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COMBUSTION EFFICIENCY

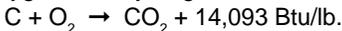
Total efficiency is defined as the effectiveness of any combustion apparatus to convert the internal energy contained in the fuel into heat energy for use by the process. Any heat losses lower the efficiency of the process. Radiant losses from heat escaping through the surfaces of the boiler is one example of efficiency losses. Combustion efficiency is the total energy contained per unit of fuel minus the energy carried away by the flue gas and unburned fuel exiting the stack.

Combustion efficiency losses are a big part of total efficiency losses. Before making large capital investments to improve boiler performance, make sure you maximize combustion efficiency. The best way to maximize combustion efficiency is to measure oxygen and combustibles in the flue gas on a continuous basis.

Combustion Theory and Stoichiometric Combustion

The three essential components of combustion are fuel, oxygen, and heat. Stoichiometric combustion is defined as having just the right amount of oxygen and fuel mixture so the most heat is released. In most fossil fuels, the chemical elements that react with oxygen to release heat are carbon and hydrogen.¹

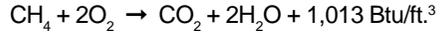
Stoichiometric reactions for pure carbon, oxygen, and hydrogen are as follows:



For these stoichiometric combustion reactions, only heat and CO₂ or H₂O result.

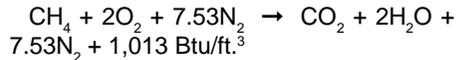
Common fuels consist of compounds containing certain amounts of hydrogen and carbon. These fuels are commonly called hydrocarbons. For example, meth-

ane (CH₄) is a hydrocarbon gas that burns as follows:



Why Use Air Instead of Pure Oxygen

Air contains about 21% oxygen and 79% nitrogen by volume, and is readily available. Pure oxygen must be processed, and on most applications the cost to process oxygen outweighs the benefit of increased combustion control. When you use air instead of oxygen, one cubic foot of methane (at standard temperature and pressure) will burn completely with 9.53 cubic feet of air as shown below:



The ratio of 9.53 cubic feet of air to one cubic foot of methane is known as the stoichiometric air/fuel ratio. The heat released when the fuel burns is known as the heat of combustion. Table 1-1 and Table 1-2 list the stoichiometric air/fuel ratios and heats of combustion for several common fuels.

Ideally, you want to provide just the right amount of air to completely burn all the fuel.

Table 1-1 — Combustion ranges for selected gaseous fuels

Fuel	Stoichiometric Air/fuel ratio (ft ³ air/ft ³ fuel)	Heat of Combustion (Btu/ft ³)
Hydrogen (H ₂)	2.38	325
Carbon Monoxide (CO)	2.38	322
Methane (CH ₄)	9.53	1013
Propane (C ₃ H ₈)	23.82	2590
Natural Gas	9.4 - 11.0	950-1150
Coke Oven Gas	3.5 - 5.5	400-600

Table 1-2 — Combustion ranges for selected solid and liquid fuels

Fuel	Stoichiometric Air/fuel ratio (ft ³ air/lb. fuel)	Heat of Combustion (Btu/lb.)
Carbon (C)	150	14,093
Sulfur (S)	56	3,983
No. 2 Oil	180-195	18,500-19,800
No. 6 Oil	170-185	17,500-19,000
Bituminous Coal	120-140	12,000-14,000

¹ Sulfur is rarely used as a fuel, but will react with oxygen as follows:
 $S + O_2 \rightarrow SO_2 + 3,983 \text{ Btu/lb.}$

But this proves elusive for a number of reasons, including inadequate mixing of air and fuel, burner performance, fluctuating operating and ambient conditions, and burner wear and tear. To ensure that the fuel is burned with little or no combustibles, some amount of excess air is provided. To ensure no more excess air than required is used, you measure excess oxygen in the flue gas. To ensure the amount of hydrogen or carbon monoxide in the flue gas is minimized, combustibles are measured.

The Importance of Excess Air

Flue gas heat loss is the single largest energy loss in a combustion process. It is impossible to eliminate all flue gas heat loss because the products of combustion are heated by the combustion process. But flue gas heat loss can be minimized by reducing the amount of excess air supplied to the burner.

Flue gas heat loss increases with both increasing excess air and temperatures as shown in Figure 1-1.

Figure 1-1 — Flue gas heat loss increases with both increasing excess air and temperatures

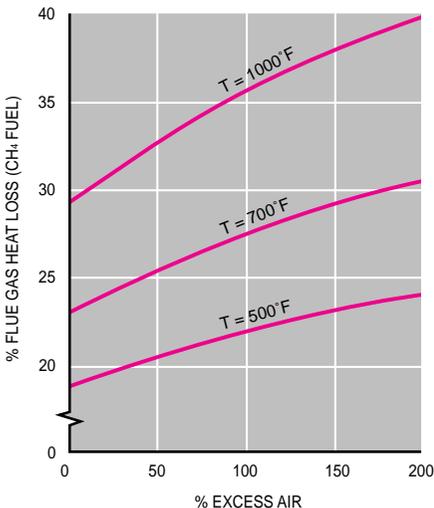
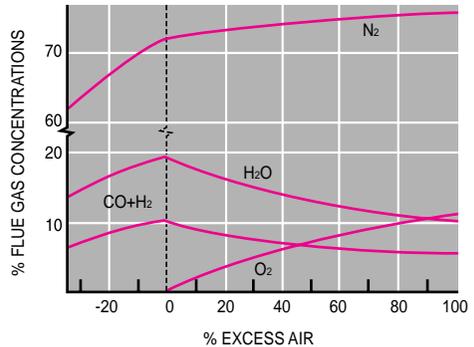


Figure 1-2 — Flue gas constituents vs. excess air for methane combustion



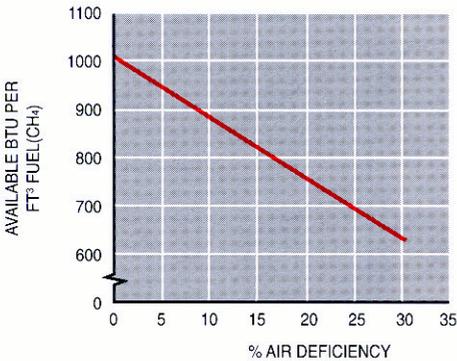
Since the oxygen in the flue gas is directly related to the amount of excess air supplied (Figure 1-2), an oxygen flue gas analyzer is the best way to effectively measure and control the amount of excess air in the flue gas and the associated heat loss.² Zirconium oxide O₂ flue gas analyzers are the preferred combustion control analysis method. Oxygen analyzers, including those using zirconium oxide technology, paramagnetic, and wet electrochemical cells, are discussed further in Chapter 2.

Unburned Fuel Loss

For combustion efficiency, you never want to operate a burner with less air than is required for stoichiometric combustion. Not only does this result in a smoking stack, but it significantly reduces the total energy released in the combustion process due to unburned fuel. Figure 1-3 shows how the energy released per cubic foot of methane falls off with decreasing combustion air.

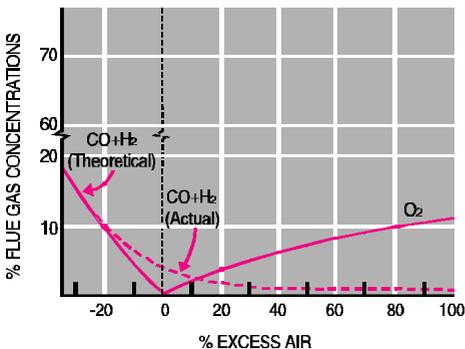
²In the past, CO₂ analyzers were also used. But as seen in Figure 1-2, a particular CO₂ level in flue gas can indicate either an excess fuel or excess air condition. This dual meaning is unacceptable in combustion control systems, and therefore CO₂ analyzers are no longer used for combustion efficiency purposes.

Figure 1-3 — Available heat drops sharply with deficient air supply



If a burner is operated with a deficiency of air, or the air and fuel are mixed improperly, all the fuel will not burn. As a result, carbon monoxide and hydrogen will appear in the products of combustion. Carbon monoxide (CO) and hydrogen (H₂), collectively referred to as combustibles, result from incomplete combustion. When insufficient excess air is available, the amount of combustibles in the flue gas increases dramatically.

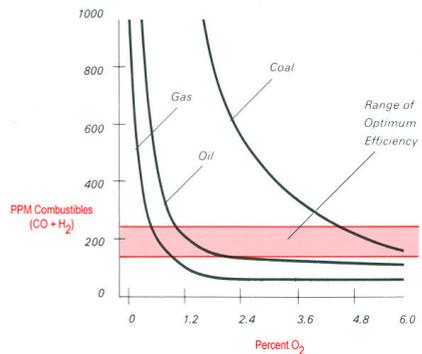
Figure 1-4 — Actual vs. theoretical combustibles



In practice, some trace levels of unburned fuel appear in the flue gas stream even with some amount of excess air, due to imperfect mixing of fuel and air at the burner or other burner conditions (see Figure 1-4). As a result, combustion processes are not operated at the stoichiometric point. Instead, combustion processes are operated with sufficient excess air to keep the amount of combustibles minimized. Combustibles levels of a few hundred parts per million (ppm) in the flue gas have an insignificant effect on efficiency.

But what is the correct O₂ level? For every combustion process, the optimum amount of excess air depends on several variables including the type of fuel, the load, and the size and condition of the burner (see Figure 1-5). There is no single O₂ level which is right for all processes.

Figure 1-5 — Optimum efficiency range



Combustibles detectors can measure both hydrogen and carbon monoxide in flue gas, with accuracies of ± 100 ppm or better. For detection of natural gas during purge-down and light-off cycles, special versions of detectors are available for % methane. Infrared or electrochemical cell analyzers measure only carbon monoxide, but are used to measure total combustibles in some cases. Combustibles detectors and CO analyzers are discussed in detail in Chapter 3.

Combustion Efficiency - Measuring Oxygen and Combustibles

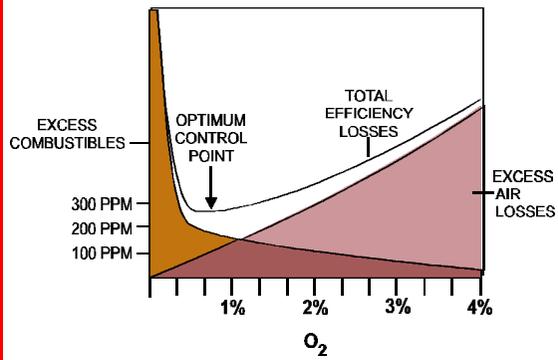
In the past, it was not practical to continuously calculate unburned fuel loss and flue gas heat loss to maintain the most efficient level of excess air. Combustion efficiency tables were used to determine optimal control points in the burner design stage. These tables help you to determine the expected efficiency of a boiler or furnace, and to assist in making cost/benefit decisions. The tables in the appendix provide efficiency curves for various fuels. These tables can be used to make a rough estimate of the efficiency improvements that can be made by decreasing the amount of excess air and the level of combustibles in the flue gas in your system. You then continuously monitor the process using a flue gas analyzer to fine tune your system.

Measuring oxygen alone is insufficient for combustion efficiency purposes because of ever-changing boiler conditions that affect the amount of combustibles in the flue gas. Similarly, measuring combustibles alone doesn't provide sufficient detail to make continuous adjustments to the process. To maintain the highest combustion efficiency level on a continuous basis, both oxygen and combustibles in the flue gas need to be measured.

This leads to the fundamental principle of combustion efficiency: "Combustion efficiency is maximized when the correct amount of excess air is supplied so that the sum of energy losses from both unburned fuel loss and flue gas heat loss is minimized." By measuring the concentrations of oxygen and combustibles, both unburned fuel loss and flue gas heat loss can be minimized (see Figure 1-6).

Combined oxygen and combustibles analyzers enable both measurements to be made at a single sample point. From this, the supply of excess air can be controlled on a continuous basis, minimizing heat loss and unburned fuel loss, and therefore ensuring the most efficient operation of your boiler.

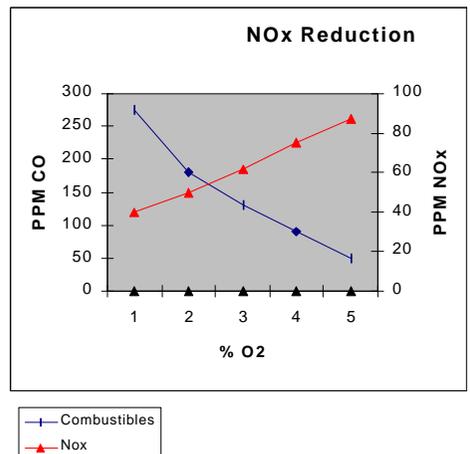
Figure 1-6 — Total combustion efficiency losses is sum of unburned fuel loss and heat losses



NOx Reduction

In addition to maximizing efficiency, low excess air firing has the benefit of reducing NOx emissions (see Figure 1-7). This should be the first step in any NOx reduction strategy.

Figure 1-7 — NOx Reduction



OXYGEN MEASUREMENT

Oxygen concentration in flue gas is an excellent indicator of excess air in the flue gas. The existing technologies used to measure excess air in flue gas are the zirconium oxide cell, the paramagnetic oxygen cell, and the wet electrochemical cell.

Zirconium oxide analyzers indicate net oxygen; that is, the oxygen remaining after burning with whatever free combustibles are present around the hot zirconium oxide cell. Paramagnetic and wet electrochemical cell oxygen analyzers measure gross oxygen. For combustion efficiency applications, the difference between net and gross measurements are small since combustibles are generally in the ppm range, while oxygen is usually in the percent range.

Differences may also occur between the technologies because zirconium oxide analyzers can measure oxygen on a wet basis where the flue gas contains water vapor. The other measuring techniques all require cool, dry samples, and measure on a dry basis. For example, assume you have a flue gas containing 5% O₂, 10% H₂O, balance nitrogen (85%). If the water (H₂O) is removed from the sample to make a dry reading, oxygen would read as 5.5% O₂ (5% of 100% vs. 5% of 90%).

There should be no cause for alarm because of wet vs. dry or gross vs. net measurements. There is no right or wrong method. All are valid conventions. It is important only to know which convention is being used and to be consistent.

Zirconium Oxide Cell

The zirconium oxide cell is the most prevalent technology for continuous monitoring of flue gases. The sensor was developed in the mid-1960s in conjunction with the U.S. Space Program's Apollo mission. Because of its inherent ability to make oxygen measurements in hot, dirty gases without sample conditioning, it was quickly accepted by industrial users.

With zirconium oxide, because it can be a wet measurement, it is important to keep the sample above the acid dewpoint to prevent condensation or corrosion in the sample line. Typically, this is not an issue since the process and the sensor operate at temperatures greater than the acid dewpoint.

Zirconium oxide analyzers now use microprocessor-based control units (see Figure 2-1) that include automatic calibrations, RS-485 two-way communications, current outputs, and alarms. Calibration, maintenance, and repair are user friendly. The sensor can be calibrated with the push of a key, or can even be calibrated automatically at timed intervals that require no operator intervention.

Maintenance and repair of these newer systems is made easier by a self-diagnostic system that, through the use of text help messages, can tell an operator what action needs to be taken or what item needs to be replaced. Components are usually modular, making repairs and replacements easier.



Figure 2-1 — Thermox Series 2000 microprocessor-based control unit.

The Nernst Equation

The sensing element itself is a closed-end tube or disk made from ceramic zirconium oxide stabilized with an oxide of yttrium or calcium. Porous platinum coatings on the inside and outside serve as a catalyst and as electrodes. At high temperatures (generally above 1200°F, 650°C), oxygen molecules coming in contact with the platinum electrodes near the sensor become ionic. As long as the oxygen partial pressures on either side of the cell are equal, the movement is random and no net flow of ions occurs. If, however, gases having different oxygen partial pressures are on either side of the cell, a potentiometric voltage is produced (See Figure 2-2). The magnitude of this voltage is a function of the ratio of the two oxygen partial pressures. If the oxygen partial pressure of one gas is known, the voltage produced by the cell indicates the

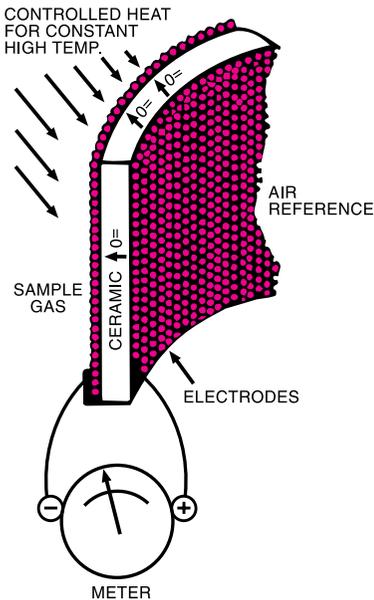


Figure 2-2 — Zirconium oxide cell principle of operation

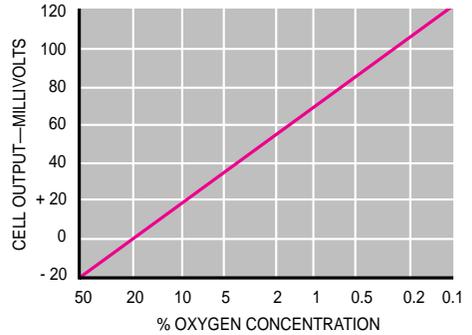


Figure 2-3 — Cell output vs. oxygen concentration

oxygen content of the other gas (See Figure 2-3). A reference gas, usually air, is used for one of the gases.

Since the voltage of the cell is temperature dependent, the cell is maintained at a constant temperature. Some newer high temperature insitu models use the heat from the process to heat the sensor, and the process temperature is continuously measured and used in the software calculation. The oxygen content is then determined from the Nernst equation:

$$E = \frac{RT}{4F} \ln \frac{O_1}{O_2}$$

where R and F are constants, T is absolute temperature, and O_1 and O_2 are the oxygen partial pressures on either side of the cell. For example, if air is the reference gas, and the cell temperature is 735°C, the equation becomes:

$$E = 0.050 \log \frac{0.209}{O_2}$$

The cell produces zero voltage when the same amount of oxygen is on both sides, and the voltage increases as the oxygen concentration of the sample decreases. The voltage created by the difference in the sample gas and the reference air is carried by a cable to the microprocessor control unit, where it is linearized to an output signal.

Advantages of Zirconium Oxide Technology

The zirconium oxide cell has several advantages over other oxygen-sensing methods. First, since the cell operates at high temperatures, there is no need to cool or dry the flue gas before it is analyzed. Most zirconium oxide analyzers make direct oxygen measurements on the stack with nothing more than a filter to keep ash or particulate away from the cell. This dramatically improves the response time. The cell is not affected by vibration, and unlike other techniques, the output actually increases with decreasing oxygen concentration. In addition, the cell has a virtually unlimited shelf life.

Zirconium Oxide Sampling Techniques

Four different sampling techniques are used to measure flue gas with a zirconium oxide sensor. These sampling techniques are the insitu, close-coupled extractive, extractive, and convective.

Insitu Analyzer

As its name implies, an insitu analyzer (See Figure 2-4) places the zirconium oxide cell directly in the flow of the flue gas. The zirconium oxide cell is located at the end of a stainless-steel probe inserted into the stack, and is inserted from a few inches to a few

feet in the process, depending on the application.

A heating element, in conjunction with a thermocouple, controls the cell temperature to ensure proper operation.

Flue gas diffuses into the probe opening and comes in contact with the zirconium oxide cell by diffusion.

The compact design of an insitu analyzer makes it a good choice for many industrial applications where oxygen measurements alone are adequate. However, the insitu design does not lend itself to combustibles measurements necessary for combustion efficiency. And because all its analyzing components are located directly in the stack, the insitu cannot be used in applications with temperatures above 1250°F.

One other drawback to older insitu models has been difficulty of servicing. When an insitu probe stopped functioning, it had to be taken completely off line and shipped back to its manufacturer for repairs. Newer models, however, employ a modular construction of the internal components so the cell, furnace, and thermocouple can be removed and repaired in the field while leaving the outer protection tube in the process. Parts can be unscrewed and replaced in minutes instead of the weeks needed for a factory repair (see Figure 2-4).

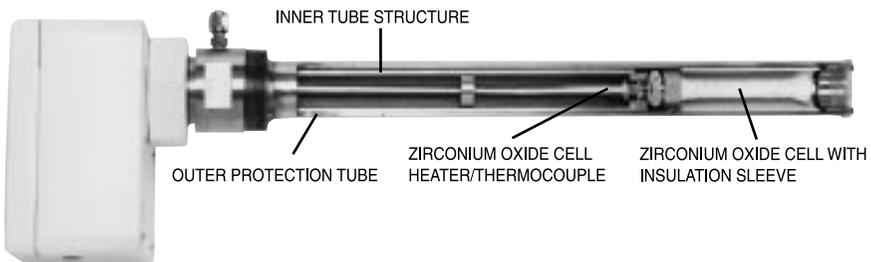


Figure 2-4 — Cross-section of Insitu probe

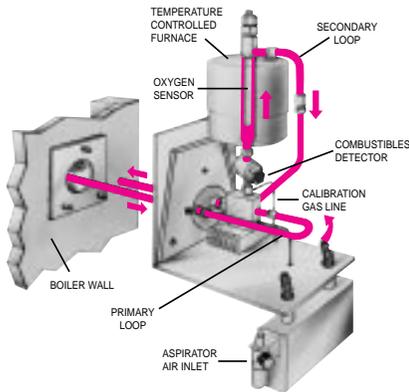


Figure 2-5 — Close-coupled extractive oxygen/combustibles analyzer

Close-coupled Extractive Analyzer

A close-coupled extractive probe (see Figure 2-5) uses the force of an air-driven aspirator to pull flue gas into the analyzer. The sensor is located just outside the process wall with a probe that extends into the flue gas to extract a sample. The flue gas is then returned to the process after being measured.

Flue gas is pulled through the primary sample loop by an aspirator. The flue gas enters the pipe to fill the vacuum created by the aspirator, and about five percent of it is lifted into the secondary loop using convection - this is where the cell and furnace are located. This analyzer yields the fastest response to process changes because of the aspirator, and can work in processes up to 3200°F (1760°C). Since the sensor is located so close to the stack and is heated, no sample line conditioning is needed. The close-coupled extractive analyzer is ideal for relatively clean-burning applications, such as natural gas and lighter grades of oil, and can be equipped with a combustibles detector (see Chapter 3).

Convective Analyzer (Hybrid Model)

This type of analyzer (See Figure 2-6) uses convection to bring the sample flue gas to the zirconium oxide cell, which is located just outside the process wall.

Since hot air rises, the temperature-controlled furnace and oxygen-sensing cell are placed above the level of the gas inlet pipe.

As gas near the cell is heated, it rises up and out of the cell housing, and is replaced by gas being drawn out of the filter chamber and into the inlet pipe. The gas that has left then cools off on its way back into the filter chamber. Process gas is constantly diffusing in and out of the filter chamber.

The intake area of a convective analyzer is surrounded by a filter. Since gases diffuse through the filter and are then drawn into the analyzer by convection, no flow through the filter occurs and thus no particles can enter the filter to plug it. This makes it ideal for high particulate applications such as coal-fired boilers, cement kilns, waste incinerators, and recovery boilers.

The convective analyzer can be used for processes up to 2800°F (1537°C). Because it works on a diffusion principle, and the sample path is longer than that of an insitu probe, the response time is slower than the close-coupled extractive technique, but

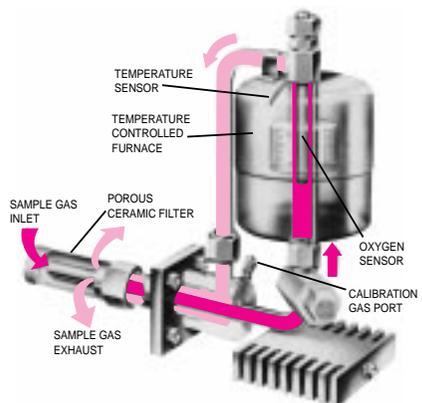


Figure 2-6 — Convective oxygen/combustibles analyzer

is comparable in response time to the insitu design since it also uses diffusion. However, the tighter temperature control of the furnace and the ability to add a combustibles detector as an option outweighs the slower response time.

Extractive Analyzers

Extractive analyzers, unlike close-coupled extractive or convective analyzers, do not return the sample to the gas stream (see Figure 2-7). This is because the gas is often extracted as far as 100 feet or more from the stack for analysis. Either wet or dry readings are possible with extractive zirconium oxide analyzers. Zirconium oxide extractive analyzers can also be placed on the stack if desired, since they require no sample conditioning.

Other Benefits of Zirconium Oxide Cell

In the absence of molecular oxygen, the zirconium oxide cell responds to the minute amount of oxygen produced by the dissociation of water and carbon dioxide at the high cell operating temperature. This dissociation is inhibited by the presence of combustibles (carbon monoxide and hydrogen) in the sample gas. As the combustibles concentration increases, the oxygen concentration decreases, and the output signal from the zirconium oxide cell increases.

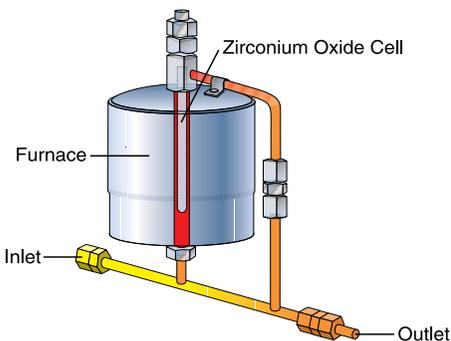


Figure 2-7 — Extractive oxygen analyzer

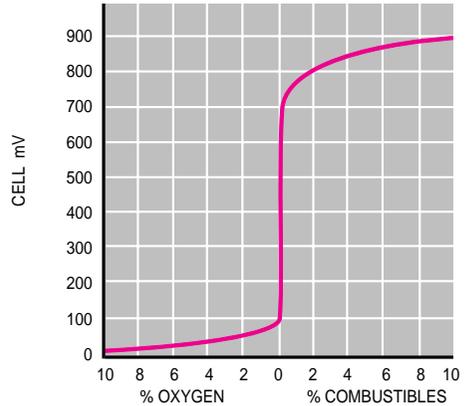


Figure 2-8 — Cell output vs. net oxygen/net combustibles (methane fuel)

This means that the zirconium oxide cell does not stop responding when there is no net oxygen in the flue gas. In fact, it becomes a sensor of net combustibles.

Equivalent Combustibles

Figure 2-8 shows how the voltage generated by the cell increases sharply as flue gas changes from a net oxygen to a net combustibles condition. This property of the zirconium oxide cell is extremely useful on some combustion processes because it permits measurement on both sides of stoichiometric combustion, either excess air or excess fuel. This is beneficial, for example, on a two stage burner where the first stage is kept reducing and the second stage is oxidizing.

Equivalent combustibles are used for low levels of free oxygen in the flue gas. It uses a summation of the zirconia cell and the combustibles detector to ensure combustibles readings are accurate and continuous under all process conditions.

Paramagnetic Oxygen Sensor

The paramagnetic sensor takes advantage of the fact that oxygen molecules are

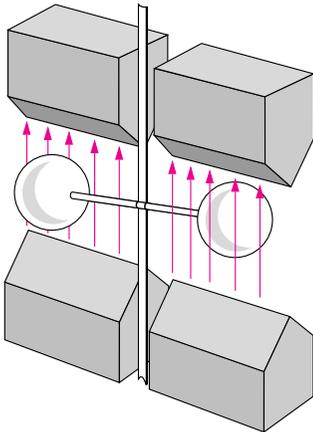


Figure 2-9 — Paramagnetic oxygen sensor

strongly influenced by a magnetic field. Although there are several variations, the most common design uses two diamagnetic, nitrogen-filled quartz spheres connected by a quartz rod to form a dumbbell shape. This is supported by a torsional suspension, and is located in a strong non-uniform magnetic field (see Figure 2-9). Because the spheres are diamagnetic, they will swing away from the strong magnetic field until the torsional forces equal the magnetic forces.

If a gas containing oxygen passes through the cavity that contains the dumbbell, the magnetic field changes, and the dumbbell moves. This movement can be detected optically or electronically, and is a measure of the oxygen concentration in the sample gas.

Because of the delicate nature of the dumbbell assembly, paramagnetic analyzers are best suited for laboratory applications. When used on flue gas, a fairly complex sampling and cleaning system is required to ensure that the gas is clean, dry, and cool before it is introduced into the analyzer.

Wet Electrochemical Cell

Wet electrochemical cells, of which there are many designs, use two electrodes in contact

with an aqueous electrolyte. Oxygen molecules diffuse through a membrane to the cathode where a chemical reaction occurs that uses electrons from the oxygen molecule to release hydroxyl ions (OH^-) into the electrolyte. At the anode, which is typically lead or cadmium, the hydroxyl ions react with the anode material, oxidizing it and releasing electrons. Since electrons are released at the anode and accepted at the cathode, the cell is essentially a battery with an electrical current that is directly proportional to the flow of oxygen through the membrane.

The best wet cells are packaged into neat, compact plastic cylinders containing the membrane, electrodes, and electrolyte. When the anode material is depleted, these cylinders can simply be removed, discarded, and replaced. A cross-section of such a cell is shown in Figure 2-10. This kind of wet cell is ideal for use in portable oxygen analyzers because it is lightweight and requires only battery power. For permanent installations, however, a sampling/cooling system must be installed between the analyzer and the combustion process. Without sample conditioning, the cell membrane quickly becomes coated and ceases to function. Care must also be taken since the anode of the cell oxidizes rapidly when exposed to air. Usually, cells are stored in air-tight packages. Finally, the response time is extremely slow compared to zirconium oxide cells.

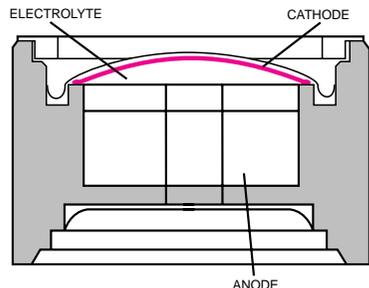


Figure 2-10 — Typical wet electrochemical cell

COMBUSTIBLES MEASUREMENT

Incomplete combustion results in combustibles, consisting of hydrogen (H_2) and carbon monoxide (CO), in the flue gas. More than a few 100 ppm of combustibles results in wasted fuel, soot formation, and reduced heat transfer efficiency. In addition, high concentrations of combustibles create an environmental concern and a potentially explosive condition.

Hydrogen measurement has often been ignored in flue gas analysis, with the focus instead being on CO. For combustion efficiency purposes, though, you need to be able to detect total combustibles, which includes both carbon monoxide and hydrogen.

The three prevalent methods for on-line monitoring of combustibles in flue gas are with a catalytic element, wet electrochemical cell, and non-dispersive infrared absorption. However, wet electrochemical cells and infrared technologies measure only CO.

Catalytic Combustibles Detector

A catalytic combustibles detector provides the required accuracy to maximize combustion efficiency, and is sensitive to both hydrogen and carbon monoxide. Also, a catalytic combustibles detector can be packaged with an oxygen analyzer, eliminating the need for a separate analyzer to measure combustibles. And these combustibles detectors can work in high temperature areas where CO infrared analyzers cannot.

The catalytic detector consists of two pellisters mounted in close proximity to each other in a housing through which the flue gas flows (See Figure 3-1). The active element is coated with a catalyst in an inert binder. The reference element is coated with the same binder without the catalyst. A current passes through the pellister to raise the temperature to over 400°F.

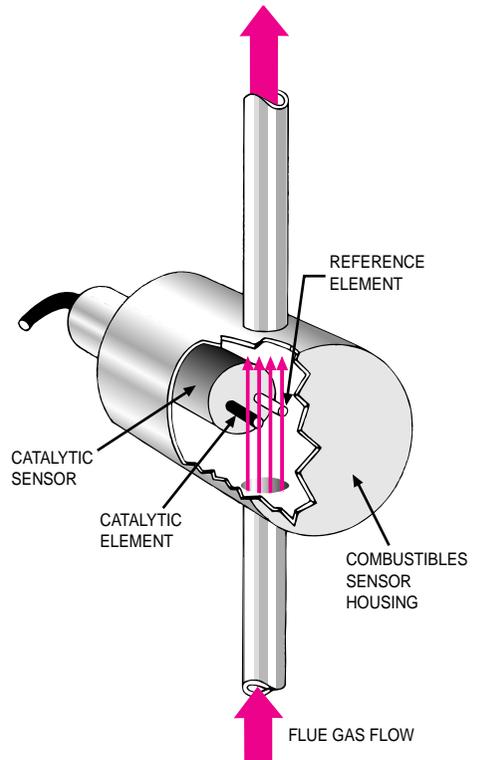


Figure 3-1 — Catalytic combustibles detector

Combustibles and oxygen do not normally burn together in a gas stream unless the temperature is elevated to above 1000°F. However, if the gas stream comes in contact with a solid catalyst, such as platinum, combustion will occur at 400°F. When flue gas containing both oxygen and combustibles passes through the housing, combustion occurs on the active element, but not on the reference element. This causes the temperature of the active element to rise and its resistance to change. The resistance of the active element will differ from the reference element proportionally to the combustibles concentration of the flue gas.

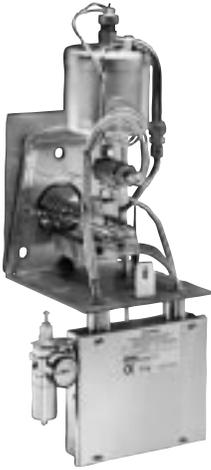


Figure 3-2 — Catalytic combustibles detector can be placed in an oxygen analyzer

Catalytic detectors (see Figure 3-2) are used in convective, close-coupled, and extractive zirconium oxide analyzers. In these sampling systems, the combustibles detector can be mounted directly in the convective loop with the oxygen sensing cell. The convective loop of these analyzers provides a stable flow and temperature (See Figure 2-5 and Figure 2-6).

For combustion efficiency, combustibles readings in the 0-200 ppm range have a negligible effect on combustion efficiency. Above 500 ppm, combustibles begin to have a dramatic effect on efficiency. Thus, combustibles detectors with full scale ranges as sensitive as 0-2000 ppm combustibles and accuracies of ± 100 ppm or better are ideal for combustion efficiency.

Infrared Carbon Monoxide Measurement

Carbon monoxide is one of many gases that absorb infrared energy at specific, discrete

wavelengths. If a beam of infrared light is passed through a gas sample containing CO, and if the emerging energy is measured with a spectrophotometer, significantly less energy will be detected for wavelengths between 4.5 and 4.7 microns than if the CO were not present. The amount of energy absorbed is a measure of the CO in accordance with Beer's Law:

$$\log (I/I_0) = -\alpha c l$$

where I_0 is the intensity of the infrared light at a specific wavelength (λ) entering the sample; I is the intensity leaving the sample; α is the absorption coefficient for CO at wavelength λ ; c is the concentration of CO in the sample; and l is the path length of the infrared light beam through the sample. By holding the path length, l , constant, the ratio I/I_0 becomes a direct measurement of the CO concentration.

Extractive Infrared CO Analyzers

Extractive infrared CO analyzers, as shown in Figure 3-3, have the infrared source, detector, and optics in a single package that is mounted away from the stack. Infrared light is generated by a thermal source. The light is mechanically chopped and then alternately passed through a cell containing the sample gas and a sealed cell containing air. If CO is present in the sample gas, some of the infrared energy is absorbed in

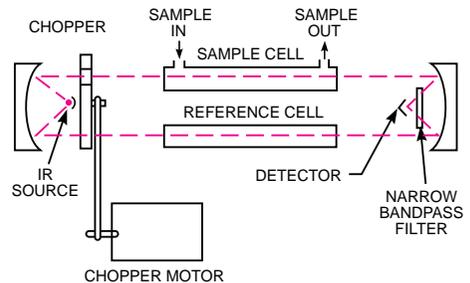


Figure 3-3 — Extractive infrared CO analyzer

the sample cell. The remaining infrared energy then passes through a narrow bandpass filter that blocks all radiation except in the 4.5 to 4.7 micron range. This filtered energy is focused on a thermal detector that generates an electrical signal related to the intensity of the radiation. The ratio of the two alternating signals is then a direct measure of the CO concentration in the sample gas. Electronic circuitry can provide an analog or digital display of the CO value as well as a current or voltage output signal suitable for a recorder or control system.

Extractive infrared CO analyzers are used primarily in emissions monitoring systems. They are usually located at easily accessible places near the combustion process. Flue gas is drawn through a sampling probe that is inserted into the stack or duct. In most cases, sample conditioning is required to clean, dry, and cool the sample before it enters the analyzer. Provisions for the introduction of calibration gases are usually an integral part of the design of the sample conditioning system.

Across-the-Stack Infrared CO Analyzers

In across-the-stack infrared CO analyzers, the infrared source is housed in an enclosure that mounts directly on the stack or duct (see Figure 3-4). The infrared beam generated by the source passes completely

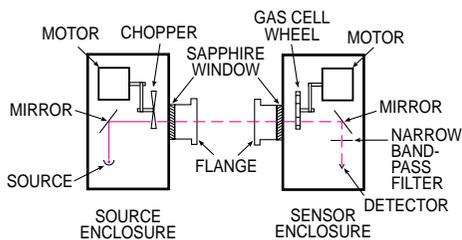


Figure 3-4 — Across-the-stack infrared CO analyzer

through the stack into a similar enclosure mounted on the other side. The beam is usually chopped mechanically in the source enclosure to differentiate it from the infrared energy emitted from the hot interior stack walls. If CO is present in the flue gas, some of the infrared energy in the 4.5 to 4.7 micron band will be absorbed. It is this absorption that is detected in the sensor enclosure and is interpreted as CO.

Obviously, an across-the-stack analyzer cannot have a reference path containing no CO, as would an extractive CO analyzer. Instead, gas filter correlation is used to solve Beer's Law and calculate CO concentration. In this technique, two physically identical sealed gas cells are alternately moved in and out of the infrared beam in the sensor enclosure just before the narrow bandpass filter and detector. One cell contains a high concentration of CO so infrared energy at the CO-sensitive wavelengths is entirely absorbed. The other cell contains only nitrogen. The difference between the two signals generated by the infrared detector is inversely proportional to the energy absorbed by any CO in the flue gas.

The intensity of the infrared beam transmitted across the stack may vary due to decay of the thermal source, darkening of the enclosure windows by soot, or particulate in the stack. To ensure that the final result is independent of any changes in light intensity, a standard signal processing technique is employed. The difference between the two gas cell signals is divided by their sum. The result is a signal that is insensitive to transmitted light changes, and varies only with the concentration of CO in the flue gas. Electronic circuitry conditions the signal for display on a meter and for a recorder or control system output.

Extractive CO analyzers may have lower installation costs than across-the-stack CO analyzers because the measuring system

can be located at ground level, while across-the-stack systems must be mounted on the stack or duct. But the lower installation cost may be offset by the cost and maintenance required by a sampling system. The ability to calibrate extractive CO analyzers with known calibration gas mixtures is an advantage. Some across-the-stack analyzers use additional sealed gas cells containing known mixtures of CO to facilitate calibration.

There are two major advantages of across-the-stack CO systems compared to extractive CO systems. First, although across-the-stack analyzers are much slower than combustibles detectors, the speed of response is significantly faster than off-stack analyzers. Extractive CO systems take several minutes to respond to a change in flue gas conditions. Second, across-the-stack systems provide a measurement of the average CO concentration in the stack. Unlike off-stack analyzers, which sample from a single point, these analyzers are unaffected by stratification or stagnation of the flue gas in various areas of the stack, and provide a good average of the CO levels in the stack.

Both extractive and across-the-stack CO systems have limitations because they can't be placed in higher temperature areas closer to the flame source that a catalytic combustibles detector can. As a result, the combustibles in the stack can be diluted or can be a combined input from a number of boilers or furnaces or heaters.

Wet Electrochemical Cell

A wet electrochemical cell can be used to measure CO. In Chapter 2, you learned how electrochemical cells are used to measure oxygen. The same principle is used to measure CO.

As with oxygen cells, CO electrochemical cells are ideal for use in portable instruments because of their compact design and low power consumption. However, the sensors are prone to zero and span drift problems because they measure CO flow through the membrane. Flow rate is affected by ambient pressure, temperature, and humidity. Furthermore, the membrane can become coated with flue gas condensation.

Understanding the importance of combustibles is key to combustion efficiency. By measuring combustibles and oxygen together at a single sampling point close to the flame source, you get a true picture of your process, and the ability to monitor different areas where stratification could be occurring. Combustibles detectors can now be easily included as part of an oxygen analyzer for a lot less than two separate analyzers.

The benefits of fine tuning your boiler or process heater using a combined oxygen and combustibles measurement are as follows:

- improved fuel efficiency
- ability to monitor burner deterioration
- ability to monitor stratification
- ability to detect air leaks
- reduce NOx emissions from your stack

PRE-COMBUSTION VS. FLUE GAS MEASUREMENT

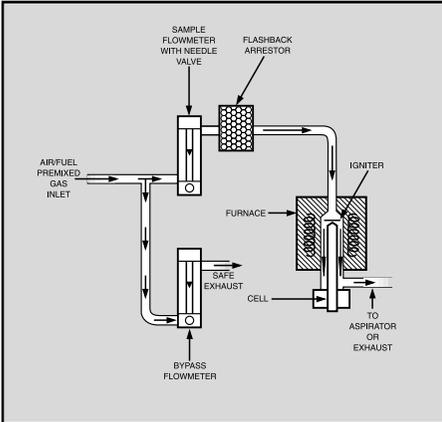


Figure 4-1 — Premix analyzer schematic

Pre-combustion applications have the air and fuel pre-mixed before being sent to the flame source. A traditional flue gas analyzer cannot be used for premix applications because either there is no practical place to measure the flue gas, such as with open flame applications, or the measurement is inaccurate due to air leakage. For these cases, premix analyzers are used.

Premix Analysis - How it Works

Most of the sample gas entering the premix analyzer passes through the bypass flow meter, which ensures a fast response and keeps the sample inlet purged of dead volume (see Figure 4-1). Only a small portion of the sample flows through the sample flow meter and flashback arrestor to the furnace. An igniter at the inlet of the furnace enables the fuel mixture to burn. The combustion products then flow past the zirconium oxide cell, where they are measured. The cell can measure the excess air (fuel lean) or excess fuel (fuel rich) composition of the flue gas, and can work in either range. These types of analyzers (see Figure 4-2) are often used for glass forehearths or glass fiber applications.



Figure 4-2 — Thermox PreMix 2000 Analyzer

Combustion Air Requirement Index (CARI)

In some applications, the heat content of the fuel is variable, such as with off-gases used in steel production. In these applications, to maximize efficiency natural gas is added to obtain a stable heat rate. A CARI analyzer measures the heat quality of the fuel being burned. The CARI analyzer provides a direct measurement of the air flow requirement for combustion of a variable composition fuel gas.

A flow of the sample gas, constant except for the change in flow caused by changes in specific gravity, is mixed with a constant flow of combustion air and is burned (see Figure 4-3). The resulting product gas (flue gas) is analyzed for excess oxygen. As discussed earlier, controlling the amount of excess oxygen improves combustion efficiency.

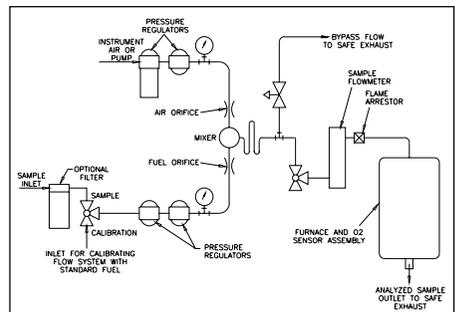


Figure 4-3 — CARI schematic

COMBUSTION EFFICIENCY TABLES

CONVERSIONS

1 Boiler Horsepower = 34.5 pounds per hour evaporation @ 212°F (100°C)

1 Horsepower-hour = 2545 Btu
 1 Kilowatt-hour = 3412 Btu } 1.34 HP - 1 KW

1 Atmosphere = 14.696 pounds per square inch
 = 760.0 mm mercury

How to Use Tables

1. At the flue gas outlet of the boiler, furnace, kiln, etc., measure the flue gas exit temperature, oxygen concentration, and combustibles concentration.
2. Locate the proper combustion efficiency table for the fuel and flue gas temperature. It may be necessary to interpolate between two tables.
3. If the combustibles measurement is in parts per million, convert to percent (100 ppm = 0.01%). Read down from the measured combustibles concentration and across from the measured oxygen concentration to find the percent combustion efficiency.

Assumptions

1. All gas concentrations are on a **wet basis**.
2. Oxygen concentrations are *net*; i.e. the oxygen left over after all combustibles have been burned on the hot zirconia cell.
3. Combustibles concentrations are *gross*; i.e. the actual combustibles prior to burning with any remaining oxygen on the zirconia cell.
4. Ambient temperature is assumed to be 60°F.
5. Combustibles are assumed to consist of 67% CO and 33% H₂.
6. Natural gas is assumed to be 85% CH₄, 10% C₂H₆ and 5% N₂ by volume with a Btu value of 1037.5 Btu/scf.
7. Fuel oil and coal are assumed to have the following compositions (by weight).

	No. 2 Oil	No. 6 Oil	Coal
Carbon (C)	86.0	88.6	72.0
Hydrogen (H)	11.0	9.4	4.4
Sulfur (S)	0.8	0.85	1.6
Oxygen (O)	1.0	0.7	3.6
Nitrogen (N)	0.2	0.3	1.4
Moisture (H ₂ O)	1.0	0.2	8.0
Ash	—	0.05	9.0
Btu Value (per lb.)	18,873	18,126	12,800

% COMBUSTION EFFICIENCY—NATURAL GAS

TEMPERATURE = 300°F (149°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	85.4	85.4	85.4	85.3	85.1	84.8	83.8	82.2	79.0	69.0
0.5	85.3	85.3	85.3	85.2	85.0	84.7	83.7	82.0	78.7	68.4
1.0	85.2	85.2	85.1	85.0	84.9	84.5	83.5	81.8	78.4	67.9
1.5	85.1	85.1	85.0	84.9	84.7	84.4	83.4	81.6	78.1	67.3
2.0	85.0	84.9	84.9	84.8	84.6	84.2	83.2	81.4	77.8	66.7
3.0	84.7	84.6	84.6	84.5	84.3	83.9	82.8	80.9	77.1	65.4
4.0	84.4	84.3	84.3	84.2	84.0	83.6	82.4	80.4	76.3	64.0
5.0	84.0	84.0	83.9	83.8	83.6	83.2	81.9	79.8	75.5	62.4
6.0	83.6	83.6	83.5	83.4	83.2	82.7	81.4	79.1	74.5	60.5
8.0	82.6	82.6	82.5	82.4	82.1	81.6	80.0	77.4	72.1	55.9
10.0	81.3	81.2	81.2	81.0	80.7	80.0	78.2	75.1	68.8	49.7
12.0	79.3	79.3	79.2	79.0	78.6	77.8	75.5	71.7	64.1	40.6
14.0	76.2	76.1	76.0	75.8	75.3	74.3	71.4	66.5	56.6	26.3

TEMPERATURE = 400°F (204°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	83.4	83.4	83.3	83.2	83.1	82.8	81.8	80.2	76.9	66.9
0.5	83.2	83.2	83.2	83.1	82.9	82.6	81.6	79.9	76.6	66.3
1.0	83.1	83.0	83.0	82.9	82.7	82.4	81.4	79.7	76.3	65.8
1.5	82.9	82.9	82.8	82.7	82.6	82.2	81.2	79.4	75.9	65.1
2.0	82.7	82.7	82.6	82.5	82.4	82.0	80.9	79.1	75.5	64.5
3.0	82.3	82.3	82.2	82.1	81.9	81.6	80.4	78.5	74.7	63.1
4.0	81.9	81.8	81.8	81.7	81.5	81.1	79.9	77.9	73.8	61.5
5.0	81.4	81.3	81.3	81.2	81.0	80.5	79.3	77.1	72.8	59.7
6.0	80.8	80.8	80.7	80.6	80.4	79.9	78.6	76.3	71.7	57.7
8.0	79.4	79.4	79.3	79.2	78.9	78.4	76.8	74.2	68.9	52.7
10.0	77.5	77.4	77.4	77.2	76.9	76.3	74.4	71.3	65.1	45.9
12.0	74.7	74.7	74.6	74.4	74.0	73.2	71.0	67.2	59.5	36.0
14.0	70.4	70.3	70.2	69.9	69.4	68.4	65.5	60.6	50.7	20.4

TEMPERATURE = 500°F (260°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	81.4	81.3	81.3	81.2	81.0	80.7	79.7	78.1	74.9	64.9
0.5	81.2	81.1	81.1	81.0	80.8	80.5	79.5	77.8	74.5	64.2
1.0	80.9	80.9	80.9	80.8	80.6	80.3	79.2	77.5	74.1	63.6
1.5	80.7	80.7	80.6	80.5	80.4	80.0	79.0	77.2	73.7	62.9
2.0	80.5	80.4	80.4	80.3	80.1	79.8	78.7	76.9	73.3	62.2
3.0	80.0	79.9	79.9	79.8	79.6	79.2	78.1	76.2	72.4	60.7
4.0	79.4	79.4	79.3	79.2	79.0	78.6	77.4	75.4	71.3	59.0
5.0	78.7	78.7	78.7	78.5	78.3	77.9	76.6	74.5	70.2	57.0
6.0	78.0	78.0	77.9	77.8	77.6	77.1	75.7	73.5	68.9	54.9
8.0	76.2	76.2	76.1	75.9	75.7	75.2	73.6	71.0	65.7	49.5
10.0	73.7	73.7	73.6	73.4	73.1	72.5	70.6	67.5	61.3	42.1
12.0	70.2	70.1	70.0	69.8	69.4	68.6	66.4	62.6	54.9	31.4
14.0	64.5	64.4	64.3	64.0	63.5	62.5	59.6	54.7	44.8	14.5

TEMPERATURE = 600°F (316°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	79.3	79.3	79.2	79.2	79.0	78.7	77.7	76.1	72.8	62.8
0.5	79.1	79.0	79.0	78.9	78.7	78.4	77.4	75.7	72.4	62.1
1.0	78.8	78.8	78.7	78.6	78.5	78.1	77.1	75.4	72.0	61.4
1.5	78.5	78.5	78.5	78.3	78.2	77.8	76.8	75.0	71.5	60.7
2.0	78.2	78.2	78.2	78.1	77.9	77.5	76.4	74.7	71.0	60.0
3.0	77.6	77.6	77.5	77.4	77.2	76.8	75.7	73.8	70.0	58.3
4.0	76.9	76.9	76.8	76.7	76.5	76.1	74.9	72.9	68.8	56.5
5.0	76.1	76.1	76.0	75.9	75.7	75.3	74.0	71.8	67.5	54.4
6.0	75.2	75.2	75.1	75.0	74.8	74.3	72.9	70.7	66.1	52.0
8.0	73.0	72.9	72.9	72.7	72.5	71.9	70.4	67.7	62.4	46.2
10.0	70.0	69.9	69.8	69.6	69.3	68.7	66.9	63.7	57.5	38.3
12.0	65.6	65.5	65.4	65.2	64.8	64.0	61.8	58.0	50.3	26.8
14.0	58.6	58.5	58.4	58.1	57.6	56.7	53.7	48.8	38.9	8.6

% COMBUSTION EFFICIENCY—NATURAL GAS

TEMPERATURE = 700°F (371°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	77.3	77.2	77.2	77.1	76.9	76.6	75.6	74.0	70.7	60.7
0.5	77.0	76.9	76.9	76.8	76.6	76.3	75.3	73.6	70.3	60.0
1.0	76.7	76.6	76.6	76.5	76.3	76.0	75.0	73.2	69.8	59.3
1.5	76.3	76.3	76.3	76.2	76.0	75.6	74.6	72.8	69.3	58.5
2.0	76.0	75.9	75.9	75.8	75.6	75.3	74.2	72.4	68.8	57.7
3.0	75.2	75.2	75.2	75.0	74.9	74.5	73.3	71.4	67.6	55.9
4.0	74.4	74.4	74.3	74.2	74.0	73.6	72.4	70.4	66.3	53.9
5.0	73.5	73.4	73.4	73.2	73.0	72.6	71.3	69.2	64.9	51.7
6.0	72.4	72.3	72.3	72.2	71.9	71.5	70.1	67.8	63.3	49.2
8.0	69.8	69.7	69.7	69.5	69.2	68.7	67.1	64.5	59.2	43.0
10.0	66.2	66.1	66.0	65.9	65.6	64.9	63.1	60.0	53.7	34.5
12.0	61.0	60.9	60.8	60.6	60.2	59.4	57.2	53.4	45.7	22.1
14.0	52.7	52.6	52.5	52.2	51.8	50.8	47.8	42.9	33.0	2.6

TEMPERATURE = 800°F (427°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	75.2	75.2	75.1	75.0	74.9	74.6	73.6	72.0	68.7	58.6
0.5	74.9	74.8	74.8	74.7	74.5	74.2	73.2	71.5	68.2	57.9
1.0	74.5	74.5	74.4	74.3	74.2	73.8	72.8	71.1	67.6	57.1
1.5	74.1	74.1	74.0	73.9	73.8	73.4	72.4	70.6	67.1	56.3
2.0	73.7	73.7	73.6	73.5	73.4	73.0	71.9	70.1	66.5	55.4
3.0	72.9	72.8	72.8	72.7	72.5	72.1	71.0	69.1	65.2	53.5
4.0	71.9	71.9	71.8	71.7	71.5	71.1	69.9	67.9	63.8	51.4
5.0	70.8	70.8	70.7	70.6	70.4	70.0	68.7	66.5	62.2	49.1
6.0	69.6	69.5	69.5	69.3	69.1	68.7	67.3	65.0	60.4	46.4
8.0	66.5	66.5	66.4	66.3	66.0	65.5	63.9	61.3	56.0	39.7
10.0	62.4	62.3	62.3	62.1	61.8	61.1	59.3	56.2	49.9	30.6
12.0	56.4	56.3	56.2	56.0	55.6	54.8	52.6	48.7	41.0	17.5
14.0	46.8	46.7	46.6	46.4	45.9	44.9	41.9	37.0	27.1	0.0

TEMPERATURE = 900°F (482°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	73.1	73.1	73.1	73.0	72.8	72.5	71.5	69.9	66.6	56.6
0.5	72.7	72.7	72.7	72.6	72.4	72.1	71.1	69.4	66.1	55.8
1.0	72.3	72.3	72.3	72.2	72.0	71.7	70.6	68.9	65.5	54.9
1.5	71.9	71.9	71.8	71.7	71.6	71.2	70.2	68.4	64.9	54.1
2.0	71.5	71.4	71.4	71.3	71.1	70.7	69.7	67.9	64.2	53.1
3.0	70.5	70.4	70.4	70.3	70.1	69.7	68.6	66.7	62.9	51.1
4.0	69.4	69.3	69.3	69.2	69.0	68.6	67.4	65.4	61.3	48.9
5.0	68.1	68.1	68.1	67.9	67.7	67.3	66.0	63.9	59.6	46.4
6.0	66.7	66.7	66.7	66.5	66.3	65.8	64.5	62.2	57.6	43.5
8.0	63.3	63.2	63.2	63.0	62.8	62.2	60.7	58.0	52.7	36.5
10.0	58.6	58.5	58.5	58.3	58.0	57.3	55.5	52.4	46.1	26.8
12.0	51.7	51.7	51.6	51.4	51.0	50.2	47.9	44.1	36.4	12.8
14.0	40.9	40.8	40.7	40.5	40.0	39.0	36.0	31.1	21.2	0.0

TEMPERATURE = 1000°F (538°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	71.1	71.0	71.0	70.9	70.7	70.4	69.4	67.8	64.5	54.5
0.5	70.6	70.6	70.6	70.5	70.3	70.0	69.0	67.3	63.9	53.6
1.0	70.2	70.1	70.1	70.0	69.8	69.5	68.5	66.8	63.3	52.8
1.5	69.7	69.6	69.6	69.5	69.3	69.0	67.9	66.2	62.6	51.8
2.0	69.2	69.1	69.1	69.0	68.8	68.5	67.4	65.6	62.0	50.8
3.0	68.1	68.0	68.0	67.9	67.7	67.3	66.2	64.3	60.5	48.7
4.0	66.9	66.8	66.8	66.7	66.5	66.1	64.8	62.8	58.8	46.4
5.0	65.5	65.4	65.4	65.3	65.0	64.6	63.3	61.2	56.9	43.7
6.0	63.9	63.9	63.8	63.7	63.5	63.0	61.6	59.3	54.7	40.7
8.0	60.0	60.0	59.9	59.8	59.5	59.0	57.4	54.8	49.5	33.2
10.0	54.8	54.7	54.6	54.5	54.1	53.5	51.7	48.5	42.2	23.0
12.0	47.1	47.0	47.0	46.7	46.4	45.6	43.3	39.5	31.8	8.2
14.0	35.0	34.9	34.8	34.5	34.1	33.1	30.1	25.2	15.3	0.0

% COMBUSTION EFFICIENCY—NO. 2 OIL

TEMPERATURE = 300°F (149°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	89.7	89.7	89.7	89.6	89.4	89.1	88.2	86.7	83.5	74.0
0.5	89.6	89.6	89.6	89.5	89.3	89.0	88.1	86.5	83.3	73.5
1.0	89.5	89.5	89.5	89.4	89.2	88.9	87.9	86.3	83.0	73.0
1.5	89.4	89.4	89.3	89.2	89.1	88.7	87.7	86.1	82.7	72.4
2.0	89.3	89.3	89.2	89.1	88.9	88.6	87.6	85.9	82.4	71.9
3.0	89.0	89.0	88.9	88.8	88.7	88.3	87.2	85.4	81.8	70.6
4.0	88.7	88.7	88.6	88.5	88.3	88.0	86.8	84.9	81.0	69.2
5.0	88.4	88.3	88.3	88.2	88.0	87.6	86.4	84.3	80.2	67.7
6.0	88.0	88.0	87.9	87.8	87.6	87.1	85.8	83.7	79.3	65.9
8.0	87.1	87.0	87.0	86.8	86.6	86.1	84.6	82.1	77.0	61.6
10.0	85.8	85.7	85.7	85.5	85.2	84.6	82.9	79.9	73.9	55.7
12.0	84.0	83.9	83.8	83.6	83.2	82.5	80.4	76.7	69.5	47.1
14.0	81.1	81.0	80.9	80.6	80.1	79.2	76.4	71.8	62.4	33.7

TEMPERATURE = 400°F (204°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	87.8	87.8	87.7	87.6	87.5	87.2	86.2	84.7	81.6	72.0
0.5	87.6	87.6	87.6	87.5	87.3	87.0	86.1	84.5	81.3	71.5
1.0	87.5	87.4	87.4	87.3	87.2	86.8	85.9	84.2	81.0	70.9
1.5	87.3	87.3	87.3	87.2	87.0	86.7	85.7	84.0	80.6	70.3
2.0	87.1	87.1	87.1	87.0	86.8	86.5	85.4	83.7	80.3	69.7
3.0	86.8	86.7	86.7	86.6	86.4	86.0	85.0	83.2	79.5	68.4
4.0	86.3	86.3	86.3	86.2	86.0	85.6	84.4	82.5	78.7	66.9
5.0	85.9	85.8	85.8	85.7	85.5	85.1	83.8	81.8	77.7	65.2
6.0	85.3	85.3	85.2	85.1	84.9	84.5	83.2	81.0	76.6	63.2
8.0	84.0	84.0	83.9	83.8	83.5	83.0	81.5	79.0	74.0	58.5
10.0	82.2	82.1	82.1	81.9	81.6	81.0	79.3	76.3	70.3	52.1
12.0	79.6	79.5	79.4	79.2	78.9	78.2	76.0	72.4	65.1	42.8
14.0	75.5	75.4	75.3	75.0	74.6	73.6	70.9	66.2	56.8	28.1

TEMPERATURE = 500°F (260°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	85.8	85.8	85.8	85.7	85.5	85.2	84.3	82.7	79.6	70.0
0.5	85.6	85.6	85.6	85.5	85.3	85.0	84.1	82.5	79.3	69.5
1.0	85.4	85.4	85.4	85.3	85.1	84.8	83.8	82.2	78.9	68.9
1.5	85.2	85.2	85.2	85.1	84.9	84.6	83.6	81.9	78.5	68.2
2.0	85.0	85.0	84.9	84.8	84.7	84.3	83.3	81.6	78.1	67.5
3.0	84.5	84.5	84.4	84.3	84.2	83.8	82.7	80.9	77.3	66.1
4.0	84.0	83.9	83.9	83.8	83.6	83.2	82.1	80.1	76.3	64.5
5.0	83.3	83.3	83.3	83.1	82.9	82.5	81.3	79.3	75.2	62.6
6.0	82.7	82.6	82.6	82.4	82.2	81.8	80.5	78.3	73.9	60.5
8.0	80.9	80.9	80.8	80.7	80.4	79.9	78.4	75.9	70.9	55.4
10.0	78.6	78.5	78.5	78.3	78.0	77.4	75.7	72.7	66.7	48.4
12.0	75.2	75.2	75.1	74.9	74.5	73.8	71.6	68.0	60.7	38.4
14.0	69.9	69.8	69.7	69.4	69.0	68.1	65.3	60.6	51.2	22.5

TEMPERATURE = 600°F (316°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	83.9	83.8	83.8	83.7	83.6	83.3	82.3	80.8	77.7	68.1
0.5	83.6	83.6	83.6	83.5	83.3	83.0	82.1	80.5	77.3	67.4
1.0	83.4	83.4	83.3	83.2	83.1	82.7	81.8	80.1	76.9	66.8
1.5	83.1	83.1	83.1	83.0	82.8	82.5	81.5	79.8	76.4	66.1
2.0	82.9	82.8	82.8	82.7	82.5	82.2	81.1	79.4	76.0	65.4
3.0	82.3	82.2	82.2	82.1	81.9	81.5	80.4	78.6	75.0	63.8
4.0	81.6	81.5	81.5	81.4	81.2	80.8	79.7	77.8	73.9	62.1
5.0	80.8	80.8	80.7	80.6	80.4	80.0	78.8	76.8	72.7	60.1
6.0	80.0	79.9	79.9	79.8	79.5	79.1	77.8	75.6	71.3	57.8
8.0	77.9	77.8	77.8	77.6	77.4	76.9	75.4	72.9	67.8	52.3
10.0	75.0	74.9	74.9	74.7	74.4	73.8	72.0	69.1	63.1	44.8
12.0	70.9	70.8	70.7	70.5	70.1	69.4	67.2	63.6	56.3	33.9
14.0	64.3	64.2	64.2	63.9	63.4	62.5	59.7	55.0	45.6	16.9

% COMBUSTION EFFICIENCY—NO. 2 OIL

TEMPERATURE = 700°F (371°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	81.9	81.9	81.9	81.8	81.6	81.3	80.4	78.8	75.7	66.1
0.5	81.6	81.6	81.6	81.5	81.3	81.0	80.1	78.5	75.3	65.4
1.0	81.3	81.3	81.3	81.2	81.0	80.7	79.7	78.1	74.8	64.7
1.5	81.0	81.0	81.0	80.9	80.7	80.4	79.4	77.7	74.3	64.0
2.0	80.7	80.7	80.6	80.5	80.4	80.0	79.0	77.3	73.8	63.2
3.0	80.0	80.0	79.9	79.8	79.6	79.3	78.2	76.4	72.7	61.5
4.0	79.2	79.2	79.1	79.0	78.8	78.4	77.3	75.4	71.5	59.7
5.0	78.3	78.3	78.2	78.1	77.9	77.5	76.3	74.2	70.1	57.5
6.0	77.3	77.2	77.2	77.1	76.9	76.4	75.1	72.9	68.6	55.1
8.0	74.8	74.7	74.7	74.5	74.3	73.8	72.3	69.8	64.7	49.2
10.0	71.4	71.3	71.3	71.1	70.8	70.2	68.4	65.5	59.5	41.2
12.0	66.5	66.4	66.3	66.1	65.8	65.0	62.9	59.2	51.9	29.5
14.0	58.8	58.7	58.6	58.3	57.8	56.9	54.1	49.4	40.0	11.3

TEMPERATURE = 800°F (427°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	80.0	79.9	79.9	79.8	79.6	79.3	78.4	76.9	73.7	64.1
0.5	79.6	79.6	79.6	79.5	79.3	79.0	78.0	76.4	73.2	63.4
1.0	79.3	79.3	79.2	79.1	79.0	78.6	77.7	76.0	72.7	62.7
1.5	78.9	78.9	78.9	78.8	78.6	78.3	77.3	75.6	72.2	61.9
2.0	78.5	78.5	78.5	78.4	78.2	77.9	76.8	75.1	71.7	61.0
3.0	77.7	77.7	77.7	77.5	77.4	77.0	75.9	74.1	70.4	59.3
4.0	76.8	76.8	76.7	76.6	76.4	76.0	74.9	73.0	69.1	57.2
5.0	75.8	75.7	75.7	75.6	75.4	75.0	73.7	71.7	67.6	55.0
6.0	74.6	74.6	74.5	74.4	74.2	73.7	72.4	70.3	65.9	52.4
8.0	71.7	71.7	71.6	71.5	71.2	70.7	69.2	66.7	61.6	46.1
10.0	67.8	67.7	67.7	67.5	67.2	66.6	64.8	61.9	55.9	37.5
12.0	62.1	62.0	62.0	61.7	61.4	60.7	58.5	54.9	47.5	25.1
14.0	53.2	53.1	53.0	52.7	52.2	51.3	48.5	43.9	34.4	5.6

TEMPERATURE = 900°F (482°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	78.0	78.0	77.9	77.8	77.7	77.4	76.4	74.9	71.7	62.1
0.5	77.6	77.6	77.6	77.5	77.3	77.0	76.0	74.4	71.2	61.4
1.0	77.2	77.2	77.2	77.1	76.9	76.6	75.6	74.0	70.7	60.6
1.5	76.8	76.8	76.8	76.7	76.5	76.2	75.1	73.5	70.1	59.8
2.0	76.4	76.4	76.3	76.2	76.0	75.7	74.7	73.0	69.5	58.9
3.0	75.5	75.4	75.4	75.3	75.1	74.7	73.6	71.8	68.2	57.0
4.0	74.4	74.4	74.3	74.2	74.0	73.6	72.5	70.6	66.7	54.8
5.0	73.2	73.2	73.2	73.0	72.8	72.4	71.2	69.2	65.0	52.4
6.0	71.9	71.9	71.8	71.7	71.5	71.0	69.7	67.6	63.2	49.7
8.0	68.6	68.6	68.5	68.4	68.1	67.6	66.1	63.6	58.6	43.0
10.0	64.2	64.1	64.1	63.9	63.6	63.0	61.2	58.2	52.3	33.9
12.0	57.7	57.7	57.6	57.4	57.0	56.3	54.1	50.5	43.2	20.7
14.0	47.6	47.5	47.4	47.1	46.7	45.7	42.9	38.3	28.8	0.0

TEMPERATURE = 1000°F (538°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	76.0	76.0	75.9	75.9	75.7	75.4	74.5	72.9	69.8	60.2
0.5	75.6	75.6	75.5	75.4	75.3	75.0	74.0	72.4	69.2	59.4
1.0	75.2	75.1	75.1	75.0	74.8	74.5	73.5	71.9	68.6	58.5
1.5	74.7	74.7	74.6	74.5	74.4	74.0	73.0	71.4	68.0	57.6
2.0	74.2	74.2	74.2	74.1	73.9	73.5	72.5	70.8	67.3	56.7
3.0	73.2	73.1	73.1	73.0	72.8	72.5	71.4	69.6	65.9	54.7
4.0	72.0	72.0	71.9	71.8	71.6	71.2	70.1	68.2	64.3	52.4
5.0	70.7	70.7	70.6	70.5	70.3	69.9	68.7	66.6	62.5	49.9
6.0	69.2	69.2	69.1	69.0	68.8	68.3	67.0	64.9	60.5	47.0
8.0	65.6	65.5	65.5	65.3	65.1	64.6	63.0	60.5	55.5	39.9
10.0	60.6	60.5	60.4	60.3	60.0	59.4	57.6	54.6	48.6	30.3
12.0	53.3	53.3	53.2	53.0	52.6	51.9	49.7	46.1	38.8	16.3
14.0	42.0	41.9	41.8	41.5	41.1	40.1	37.3	32.7	23.2	0.0

% COMBUSTION EFFICIENCY—NO. 6 OIL

TEMPERATURE = 300°F (149°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	90.4	90.4	90.3	90.2	90.1	89.8	88.8	87.3	84.1	74.4
0.5	90.3	90.3	90.2	90.1	90.0	89.6	88.7	87.1	83.8	73.9
1.0	90.2	90.1	90.1	90.0	89.8	89.5	88.5	86.9	83.6	73.4
1.5	90.1	90.0	90.0	89.9	89.7	89.4	88.4	86.7	83.3	72.9
2.0	89.9	89.9	89.9	89.8	89.6	89.2	88.2	86.5	83.0	72.3
3.0	89.7	89.6	89.6	89.5	89.3	88.9	87.8	86.0	82.3	71.1
4.0	89.4	89.3	89.3	89.2	89.0	88.6	87.4	85.5	81.6	69.7
5.0	89.0	89.0	88.9	88.8	88.6	88.2	87.0	84.9	80.8	68.1
6.0	88.6	88.6	88.5	88.4	88.2	87.8	86.5	84.3	79.8	66.3
8.0	87.7	87.6	87.6	87.4	87.2	86.7	85.2	82.6	77.5	61.9
10.0	86.4	86.3	86.3	86.1	85.8	85.2	83.4	80.4	74.4	55.9
12.0	84.5	84.5	84.4	84.2	83.8	83.1	80.9	77.2	69.9	47.3
14.0	81.6	81.5	81.4	81.1	80.7	79.7	76.9	72.2	62.7	33.7

TEMPERATURE = 400°F (204°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	88.4	88.4	88.4	88.3	88.1	87.8	86.9	85.3	82.1	72.5
0.5	88.3	88.2	88.2	88.1	87.9	87.6	86.7	85.1	81.8	71.9
1.0	88.1	88.1	88.0	87.9	87.8	87.5	86.5	84.8	81.5	71.3
1.5	87.9	87.9	87.9	87.8	87.6	87.3	86.3	84.6	81.2	70.7
2.0	87.8	87.7	87.7	87.6	87.4	87.1	86.0	84.3	80.8	70.1
3.0	87.4	87.3	87.3	87.2	87.0	86.7	85.6	83.7	80.0	68.8
4.0	87.0	86.9	86.9	86.8	86.6	86.2	85.0	83.1	79.2	67.2
5.0	86.5	86.4	86.4	86.3	86.1	85.7	84.4	82.4	78.2	65.5
6.0	85.9	85.9	85.8	85.7	85.5	85.1	83.7	81.5	77.1	63.6
8.0	84.6	84.5	84.5	84.3	84.1	83.6	82.1	79.5	74.4	58.8
10.0	82.8	82.7	82.6	82.5	82.2	81.6	79.8	76.8	70.8	52.3
12.0	80.1	80.0	80.0	79.8	79.4	78.7	76.5	72.8	65.4	42.8
14.0	76.0	75.9	75.8	75.5	75.0	74.1	71.3	66.6	57.1	28.0

TEMPERATURE = 500°F (260°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	86.4	86.4	86.4	86.3	86.1	85.8	84.9	83.3	80.1	70.5
0.5	86.2	86.2	86.2	86.1	85.9	85.6	84.6	83.0	79.8	69.9
1.0	86.0	86.0	86.0	85.9	85.7	85.4	84.4	82.8	79.4	69.3
1.5	85.8	85.8	85.8	85.7	85.5	85.2	84.1	82.4	79.0	68.6
2.0	85.6	85.6	85.5	85.4	85.2	84.9	83.9	82.1	78.6	67.9
3.0	85.1	85.1	85.0	84.9	84.7	84.4	83.3	81.4	77.8	66.5
4.0	84.5	84.5	84.5	84.4	84.2	83.8	82.6	80.7	76.8	64.8
5.0	83.9	83.9	83.8	83.7	83.5	83.1	81.9	79.8	75.7	63.0
6.0	83.2	83.2	83.1	83.0	82.8	82.3	81.0	78.8	74.4	60.8
8.0	81.5	81.4	81.4	81.2	81.0	80.5	79.0	76.4	71.3	55.7
10.0	79.1	79.1	79.0	78.8	78.5	77.9	76.1	73.1	67.1	48.6
12.0	75.7	75.6	75.6	75.3	75.0	74.2	72.1	68.4	61.0	38.4
14.0	70.3	70.2	70.1	69.9	69.4	68.5	65.6	60.9	51.4	22.3

TEMPERATURE = 600°F (316°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	84.5	84.4	84.4	84.3	84.2	83.8	82.9	81.3	78.2	68.5
0.5	84.2	84.2	84.2	84.1	83.9	83.6	82.6	81.0	77.8	67.8
1.0	84.0	83.9	83.9	83.8	83.6	83.3	82.3	80.7	77.4	67.2
1.5	83.7	83.7	83.6	83.5	83.4	83.0	82.0	80.3	76.9	66.5
2.0	83.4	83.4	83.4	83.3	83.1	82.7	81.7	80.0	76.5	65.7
3.0	82.8	82.8	82.7	82.6	82.5	82.1	81.0	79.2	75.5	64.2
4.0	82.1	82.1	82.1	81.9	81.8	81.4	80.2	78.3	74.4	62.4
5.0	81.4	81.3	81.3	81.2	81.0	80.6	79.3	77.3	73.1	60.4
6.0	80.5	80.5	80.4	80.3	80.1	79.6	78.3	76.1	71.7	58.1
8.0	78.4	78.3	78.3	78.1	77.9	77.4	75.9	73.3	68.2	52.5
10.0	75.5	75.4	75.4	75.2	74.9	74.3	72.5	69.5	63.4	44.9
12.0	71.3	71.2	71.1	70.9	70.6	69.8	67.6	64.0	56.6	33.9
14.0	64.7	64.6	64.5	64.2	63.8	62.8	60.0	55.3	45.8	16.7

% COMBUSTION EFFICIENCY—NO. 6 OIL

TEMPERATURE = 700°F (371°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	82.5	82.4	82.4	82.3	82.2	81.9	80.9	79.3	76.2	66.5
0.5	82.2	82.2	82.1	82.0	81.9	81.6	80.6	79.0	75.7	65.8
1.0	81.9	81.9	81.8	81.7	81.6	81.2	80.3	78.6	75.3	65.1
1.5	81.6	81.5	81.5	81.4	81.2	80.9	79.9	78.2	74.8	64.3
2.0	81.2	81.2	81.2	81.1	80.9	80.6	79.5	77.8	74.3	63.6
3.0	80.5	80.5	80.5	80.3	80.2	79.8	78.7	76.9	73.2	61.9
4.0	79.7	79.7	79.6	79.5	79.3	79.0	77.8	75.9	71.9	60.0
5.0	78.8	78.8	78.7	78.6	78.4	78.0	76.8	74.7	70.5	57.8
6.0	77.8	77.8	77.7	77.6	77.4	76.9	75.6	73.4	69.0	55.4
8.0	75.3	75.2	75.2	75.0	74.8	74.3	72.7	70.2	65.1	49.4
10.0	71.8	71.8	71.7	71.5	71.2	70.6	68.8	65.8	59.8	41.3
12.0	66.9	66.8	66.7	66.5	66.1	65.4	63.2	59.5	52.1	29.5
14.0	59.0	59.0	58.9	58.6	58.1	57.2	54.3	49.6	40.1	11.0

TEMPERATURE = 800°F (427°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	80.5	80.5	80.4	80.3	80.2	79.9	78.9	77.4	74.2	64.5
0.5	80.2	80.1	80.1	80.0	79.8	79.5	78.6	76.9	73.7	63.8
1.0	79.8	79.8	79.8	79.7	79.5	79.2	78.2	76.5	73.2	63.0
1.5	79.5	79.4	79.4	79.3	79.1	78.8	77.8	76.1	72.7	62.2
2.0	79.1	79.0	79.0	78.9	78.7	78.4	77.3	75.6	72.1	61.4
3.0	78.2	78.2	78.2	78.1	77.9	77.5	76.4	74.6	70.9	59.5
4.0	77.3	77.3	77.2	77.1	76.9	76.5	75.4	73.4	69.5	57.5
5.0	76.3	76.2	76.2	76.1	75.9	75.4	74.2	72.1	68.0	55.2
6.0	75.1	75.0	75.0	74.9	74.6	74.2	72.9	70.7	66.2	52.6
8.0	72.2	72.1	72.1	71.9	71.7	71.2	69.6	67.1	62.0	46.3
10.0	68.2	68.1	68.1	67.9	67.6	67.0	65.2	62.2	56.1	37.6
12.0	62.4	62.4	62.3	62.1	61.7	61.0	58.8	55.1	47.7	25.0
14.0	53.4	53.3	53.2	52.9	52.5	51.5	48.7	44.0	34.4	5.3

TEMPERATURE = 900°F (482°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	78.5	78.5	78.4	78.3	78.2	77.9	76.9	75.4	72.2	62.5
0.5	78.1	78.1	78.1	78.0	77.8	77.5	76.5	74.9	71.7	61.7
1.0	77.7	77.7	77.7	77.6	77.4	77.1	76.1	74.4	71.1	60.9
1.5	77.3	77.3	77.3	77.2	77.0	76.7	75.6	73.9	70.5	60.1
2.0	76.9	76.9	76.8	76.7	76.5	76.2	75.2	73.4	69.9	59.2
3.0	75.9	75.9	75.9	75.8	75.6	75.2	74.1	72.3	68.6	57.2
4.0	74.9	74.9	74.8	74.7	74.5	74.1	73.0	71.0	67.1	55.1
5.0	73.7	73.7	73.6	73.5	73.3	72.9	71.6	69.6	65.4	52.7
6.0	72.4	72.3	72.3	72.1	71.9	71.5	70.2	68.0	63.5	49.9
8.0	69.0	69.0	68.9	68.8	68.5	68.0	66.5	64.0	58.8	43.1
10.0	64.5	64.5	64.4	64.2	63.9	63.3	61.5	58.5	52.5	33.9
12.0	58.0	57.9	57.9	57.6	57.3	56.5	54.3	50.7	43.3	20.6
14.0	47.7	47.7	47.6	47.3	46.8	45.9	43.0	38.3	28.8	0.0

TEMPERATURE = 1000°F (538°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	76.5	76.5	76.5	76.4	76.2	75.9	74.9	73.4	70.2	60.5
0.5	76.1	76.1	76.0	75.9	75.8	75.5	74.5	72.9	69.6	59.7
1.0	75.7	75.6	75.6	75.5	75.3	75.0	74.0	72.4	69.0	58.8
1.5	75.2	75.2	75.1	75.0	74.9	74.5	73.5	71.8	68.4	57.9
2.0	74.7	74.7	74.6	74.5	74.4	74.0	73.0	71.2	67.7	57.0
3.0	73.6	73.6	73.6	73.5	73.3	72.9	71.8	70.0	66.3	54.9
4.0	72.5	72.4	72.4	72.3	72.1	71.7	70.5	68.6	64.7	52.6
5.0	71.1	71.1	71.1	70.9	70.7	70.3	69.1	67.0	62.8	50.1
6.0	69.6	69.6	69.5	69.4	69.2	68.8	67.4	65.2	60.8	47.2
8.0	65.9	65.9	65.8	65.7	65.4	64.9	63.4	60.8	55.7	40.0
10.0	60.9	60.8	60.8	60.6	60.3	59.7	57.9	54.9	48.8	30.2
12.0	53.6	53.5	53.4	53.2	52.8	52.1	49.9	46.2	38.8	16.1
14.0	42.1	42.0	41.9	41.6	41.2	40.2	37.4	32.7	23.1	0.0

% COMBUSTION EFFICIENCY—BITUMINOUS COAL

TEMPERATURE = 300°F (149°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	91.2	91.2	91.2	91.1	90.9	90.6	89.6	88.0	84.8	74.9
0.5	91.1	91.1	91.0	90.9	90.8	90.5	89.5	87.8	84.5	74.3
1.0	91.0	91.0	90.9	90.8	90.7	90.3	89.3	87.6	84.2	73.8
1.5	90.9	90.8	90.8	90.7	90.5	90.2	89.1	87.4	83.9	73.3
2.0	90.7	90.7	90.7	90.6	90.4	90.0	89.0	87.2	83.6	72.7
3.0	90.5	90.4	90.4	90.3	90.1	89.7	88.6	86.7	82.9	71.4
4.0	90.2	90.1	90.1	90.0	89.8	89.4	88.2	86.2	82.2	69.9
5.0	89.8	89.8	89.7	89.6	89.4	89.0	87.7	85.6	81.3	68.3
6.0	89.4	89.4	89.3	89.2	89.0	88.5	87.2	84.9	80.4	66.5
8.0	88.4	88.4	88.3	88.2	87.9	87.4	85.9	83.3	78.0	62.0
10.0	87.1	87.1	87.0	86.8	86.5	85.9	84.1	81.0	74.8	55.9
12.0	85.2	85.1	85.1	84.8	84.5	83.7	81.5	77.7	70.2	47.0
14.0	82.2	82.1	82.0	81.7	81.2	80.3	77.4	72.6	62.8	33.1

TEMPERATURE = 400°F (204°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	89.2	89.2	89.1	89.0	88.9	88.5	87.6	86.0	82.7	72.8
0.5	89.0	89.0	89.0	88.9	88.7	88.4	87.4	85.7	82.4	72.3
1.0	88.9	88.8	88.8	88.7	88.5	88.2	87.2	85.5	82.1	71.7
1.5	88.7	88.7	88.6	88.5	88.3	88.0	87.0	85.2	81.7	71.1
2.0	88.5	88.5	88.4	88.3	88.2	87.8	86.7	85.0	81.4	70.4
3.0	88.1	88.1	88.0	87.9	87.7	87.4	86.3	84.4	80.6	69.0
4.0	87.7	87.6	87.6	87.5	87.3	86.9	85.7	83.7	79.7	67.5
5.0	87.2	87.1	87.1	87.0	86.8	86.4	85.1	83.0	78.7	65.7
6.0	86.6	86.6	86.5	86.4	86.2	85.7	84.4	82.1	77.6	63.7
8.0	85.3	85.2	85.2	85.0	84.7	84.2	82.7	80.1	74.8	58.8
10.0	83.4	83.3	83.3	83.1	82.8	82.2	80.3	77.3	71.1	52.1
12.0	80.7	80.6	80.5	80.3	79.9	79.2	76.9	73.2	65.6	42.4
14.0	76.4	76.3	76.2	75.9	75.5	74.5	71.6	66.8	57.0	27.2

TEMPERATURE = 500°F (260°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	87.2	87.1	87.1	87.0	86.8	86.5	85.6	83.9	80.7	70.8
0.5	87.0	86.9	86.9	86.8	86.6	86.3	85.3	83.7	80.3	70.2
1.0	86.7	86.7	86.7	86.6	86.4	86.1	85.1	83.4	80.0	69.5
1.5	86.5	86.5	86.4	86.3	86.2	85.8	84.8	83.1	79.6	68.9
2.0	86.3	86.2	86.2	86.1	85.9	85.6	84.5	82.7	79.1	68.2
3.0	85.8	85.7	85.7	85.6	85.4	85.0	83.9	82.0	78.2	66.7
4.0	85.2	85.2	85.1	85.0	84.8	84.4	83.2	81.2	77.2	65.0
5.0	84.6	84.5	84.5	84.4	84.2	83.7	82.5	80.4	76.1	63.1
6.0	83.8	83.8	83.8	83.6	83.4	83.0	81.6	79.4	74.8	60.9
8.0	82.1	82.0	82.0	81.8	81.6	81.0	79.5	76.9	71.6	55.6
10.0	79.6	79.6	79.5	79.3	79.0	78.4	76.6	73.5	67.3	48.3
12.0	76.1	76.1	76.0	75.8	75.4	74.6	72.4	68.6	61.1	37.9
14.0	70.6	70.5	70.4	70.1	69.7	68.7	65.8	61.0	51.2	21.4

TEMPERATURE = 600°F (316°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	85.1	85.1	85.1	85.0	84.8	84.5	83.5	81.9	78.7	68.7
0.5	84.9	84.8	84.8	84.7	84.5	84.2	83.2	81.6	78.3	68.1
1.0	84.6	84.6	84.5	84.4	84.3	83.9	82.9	81.2	77.8	67.4
1.5	84.3	84.3	84.3	84.2	84.0	83.6	82.6	80.9	77.4	66.7
2.0	84.1	84.0	84.0	83.9	83.7	83.3	82.3	80.5	76.9	65.9
3.0	83.4	83.4	83.4	83.2	83.1	82.7	81.6	79.7	75.9	64.3
4.0	82.7	82.7	82.7	82.5	82.3	81.9	80.8	78.8	74.8	62.5
5.0	82.0	81.9	81.9	81.7	81.5	81.1	79.8	77.7	73.5	60.4
6.0	81.1	81.0	81.0	80.8	80.6	80.2	78.8	76.6	72.0	58.1
8.0	78.9	78.8	78.8	78.6	78.4	77.8	76.3	73.7	68.4	52.4
10.0	75.9	75.8	75.8	75.6	75.3	74.7	72.8	69.8	63.6	44.6
12.0	71.6	71.5	71.5	71.2	70.9	70.1	67.9	64.1	56.5	33.3
14.0	64.8	64.7	64.6	64.4	63.9	62.9	60.0	55.2	45.4	15.6

% COMBUSTION EFFICIENCY—BITUMINOUS COAL

TEMPERATURE = 700°F (371°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	83.1	83.1	83.0	82.9	82.8	82.4	81.5	79.9	76.6	66.7
0.5	82.8	82.8	82.7	82.6	82.5	82.1	81.1	79.5	76.2	66.0
1.0	82.5	82.4	82.4	82.3	82.1	81.8	80.8	79.1	75.7	65.2
1.5	82.2	82.1	82.1	82.0	81.8	81.5	80.4	78.7	75.2	64.5
2.0	81.8	81.8	81.7	81.6	81.5	81.1	80.0	78.3	74.7	63.7
3.0	81.1	81.0	81.0	80.9	80.7	80.3	79.2	77.3	73.5	61.9
4.0	80.3	80.2	80.2	80.1	79.9	79.5	78.3	76.3	72.3	60.0
5.0	79.3	79.3	79.2	79.1	78.9	78.5	77.2	75.1	70.8	57.8
6.0	78.3	78.2	78.2	78.1	77.8	77.4	76.0	73.8	69.2	55.3
8.0	75.7	75.6	75.6	75.4	75.2	74.7	73.1	70.5	65.2	49.2
10.0	72.2	72.1	72.0	71.9	71.5	70.9	69.1	66.0	59.8	40.8
12.0	67.1	67.0	66.9	66.7	66.3	65.6	63.3	59.5	52.0	28.7
14.0	59.0	58.9	58.9	58.6	58.1	57.1	54.2	49.4	39.6	9.7

TEMPERATURE = 800°F (427°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	81.0	81.0	81.0	80.9	80.7	80.4	79.4	77.8	74.6	64.6
0.5	80.7	80.7	80.6	80.5	80.4	80.0	79.1	77.4	74.1	63.9
1.0	80.3	80.3	80.3	80.2	80.0	79.7	78.7	77.0	73.6	63.1
1.5	80.0	79.9	79.9	79.8	79.6	79.3	78.2	76.5	73.0	62.3
2.0	79.6	79.5	79.5	79.4	79.2	78.9	77.8	76.0	72.4	61.4
3.0	78.7	78.7	78.7	78.5	78.4	78.0	76.9	75.0	71.2	59.6
4.0	77.8	77.7	77.7	77.6	77.4	77.0	75.8	73.8	69.8	57.5
5.0	76.7	76.7	76.6	76.5	76.3	75.9	74.6	72.5	68.2	55.1
6.0	75.5	75.4	75.4	75.3	75.0	74.6	73.2	71.0	66.4	52.5
8.0	72.5	72.4	72.4	72.2	72.0	71.5	69.9	67.3	62.0	45.9
10.0	68.4	68.4	68.3	68.1	67.8	67.2	65.3	62.3	56.1	37.0
12.0	62.5	62.4	62.4	62.1	61.8	61.0	58.8	55.0	47.4	24.2
14.0	53.2	53.2	53.1	52.8	52.3	51.3	48.4	43.6	33.8	3.9

TEMPERATURE = 900°F (482°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	79.0	79.0	78.9	78.8	78.7	78.4	77.4	75.8	72.5	62.6
0.5	78.6	78.6	78.6	78.5	78.3	78.0	77.0	75.3	72.0	61.8
1.0	78.2	78.2	78.1	78.0	77.9	77.5	76.5	74.8	71.4	60.9
1.5	77.8	77.8	77.7	77.6	77.4	77.1	76.1	74.3	70.8	60.1
2.0	77.3	77.3	77.3	77.2	77.0	76.6	75.6	73.8	70.2	59.2
3.0	76.4	76.3	76.3	76.2	76.0	75.6	74.5	72.6	68.8	57.2
4.0	75.3	75.3	75.2	75.1	74.9	74.5	73.3	71.3	67.3	55.0
5.0	74.1	74.0	74.0	73.9	73.7	73.2	72.0	69.8	65.6	52.5
6.0	72.7	72.7	72.6	72.5	72.2	71.8	70.4	68.2	63.6	49.7
8.0	69.3	69.2	69.2	69.0	68.8	68.3	66.7	64.1	58.8	42.7
10.0	64.7	64.6	64.5	64.4	64.1	63.4	61.6	58.5	52.3	33.3
12.0	58.0	57.9	57.8	57.6	57.2	56.5	54.2	50.4	42.8	19.6
14.0	47.5	47.4	47.3	47.0	46.5	45.5	42.6	37.8	28.0	0.0

TEMPERATURE = 1000°F (538°C)

% Oxygen	PERCENT COMBUSTIBLES IN FLUE GAS									
	0.00	0.01	0.02	0.05	0.10	0.20	0.50	1.00	2.00	5.00
0.0	77.0	76.9	76.9	76.8	76.6	76.3	75.3	73.7	70.5	60.5
0.5	76.5	76.5	76.5	76.4	76.2	75.9	74.9	73.2	69.9	59.7
1.0	76.1	76.0	76.0	75.9	75.7	75.4	74.4	72.7	69.3	58.8
1.5	75.6	75.6	75.5	75.4	75.3	74.9	73.9	72.1	68.6	57.9
2.0	75.1	75.1	75.0	74.9	74.7	74.4	73.3	71.5	67.9	56.9
3.0	74.0	74.0	73.9	73.8	73.6	73.3	72.1	70.3	66.5	54.8
4.0	72.8	72.8	72.7	72.6	72.4	72.0	70.8	68.8	64.8	52.5
5.0	71.4	71.4	71.4	71.2	71.0	70.6	69.3	67.2	62.9	49.8
6.0	69.9	69.9	69.8	69.7	69.4	69.0	67.6	65.4	60.8	46.9
8.0	66.1	66.0	66.0	65.8	65.6	65.1	63.5	60.9	55.6	39.5
10.0	60.9	60.9	60.8	60.6	60.3	59.7	57.8	54.8	48.5	29.5
12.0	53.4	53.4	53.3	53.1	52.7	51.9	49.7	45.9	38.3	15.0
14.0	41.6	41.6	41.5	41.2	40.7	39.7	36.8	32.0	22.2	0.0