up to eight loops. This controller is complete with digital displays, pushbuttons, and an engineer's panel on the side for configuration setting. There are 70 control algorithms available in the P-200, any 20 of which may be applied to a specific control loop in any order desired. Reliability of this system can be ensured to any degree desired by means of manual backup stations or a spare controller which can be arranged to provide uninterrupted automatic control for up to eight controllers (64 loops). It will automatically replace a failed unit (including configuration memory transfer) in less than 1 second. A CRT operator's station may control up to 32 controllers (256 loops) including printers and strip chart recorders. A complete set of CRT displays are available including custom graphics, alarms, loops and trending. For use with the CRT operator's station, the controllers may be purchased without the local displays and control buttons, or without the engineers configuring panel. The cost of this system is in the lower intermediate range and they have a significant number of boiler applications in service, so it should receive serious consideration for the Navy small heating boiler application.

Bristol Babcock -- System 3000

The System 3000 is a distributed digital control system made up of a family of stand-alone controllers with capacities of one loop, eight loops, or 40 to 60 loops. A CRT keyboard operator's control and monitoring station is available as are printers, records, and backup hardware. Communications are either local or long range with a redundant communication link. Reliability features permit a wide choice of arrangement from manual backup to uninterrupted automatic control. A very simple operator's keyboard is used with this system and it is augmented by cursor selection of "poke-points" on the CRT screen for display selection, etc. A multi-level software security system requires operator log-ons and prevents unauthorized access to selected displays and parameters. Among the software "modules" is a calculator which permits boiler efficiency to be calculated continuously as well as the usual PID controllers, lead-lag, peak detector, and function generators. The cost of the System 3000 is low, just above the lowest priced systems.

Bailey -- Network 90

Network 90 is a very flexible distributed digital control system that is applicable across the board from very small single loop controls to the complete control of a large plant. It is a difficult system to fully describe because of the flexibility offered by the large number of system components. Therefore, the following discussion will only consider the elements of the system which are applicable to small boilers, either singly or in groups.

The basic controller module can be configured for one or two loops and includes a comprehensive library of software functions including a function generator and diagnostic routines. A configuration and timing module in conjunction with controller modules and a digital control station make an excellent low cost all-digital system. Redundant communications, local and long distance, are offered as well as redundant power supplies and communication termination modules. However, the Network 90 system does not include an uninterrupted automatic control option even though the controllers are designed to be as reliable and "fail safe" as possible. The cost of the Network 90 system is in the "upper-intermediate" range for small boilers when a CRT is supplied, and among the least expensive when used with a digital control station and no CRT.

Honeywell -- TDC-2000

The TDC-2000 was one of the first digital process control systems with distributed control logic and centralized monitoring capabilities to achieve wide acceptance. A possible disadvantage of this system for the Navy single small boiler application is that it uses a communication link (data highway) which is necessary for large geographically dispersed systems, but must make small systems less cost effective than some of the others systems in which a data highway is not mandatory. This possible disadvantage may not apply for multi-boiler systems. This system offers an uninterrupted automatic control option which is based on one backup controller for up to eight operating controllers. The transfer of control and configuration memory takes place in less than 1 second. A function generator is not available with the basic controllers, however, it is offered in their most expensive, enhanced controllers. A function generator may be required for use with some oxygen trim systems. The reliability and security of this system are not only well planned and executed, but the very extensive experience and application of this system has led to outstanding refinement and development. The cost of this system is estimated to be in the intermediate range and it has many excellent capabilities.

Foxboro -- Spectrum

The Spectrum system is just what the name implies, a broad spectrum of computers, controllers and communications going under the trade names Fox 3, Fox 1A, Foxnet, Videospec, Microspec, Spec 200, and Interspec. Space does not permit a complete delineation of the functions and capabilities of these controls, but it is apparent that systems of very large capability, including supervisory computers, can be assembled from the elements available from Foxboro.

The reliability provisions incorporated into this system include redundant power supplies, redundant communications, and an uninterrupted automatic control option. Full internal diagnostics, a watchdog timer, and memory checking are included as well as thorough communication checks. A broad scope of control algorithms is offered including adaptive tuning and output clamping. The supervisory computers offered as part of the Spectrum system can provide report preparation in any format desired as well as EMCS functions.

The cost of this system is difficult to define due to the many possible ways of arranging it, but on an equal capabilities basis, it is very competitive with the other systems analyzed.

<u>Gould -- Modicon</u>

The Modicon system is a direct digital control system with several features that are unique among the systems surveyed in this study. One is the use of a touch sensitive screen on a bit-mapped color graphics CRT which leads to a very simple operator interface for monitoring and controlling process variables. A menu type of display can present a pictorial representation of the operator's choices in a given situation, which he can select by a touch of his finger to the CRT screen. An operator can use this system without any "typing" knowledge whatsoever. The system has good computational capability as well as an uninterrupted automatic control option. A standard keyboard is offered as an option for configuring and display programming, but a separate programmer unit with its own small CRT display is also available. It should be pointed out that one programmer can be used to set up many systems, as it is not needed after the system is configured. The estimated prices for this unit are very competitive for both single and multiple boiler applications.

Measurex -- 2002 Energy Master

This system is computer arranged for direct digital boiler control and energy optimization. It is not a distributed control system and so does not offer the same control reliability offered by most of the other systems studied, even though a redundant power supply is offered. It is primarily designed to operate with the Measurex carbon monoxide-carbon dioxide analyzer probe system and to do a somewhat more sophisticated energy optimization than many of the control systems considered in this study.

The fact that it has been applied to a large number of boilers in a short time indicates that it has significant merit in these days of very high fuel costs. The control algorithms available allow for the compensation for imperfect sensor and actuator characteristics in order to achieve the highest possible boiler efficiency.

The cost estimates for this system for either a single boiler, or for four boilers in a shared control arrangement, are among the highest of the systems examined. The architecture of this system does not lend itself to the progressive or "stepped" installation approach, but must be effected in a single installation step.

Fisher -- PRoVOX

This system appears to be very well thought out in that it provides a great deal of flexibility in its application and has an architecture that has excellent reliability potential. The controllers can be operated from single loop operator display station or from a central CRT console. Configuration and loop timing are provided by a hand held programmer about the size of a pocket calculator which includes a magnetic card encoder/reader for backup storage of the configuration and tuning parameters for each loop.

Redundant power supplies, communications, and controllers are available for uninterrupted automatic control. Thorough self-diagnostic routines and alarms are provided, and any circuit board can be replaced without disturbing any other circuit board or wiring. A good selection of standard displays are available as well as custom graphic displays.

The estimated costs for this system compare very well for a single boiler and the system can be economically applied to multiple boiler installations.

Appendix E

MANUFACTURERS OF DDC BOILER CONTROL SYSTEMS

The following manufacturers offer digital control systems suitable for the control of small boilers in the size range of 30,000 to 100,000 pph of steam. The order of listing is completely random with no ranking or preference.

A. Leeds & Northrup
A Unit of General Signal
North Walkes, PA 19454

B. Fisher & Porter
Corporate Headquarters
Horsham, PA 19044

C. Westinghouse-Hagen
Westinghouse Electric Corporation
Orrville, OH 44667

D. Rosemount Inc.
P.O. Box 35129
Minneapolis, MN 55435

E. Beckman Instruments Inc.
Process Instruments Division
2500 Harbor Blvd.
Fullerton, CA 92634

F. Moore Products Company
Spring House, PA 19477

G. Texas Instruments Inc.
Industrial Controls Division
Johnson City, TN 37601

H. Robertshaw Controls Company
Digital Controls Group
700 Industrial Road
Sugar Land, TX 77478

I. Process Systems, Inc.
8540 Mosely Drive
Houston, TX 77075

J. Bristol Babcock, Inc.
40 Bristol Street
Waterbury, CT 06708

K. Bailey Controls
29801 Euclid Avenue
Wickliffe, OH 44092

L. Honeywell
1100 Virginia Drive
Ft. Washington, PA 19034

M. The Foxboro Company
38 Neponset Avenue
Foxboro, MA 02035

N. Gould Inc.
P.O. Box 83
Shawsheen Villiage Station
Andover, MA 01810

O. Measurex Corporation
One Results Way
Cupertino, CA 05014

P. Fisher Controls Company
P.O. Box 190
Marshalltown, IA 50158