Chapter 7

Combustion

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Chapter 7

Combustion

Technicians have an obligation to ensure the equipment they are working on is operating at peak performance levels. Understanding combustion theory is the basis for adjusting burners for safe, clean, reliable and economical operation.

What is Combustion?

By definition, "Combustion is the rapid oxidation of any material that will combine readily with oxygen." In a fuel fired appliance, it is a controlled chemical reaction meaning that ***combustion is more than just a flame*** that is controlled by adding or subtracting air, adjusting fuel unit pressure, moving the firing assembly or changing the nozzle specifications. Combustion is a chemical process that is affected by many environmental conditions and components of the heating appliance and the venting system. A visible flame is the result of many variables. To properly adjust a burner, it is essential to understand both what is seen and unseen in the combustion process.

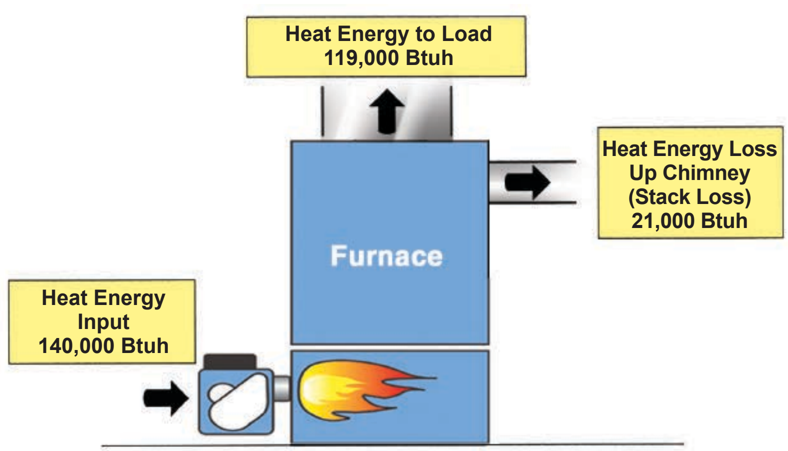
Three things are needed for combustion: **oxygen, heat and fuel**. The oxygen is contained in the air that is delivered by the burner fan. The spark generated by the high voltage ignitor and delivered by the electrodes provides the heat. The nozzle delivers the atomized fuel.

The heat from the spark raises the fuel to its ignition temperature (fire point), the oxygen molecules in the air combine with the fuel in a chemical reaction that produces light and large quantities of heat. As the fuel/air mixture combusts, the heat generated perpetuates the combustion process if adequate fuel and oxygen supplies are available. This is why the ignition can be turned off after flame is established, it is only needed to start the process.

During combustion, new chemical substances are created from the fuel and the air. The primary chemical substances are carbon dioxide (CO_2) and water, as vapor. Additionally, carbon monoxide (CO) is usually created in small amounts. If it is created in high amounts and a leak in the system allows CO to get into the house, it can be lethal. The sole purpose of the burner is to efficiently combine the fuel and oxygen in a manner that will result in safe, clean and complete combustion.

Heat from the combustion gases is extracted by the heat exchanger in the

Figure 7-1: Heat loads, heat loss



Heat to Load = Heat Energy Input - Stack Loss

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appliance for space and/or domestic water heating. Heat energy is measured in BTUs (British Thermal Units). By definition, a BTU is the amount of energy required to raise one pound of water 1ºF—about the amount of energy contained in a flame the size of birthday candle. Each gallon of #2 fuel contains approximately140,000 BTU's. In a typical 86% efficient appliance, every gallon of fuel burned puts about 119,000 BTUs into the appliance and about 21,000 BTUs exit the appliance through the venting system. Figure 7-1, previous page.

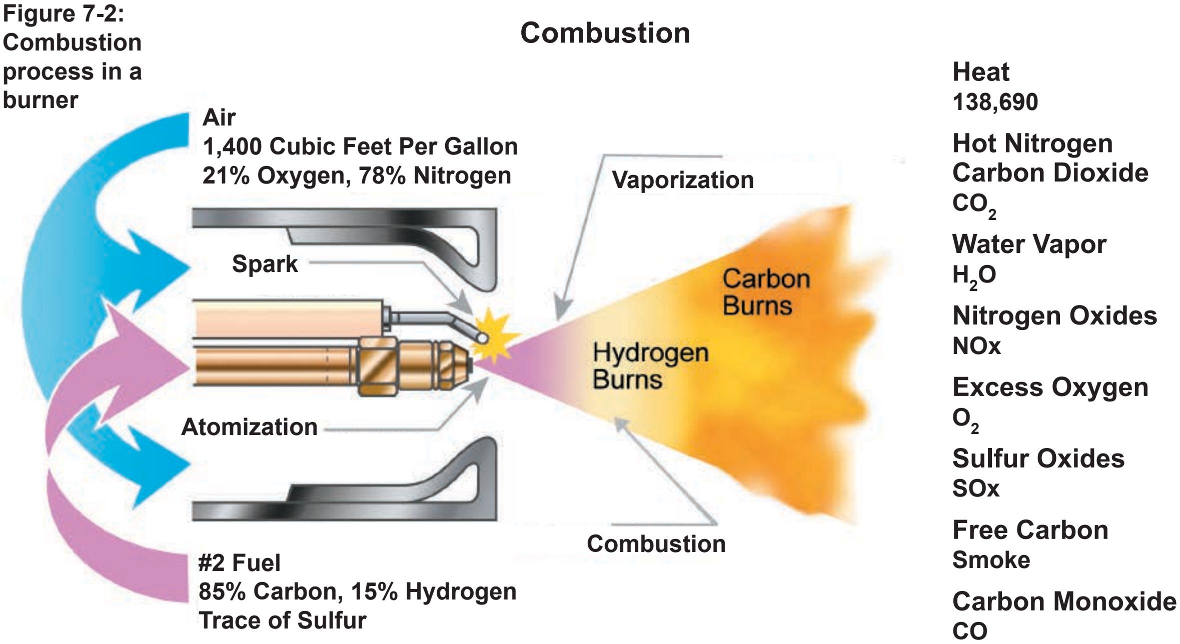
How Does it All Work?

#2 fuel is 85% carbon and 15% hydrogen. Biodiesel contains carbon, hydrogen and oxygen. When #2 fuel or biodiesel burns, the carbon in the fuel combines with the oxygen in the air to make CO_2 and the hydrogen in the fuel combines with the oxygen in the air or fuel to make water. These reactions do not occur with liquid fuel, instead it must first be vaporized before the rapid reaction between the fuel and the oxygen can produce a flame.

Air contains 20.9% oxygen, 78% nitrogen, and 1.1% other gases, Figure 7-2. Most of the oxygen in the air combines with the carbon and hydrogen in the fuel to form CO_2 and H_2O. The nitrogen and the other gases usually go through the combustion process unchanged.

The precise ratio of air to fuel is critical in the combustion process. Too little air leads to incomplete combustion, smoke and elevated CO levels. Too much air will also cause incomplete combustion and elevated CO levels. Too much air also cools the flame temperature and lowers the heat content deliverable by the fuel. It is the function of the burner to properly mix air and fuel, the better the air and the fuel vapor are mixed, the better the combustion. Combustion is a series of exact chemical reactions that create exact quantities of combustion gases. 14.4 pounds of air

Figure 7-2: Combustion process in a burner



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supplies adequate oxygen to burn 1 pound of #2 fuel and produce 15.4 pounds of combustion gases, Figure 7-3.

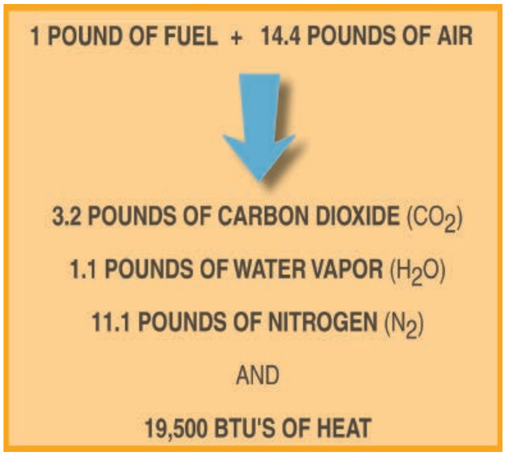


Figure 7-3: #2 fuel combustion

More simply, to burn a gallon of #2 fuel, requires about 1,360 cubic feet of air. This is equal to the air in a room that is 14' x 12' x 8'.

If perfect (stoichiometric) combustion could be achieved, less air would be required. However, in a burner not all of the oxygen in the air combines with the fuel. To ensure all the fuel is burned, extra air must be added to the process. That is why the usual amount of air required is higher than the 1,360 cubic feet.

- Additionally, some excess air is necessary to provide for changes in the system over time, such as air bands and/or burner fans that become clogged with animal hair, lint or dust.
- Varying air temperature can affect the volume of air – warmer air is less dense and provides less oxygen, colder air is denser and provides more oxygen.
- Draft variations can occur that are beyond the barometric damper's ability to compensate.
- Variations in the heating content (BTUs) of fuel delivered – bio-blends, kerosene blends, etc.

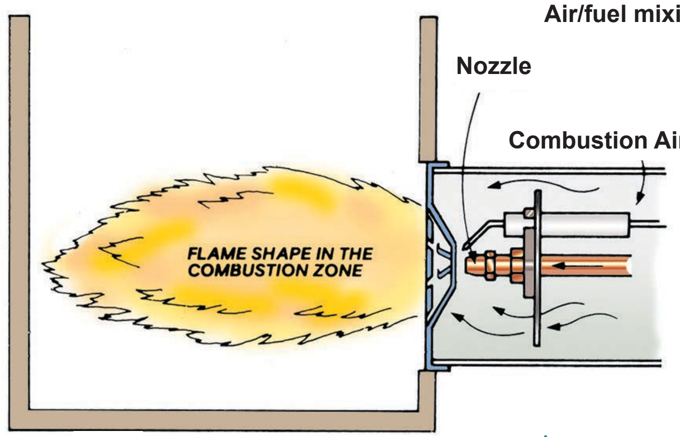
Proper nozzle selection and burner settings are critical for safe and efficient combustion. Improper set up will result in poor operation and additional service. To be safe, always consult the manufacturer's operating and service manual for specific information about the appliance being worked on.

Air/fuel mixing

Several factors control the quality of air-fuel mixing. The spray pattern of the fuel droplets must match the air pattern created by the burner, so that each droplet of fuel that leaves the nozzle mixes with the oxygen in the air. The amount of air required is determined by the quantity of fuel delivered by the nozzle. Figure 7-4

Modern burners use high speed motors (3,450 RPM) to deliver the high static air pressure needed inside the burner air tube to create the air pattern at the end of the tube that is required for clean, efficient combustion. This air pattern is critical and cannot be seen. It is fixed by the burner design and affected by the appliance in which it fires. Thorough testing by manufacturers

Figure 7-4: Air/fuel mixing



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determines which nozzle spray and pattern delivers the best match to the air pattern for the most efficient combustion.

As high pressure air travels across the retention head of the burner, recirculation is created by the drop in pressure in the center of the air swirl. This pressure difference pulls some of air back towards the retention head allowing for most of the combustion to occur just in front of the head. This causes the hottest gases to form close to, and in the center of the flame, adding heat to the fuel droplets coming out of the nozzle to give a clean, stable fire close to the burner head.

Combustion testing and analysis

Combustion testing is one of the most important tasks technicians perform when servicing burners, Figure 7-5. Testing is done to determine the quality of the combustion process and the results are used to analyze, diagnose and make needed adjustments to the burner. This section addresses how to use instruments to measure efficiency, cleanliness and safety of the appliance, plus how testing can pinpoint current and potential problems.

Combustion testing is required by code and provides numerous benefits to both the customer and the service technician including:

- Increasing energy efficiency (fuel savings)
- Lowering environmental emissions
- Reduced maintenance
- Avoiding callbacks
- Limiting liability
- Maintaining equipment warranty
- Providing confidence
- Increased comfort
- Increased safety

It is critical that technicians leave equipment operating in the safest and cleanest way possible. Adjusting the flame by eye is prone to mistakes that could lead to damage to property and endanger the health and lives of people who occupy the building.

**If you're not testing...
You're guessing!**

Figure 7-5: Combustion Analysis

Checking composition & temperature of the flue gases at the breech

Figure 7-6 Combustion Analysis

Checking draft over the fire

Experimenting with "out-of-spec" adjustments can lead to equipment malfunction and severe consequences.

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Principles of combustion testing

Combustion testing includes measuring draft plus the composition and temperature of flue gases as they exit the appliance. This information is used to determine how well the system is operating and to calculate the appliance's combustion efficiency.

Combustion testing is normally performed after a tune-up and any time the technician has serviced combustion related components of the system. For example, a combustion analysis is not usually performed after a component such as a circulator or limit control is replaced. However, one should be completed every time something that affects combustion is worked on for any reason, for example:

- A combustion related component is changed (nozzle, burner motor, fuel unit, filter, retention head, combustion chamber, etc.)
- The fan or air band is cleaned or adjusted
- Fuel pressure is changed
- The chimney or appliance is cleaned

There are three main factors that affect the combustion process: fuel, combustion air and draft

Careful attention must be given to make specific adjustments as recommended by appliance manufacturers. Experimenting with "out-of-spec" adjustments can lead to equipment malfunction and severe consequences. Prior to beginning the test procedure, the burner should be set to the manufacturer's recommended settings including nozzle size, fuel pressure, air band adjustment, etc. Then:

- Perform a brief visual inspection of the combustion chamber/refractory for integrity and make any repairs necessary.
- Check the chamber for cleanliness and remove soot and scale accumulations.
- If there is an inspection port, fire the unit and check for flame impingement. If impingement is found, determine the cause and correct it before proceeding.

Understand that opening the flame inspection port while the burner is operating will allow extra air to affect the flame and invalidate combustion test results. Flame doors are for inspection only, not for adjustment purposes.

Basic combustion testing measurements are:

- Temperature of the flue gases – to determine how well the heat exchanger absorbs heat.
- Draft – to verify that it is set to manufacturer specifications. Draft readings are taken in 2 locations, in the flue and "over the fire".
- Smoke concentrations in the flue gases - to verify that the unit is burning cleanly
- CO_2 in the flue gases – to determine the amount of "excess air" that is provided to the flame.

These measurements singularly measure specific elements of the combustion process, together they will determine efficient or inefficient combustion. Individually, each measurement has a specific range, and those measurements can assist in proper burner set up and diagnosis.

In addition to these basic measurements, electronic analyzers also display oxygen (O_2), excess air and carbon monoxide (CO) concentrations in the flue gases.

Steady state

For accurate test results, measurements should be made after the unit has achieved "steady state." Steady state is the point at

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which the flue gas temperature reaches its highest point and levels off. At steady state there are no changes in the combustion gases. The unit has thoroughly warmed-up and will maintain constant conditions as long as the burner runs. This could require the burner to run for 5 to 10 minutes or longer.

Sample (or test hole) location

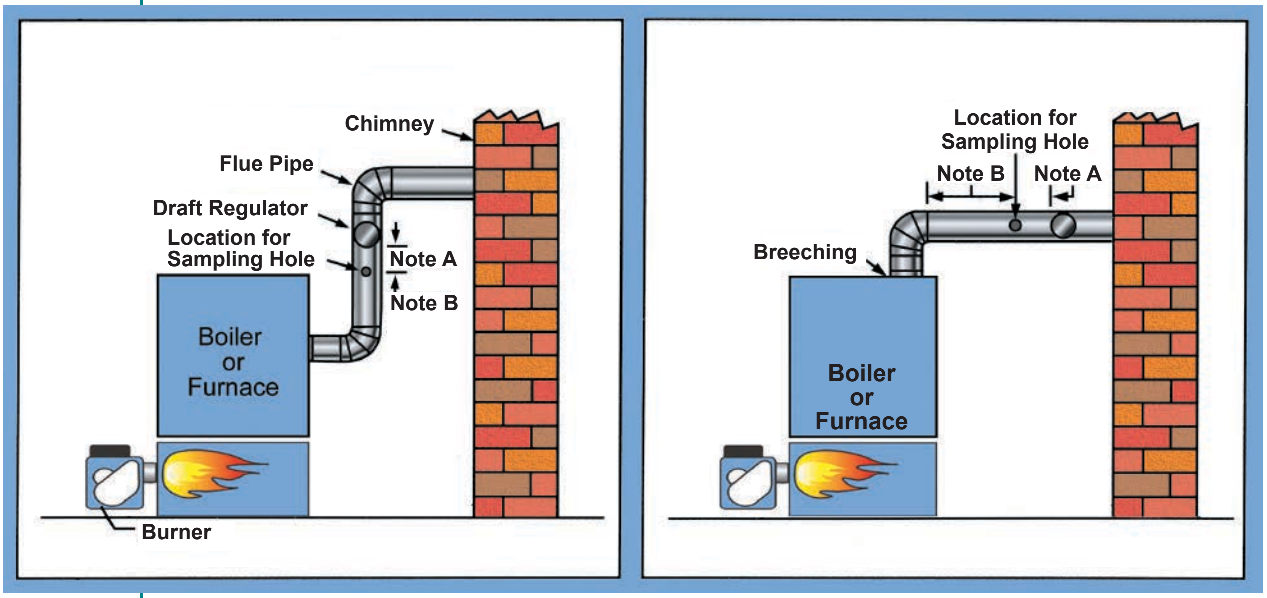
Flue gas measurements are taken through a small hole drilled into the flue pipe near the appliance outlet (the breech), see Figure 7-6. Typically, the sample hole should be in a straight piece of flue pipe between the appliance and the barometric draft regulator, at least 6” away from the regulator. Sealing this hole(s) when the test is completed is optional, but recommended, since it is often requested by the customer.

All measurements should be taken in the “flue gas hot spot”. This is the point in the center of the flue where the temperature and CO_2 are at the highest levels.

There is usually an observation door over the combustion chamber that is used to check over fire draft. Some appliances have a special port for the over-fire test. See Figure 7-7.

Figure 7-7: Over-fire draft measurement

Figure 7-6: Measuring for combustion efficiency



A. Locate hole at least one flue pipe diameter on the furnace or boiler side of draft control.

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Combustion test equipment

Combustion testing equipment can be separated into two groups:

- Manual, known as wet kits (Figure 7-8),
- Continuous sampling digital electronic instruments, known as combustion analyzers (Figure 7-9).

Figure 7-8: Manual instruments

Figure 7-9: Continuous sampling digital electronic instruments

As with any tool, technicians must be familiar with the safe and proper use of the device before proceeding. Always follow manufacturers' guidelines.

Testing with Wet Kits

The procedure for testing and adjusting with a wet kit differs slightly than doing so with a digital-electronic type. To test burners with a wet kit, the following components are needed:

- A draft gauge (Figure 7-10)
- A smoke tester and a smoke scale (Figure 7-11)
- A CO_2 gas analyzer (Figure 7-12)
- A stack thermometer (Figure 7-13)
- A Bacharach “Fire Efficiency Finder” slide rule calculator, or equivalent (Figure 7-14)

When using a wet kit, it’s a good practice to make an additional sample hole in the flue to allow for the stack thermometer to stay in the flue throughout the test.

Figure 7-10: Draft gauge

Step by step procedures for conducting a combustion test with a wet kit

There are two similar, but slightly different, procedures for conducting tests with wet kits, each is shown below. The differences between the two procedures are in smoke and CO_2 testing.

Original procedure:

1. **Stack temperature:** Stack temperature is done first to make sure that the unit has reached “steady state”. Slide the holding clip out to the end of the thermometer stem. Insert the small tab into the top of the sampling hole in the flue and push the thermometer in far enough so the tip is in the center

Figure 7-11: Smoke tester

Figure 7-12: CO_2 tester

Figure 7-13: Stack thermometer

Figure 7-14: Slide rule calculator

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of the flue pipe. Operate the burner until the thermometer reading is rising no faster than 3°F per minute and record the reading. If the stack temperature begins to approach 1,000°F, remove the thermometer and contact your supervisor. Readings above this temperature will damage it.

2. **Draft:** Draft is measured second because the rest of the test results will be affected by any increase or decrease in draft. Insert the draft gauge probe into the flue gas hot spot and measure the "breech draft" reading. Then insert it into the opening at the flame observation door and record the "over the fire draft" reading. Adjust the draft regulator, if necessary, to set the draft to manufacturers specifications, typically -.04 at the breech and -.02 over the fire.

3. **Smoke:** Insert a clean piece of smoke test paper into the tester's slot and tighten the screw. Insert the sampling tube to the flue gas hot spot and slowly pull the tester's handle 10 full pump strokes. Remove the paper and match the color of the resulting smoke stain on the filter paper to the closest shaded spot on the smoke scale.

   Although the goal is to set the burner for zero smoke, if the test shows zero smoke on the first try, do NOT move on to the next step as the air shutter might be adjusted to a position where it was allowing too much combustion air to enter. To properly adjust for zero smoke, first adjust the burner for a trace of smoke (between 0 and 1) and then add slightly more combustion air.

   For example, if the first smoke test showed zero smoke, close the air shutter slightly and test again. Repeat this procedure until a trace of smoke shows on the test paper. Then open the air shutter slightly and test again. It is not uncommon for a technician to perform 3 or more smoke tests before getting the proper air adjustment.

4. **CO_2:** Carbon Dioxide (CO_2) is measured after the draft and smoke tests because adjustments made to correct draft or smoke issues will affect the CO_2 reading.

To use the tester:

- Hold it in the upright position, depress the plunger momentarily and release
- Loosen the locknut at the rear of the scale and slide the scale until the top of the fluid column lines up with the zero line on the scale and then tighten the locknut
- Insert the CO_2 sampling probe into the flue gas hot spot
- Hold the tester in the upright position and place the rubber connector of the sampling assembly over the plunger valve
- Depress the plunger valve firmly and pump a sample by squeezing and releasing the aspirator bulb 18 times
- During the 18th squeeze, with the bulb held deflated, release the connector tip and plunger valve
- Absorb the flue gas sample into the tester by inverting it until fluid drains into top reservoir, then turn upright to drain fluid back into the bottom reservoir. Repeat this step one more time
- Momentarily hold the tester at a 45° angle to allow fluid to drain into the bottom reservoir
- With the tester held upright, permit the fluid in the column to stabilize for a few seconds, then immediately record the percent CO_2 on the scale corresponding to the top of the fluid column

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***Note:** a 5 or 10 second delay in reading may decrease the accuracy of the reading slightly, longer delays may cause a substantial error*

5. **Stack temperature:** Although the temperature was taken during the first step in this process, the burner adjustments made to address draft, smoke and CO_2 issues affect the temperature reading. Record the temperature displayed on the stack thermometer and subtract the combustion air temperature to determine "net stack temperature."
6. **Calculate efficiency:** Use the wet kit's Fire Efficiency Finder with Oil Slider to determine the efficiency by lining up the CO_2 and net stack temperature.

Alternative procedure

The "slightly different" procedure follows the same order but the smoke and CO_2 adjustments differ.

1. **Stack temperature:** Stack temperature is measured first to make sure that the unit has reached "steady state." Slide the holding clip out to the end of the thermometer stem. Insert the small tab into the top of the sampling hole in the flue and push the thermometer in far enough so the tip is in the center of the flue pipe. Operate the burner until the thermometer reading is rising no faster than 3°F per minute and record the reading. If the stack temperature begins to approach 1,000°F, remove the thermometer. Readings above this temperature will damage it.
2. **Draft:** Draft is measured second because the rest of the test results will be affected by any increase or decrease in draft. Insert the draft gauge probe into the flue gas hot spot and measure the "flue draft" reading. Then insert it into the opening at the flame observation door and record the "over the fire draft" reading. Adjust the draft regulator, if necessary, to set the draft to manufacturers specifications, typically -.04 at the breech and -.02 over the fire.
3. **Smoke:** Insert a clean piece of smoke test paper into the tester's slot and tighten the screw. Insert the sampling tube to the flue gas hot spot and slowly pull the tester's handle 10 full pump strokes. Remove the paper and match the color of the resulting smoke stain on the filter paper to the closest shaded spot on the smoke scale.

   Although the goal is to set the burner for zero smoke, if the test shows zero smoke on the first try, then do NOT move on to the next step because the air shutter could be adjusted to a position where it was allowing too much combustion air to enter. ***To properly adjust for zero smoke, first adjust the burner for a trace (between 0 and 1) smoke and move on to the next step. (The initial CO_2 sample will be taken at trace level).***
4. **CO_2:** Carbon Dioxide (CO_2) is measured after draft and smoke tests because adjustments made to correct draft or smoke issues will affect the CO_2 reading. To use the tester:
   - Hold it in the upright position, depress the plunger momentarily and release
   - Loosen the locknut at the rear of the scale and slide the scale until the top of the fluid column lines up with the zero line on the scale and then tighten the locknut
   - Insert the CO_2 sampling probe into the flue gas hot spot
   - Hold the tester in the upright position and place the rubber connector tip of the sampling assembly over the plunger valve
   - Depress the plunger valve firmly and

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23:43

pump a sample by squeezing and releasing the aspirator bulb 18 times

- During the 18th squeeze, with the bulb held deflated, release the connector tip and plunger valve
- Absorb the flue gas sample into the tester by inverting until fluid drains into top reservoir, then turn upright to drain fluid back into bottom reservoir. Repeat this step one more time
- Momentarily hold the tester at a 45° angle to allow fluid to drain into the bottom reservoir
- With the tester held upright permit the fluid in the column to stabilize for a few seconds, then immediately record the percent CO_2 on the scale corresponding to the top of the fluid column. **Note: a 5 or 10 second delay in reading may decrease the accuracy of the reading slightly, longer delays may cause a substantial error**
- Increase combustion air until the CO_2 is 1% to 1.5% lower than recorded AND make sure that it is lowered to 12.5% or less to assure safe carbon monoxide (CO) levels.
  Example: If the trace level recorded is 12.5%, increase air to lower the CO2 between 1% - 1.5% so it is 11% – 11.5%.
- *If the CO_2 recorded is 14.5%, increase air to lower the CO_2 by 2% to 12.5%.* This procedure will create a safety margin of excess air to make sure that variations in combustion conditions (air, fuel or draft) don't create soot or other dangerous situations. For safety reasons, perform another smoke test to be sure the reading is zero.

5. **Stack temperature**: Although the temperature was taken during the first step in this process, the burner adjustments made to address draft, smoke and CO_2 issues affect the temperature reading. Record the temperature displayed on the stack thermometer and subtract the combustion air temperature to get "net stack temperature."
6. **Calculate Efficiency**: Use the wet kit's Fire Efficiency Finder with Oil Slider to determine the efficiency by lining up the CO_2 and net stack temperature.

Testing with electronic analyzers

Properly testing with a wet kit is time consuming. This is especially true when the tests must be repeated during burner fine-tuning. Modern, multi-function electronic testing instruments, reduce the time needed for combustion testing and also provide additional information while performing the calculations needed to determine combustion efficiency. Only digital analyzers enable real time testing, this allows the user to make adjustments to the burner and view the results of those changes within seconds.

With the optional printer, data can be recorded as an uneditable record, so the printout is an accurate record that becomes part of the job site log. Permanent records allow for accurate tracking of any system changes and provide valuable information for servicing the equipment.

Technicians should not leave their testers in a cold vehicle overnight, freezing temperatures have an impact on sensor life.

How it works

Electronic combustion analyzers use advanced methods of measuring flue gas composition and temperature through a single probe. A pump within the analyzer draws a flue gas sample through a series of sensors to measure the gas composition.

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Figure 7-15: Analyzer fuel selection

Most electronic analyzers have sensors capable of measuring oxygen percentage (O_2), draft, stack and ambient temperatures. Because most analyzers do not have CO_2 sensors, carbon dioxide is calculated based on the oxygen reading and the type of fuel selected. Excess air (EA) is also calculated. Smoke levels in the flue gases are not measured by an electronic analyzer, in fact high concentrations of smoke are harmful and will affect the life expectancy of the sensors. To extend the life of the sensors, always perform a smoke test and adjust for a zero smoke reading before using an electronic analyzer.

To perform a combustion analysis with an electronic analyzer, the following components are needed:

- A smoke tester and a smoke scale
- An electronic analyzer
- A draft gauge, if the electronic analyzer doesn't include that feature

Step by step procedure for conducting a combustion test with an electronic analyzer:

1. Start the analyzer and allow it to calibrate in room air, set fuel selection to the fuel in use, Figure 7-15. CO should be zero and O_2 should be 20.9%. If they are not, move the analyzer to the outdoors and allow it to recalibrate. If the numbers are correct outside, the combustion zone air is unsatisfactory. If the numbers are still incorrect, the analyzer needs service, or in rare situations, there could be CO outside.
2. Perform a smoke test and adjust to zero smoke.
3. Adjust draft using a separate draft gauge if the analyzer doesn't include that feature. Adjust the draft regulator, if necessary, to set the draft to manufacturers specifications, typically -.04 at the breech and -.02 over the fire. Be careful when using an analyzer to measure over fire draft, it can be damaged by exposure to extreme heat. Use a pigtail, Figure 7-16, or follow the manufacturer's recommended procedure.

Figure 7-16: When taking over fire measurements with an analyzer, the use of a small diameter steel pipe with attached flexible tube, commonly referred to as a pigtail, will protect probe from extreme temperatures.

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30:00

4. Perform a smoke test again to confirm zero smoke after the draft adjustment.
5. Insert the analyzer probe in the flue gas hot spot, centered in the flue pipe for proper sampling, not to close to or touching the sides of the flue pipe.
6. When the unit reaches steady state, observe the readings:
   - Ambient temperature - This is the temperature at the analyzer itself, it is subtracted from the gross stack temperature to give the net stack temperature
   - Stack temperature - The temperature of the flue gas minus the ambient temperature
   - Oxygen (O_2) - The vast majority of analyzers use an O_2 sensor to directly measure the O_2 in the flue gas and use that reading to calculate CO_2 and excess air based on the fuel selected
   - Carbon Dioxide (CO_2) - The calculated value of the CO_2 in the flue gas sample
   - Carbon Monoxide (CO) - Analyzers measure this value directly using a CO sensor and then using the excess air to calculate the CO air, or in rare situations there could be CO outside
   - Carbon monoxide air free (COaf) - The amount of CO in the flue gas calculated as if there were no excess air. This allows an equal comparison between units with widely varying excess air levels
   - Excess air (EA) - A number calculated from the O_2 content of the flue gas for the fuel selected. This is a measure of the amount of air present above the stoichiometric quantity and includes the "safety margin" in case of adverse conditions

Smoke damages electronic analyzers. NEVER use an analyzer if the smoke reading is greater than number 1.

7. If the optional printer is being used, print a record of the readings. If the optional printer is not being used, record the readings on the service ticket.

Alternative procedure

As with the wet kit alternative procedure, the "slightly different" procedure has a different way of handling smoke and CO_2 adjustments.

1. Start the analyzer and allow it to calibrate in room air, set fuel selection to the fuel in use. CO should be zero and O_2 should be 20.9%. If they are not, move the analyzer to the outdoors and allow it to recalibrate. If the numbers are correct outside, the combustion zone air is unsatisfactory. If the numbers are still incorrect, the analyzer needs service.
2. Perform a smoke test and adjust to a trace of smoke.
3. Adjust draft using a separate draft gauge if the analyzer doesn't include that feature. Adjust the draft regulator, if necessary, to set the draft to manufacturers specifications, typically -.04 at the breech and -.02 over the fire. Be careful when using an analyzer to measure over fire draft, it can be damaged by exposure to extreme heat. Use a pigtail (see Figure 16 on previous page) or follow the manufacturer's recommended procedure.
4. Perform a smoke test again to confirm a trace of smoke after the draft adjustment.

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33:33

5. Insert the analyzer probe in the flue gas hot spot, centered in the flue pipe for proper sampling, not to close to or touching the sides of the flue pipe.
6. When the unit reaches steady state, observe the readings:
   - Ambient temperature - This is the temperature of the incoming combustion air, either room temperature or the temperature of the air being delivered by a combustion air kit
   - Stack temperature - The temperature of the flue gas minus the ambient temperature
   - Oxygen (O_2) - The vast majority of analyzers use an O_2 sensor to directly measure the O_2 in the flue gas and use that reading to calculate CO_2 and excess air based on the fuel selected
   - Carbon Dioxide (CO_2) - The calculated value of the CO_2 in the flue gas sample
   - Carbon Monoxide (CO) - Analyzers measure this value directly using a CO sensor and then use the excess air to calculate the CO air free
   - Carbon monoxide air free (COaf) - The amount of CO in the flue gas calculated as if there were no excess air. This allows an equal comparison between units with widely varying excess air levels
   - Excess air (EA) - A number calculated from the O_2 content of the flue gas for the fuel selected. This is a measure of the amount of air present above the stoichiometric quantity and includes the "safety margin" in case of adverse conditions
7. Increase combustion air until the CO_2 shown on the screen is 1% - 1.5% lower than recorded plus make sure that it is lowered to 12.5% to assure safe CO levels. Example: If the trace level recorded is 12.5%, increase air to lower the CO_2 1% - 1.5% so it is 11% - 11.5%. If the CO_2 recorded is 14.5%, increase air to lower the CO_2 by 2% to 12.5%. This procedure will create a safety margin of excess air to make sure that variations in combustion conditions (air, fuel or draft) do not create soot or other dangerous situations.
8. If the optional printer is being used, print a record of the readings taken after step 7. If the optional printer is not being used, record the readings taken after step 7 on the service ticket.

It's better to use an electronic analyzer

While wet kits have been used for many years and can produce reasonably reliable results if used and maintained properly, there are a number of reasons why technicians should use electronic analyzers:

1. Performing a combustion test with a wet kit is time-consuming and only gives a vague snapshot of the burner performance.
2. Carbon monoxide testing cannot be performed with wet kits. A separate CO tester must be used to ensure that the appliance is operating at safe levels of CO.
3. Wet kits are not capable of calculating excess air. A technician using a wet kit would have to do manual calculations to determine excess air levels.
4. Electronic analyzers provide readings much quicker and perform efficiency calculations automatically. With a wet kit a "Fire Efficiency Finder" scale must be used.

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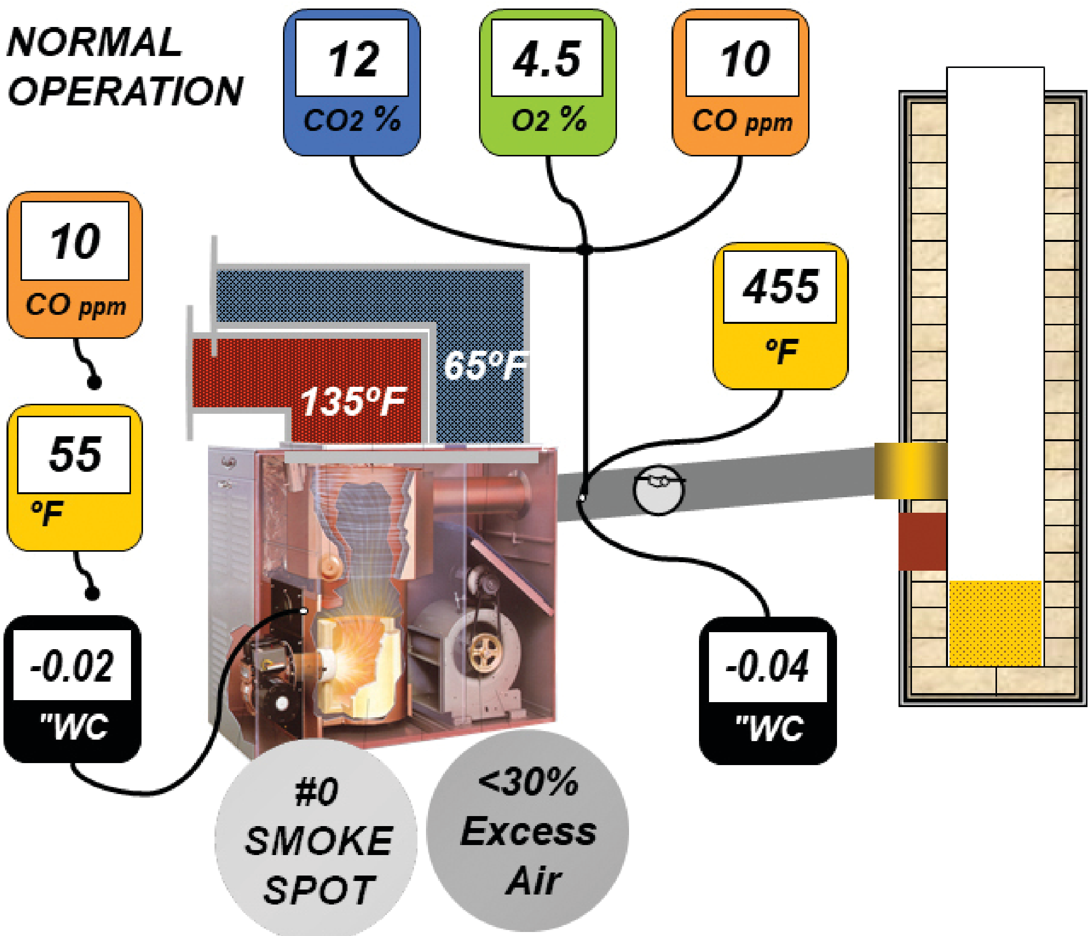
5. Digital combustion analyzers sample flue gas continuously in real time, so the technician can see the CO_2, O_2 and temperature results change as adjustments are made.

Interpreting the test results

While it is important for a technician to understand how to properly perform a combustion test, it is equally important to understand what the results of the tests mean. Each reading tells a specific story that enables the technician to make adjustments to the combustion process that will ensure that the appliance is operating safely, cleanly and efficiently.

Remember to ALWAYS refer to manufacturer instructions regarding burner setup. The following "ranges" are provided as a guide for typical appliances; however, individual appliance guidelines ***must*** be followed. See Figure 7-17

Figure 7-17: Typical test results



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Flue Gas temperature
(aka stack temperature)

Typical range: 350° to 500°F Net

The flue gas temperature is the temperature of the combustion gases leaving the appliance and reflects the heat energy that did not transfer to the heat exchanger during the combustion process. This temperature is a measurement of the heat exchanger's ability to draw heat from the combustion gases. Managing stack temperatures is a delicate balance of fuel-air mixture ratios, the efficiency of the appliance heat exchanger, the condition of the heat exchanger and draft.

Flue gas temperatures measured at the breech are "gross" readings. To complete the calculation for stack temperature, the ambient air temperature at the burner inlet air must be deducted to arrive at the "net" flue gas temperature. Electronic analyzers automatically make this deduction in the data they provide. When using a wet kit, this deduction must be done manually.

In non-condensing, chimney vented appliances, the temperature of the gases must be above 350° gross to prevent condensation either in the appliance, flue pipe or chimney.

Some causes of high flue gas temperature:

- **Soot/Carbon Deposits:** The insulating effect of soot prevents good heat transfer through the heat exchanger. Inspect the heat exchanger, clean if necessary, and adjust the burner for zero smoke
- **High excess air:** Excess air cools the combustion gases and increases their volume. This results in lower heat exchanger efficiency. Excess air can be due to poor air-fuel mixing, poor burner adjustment, and/or air leaks into the heat exchanger
- **Overfiring:** Firing a heating system at a higher input GPH (gallons per hour) than it was designed for exceeds the heat exchanger's ability to absorb heat
- **Excessive draft:** Too much draft will cause the combustion gases to travel rapidly through the heat exchanger leaving little contact time to absorb heat

Low flue gas temperatures

Flue gas temperatures that are too low should be investigated. Flue gases must exit the chimney at a temperature above the dew point to avoid unwanted condensation. To prevent condensation, the net stack temperature should range from 270°F to 370°F depending upon chimney type, material and construction. With high efficiency equipment that does not have a draft regulator, combustion gases can be on the low end of this range; if there is a draft regulator, they should be closer to the high end.

Dew Point temperature

The dew point temperature is the temperature below which the water vapor contained in the flue gas turns into a liquid. This change is often referred to as condensation. Below the dew point temperature, moisture exists; above the dew point temperature, vapor exists. If the temperature in the chimney or vent falls below the dew point temperature, flue gas condensation will occur.

Draft

Typical range: -.04" (negative point zero four inches) at breech and -.01" to -.02" over fire.

NOTE: Some appliances operate with positive draft over the fire, this is another reason to ALWAYS refer to the manufacturer's instructions.

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41:48

Draft is measured, in inches of water column, at two places: over-the-fire (at the top of the combustion area) and in the flue pipe, as close to the breech as possible. The difference between breech draft and over fire draft is referred to as "draft drop." Refer to the appliance manufacturer's instructions for the recommended draft drop for the specific appliance being worked on. If draft is too high, the flue gases will travel through the appliance too quickly and efficiency will be lowered. In addition, excessive draft can cause the flame to be "pulled" away from the combustion head (aka flame detachment) and cause operational problems. High draft problems can usually be solved by adjusting the draft regulator.

If draft is too low, the combustion air flow will be reduced, causing incomplete combustion and possible smoke.

Common causes of low draft at the breech:

- Leakage of air into chimney, thimble, stack, or breeching—allowing ambient air to cool the flue gases and prevent them from developing sufficient draft. *Suggestion: Seal any leaks that are found*
- Obstruction in chimney or at top of chimney—any blockage prevents the flow of gases. *Suggestion: Check to be sure that the base of the chimney is clear of soot and debris. Verify that the top of the chimney is not obstructed by trees or other sources*
- Improper adjustment of the draft regulator. *Suggestion: Adjust to appliance manufacturer specifications*

Common causes of low draft over the fire

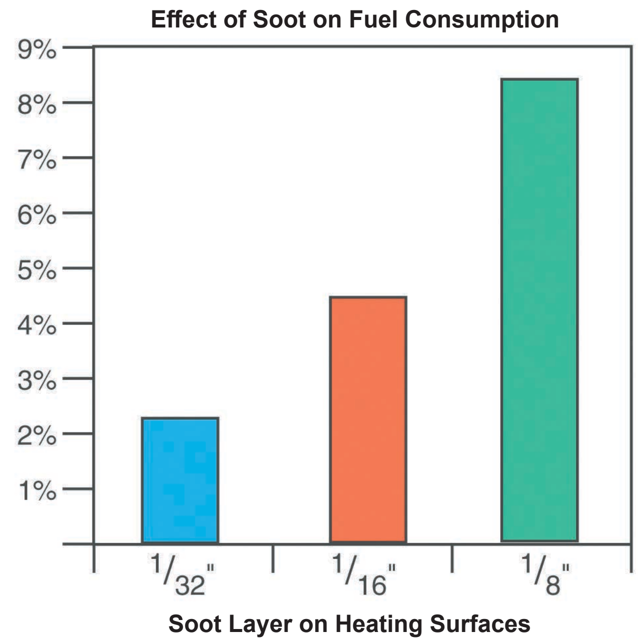
- Heat exchanger passages are clogged with soot and scale. *Suggestion: Inspect the flue passes in the appliance, clean as necessary*
- Appliance is overfired - the volume of the combustion gases is too great for the heat exchanger design. *Suggestion: Set the firing rate to manufacturer specifications*
- Unit is underfired - the flue gases never get hot enough to create normal draft conditions. *Suggestion: Set the firing rate to manufacturer specifications*

Smoke

Typical range: Zero

Smoke and soot, which are nothing more than unburned carbon, are created by incorrect burner service and adjustment or outdated burner designs. Smoke production is unacceptable and must be eliminated because it reduces efficiency, increases service calls, and risks damage and injury to people and property. Smoke wastes fuel because it deposits soot on the heat exchanger surfaces, Figure 7-18. This insulates the heat exchanger, limiting its ability to extract the

Figure 7-18:



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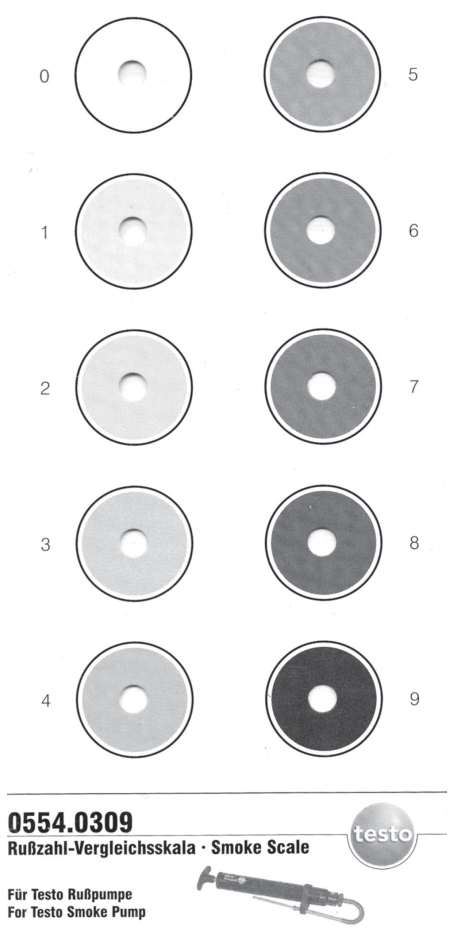
heat from the combustion gases. A layer of soot only 1/8" thick can reduce heat absorption by over 8%.

Efficiency loss occurs as the soot slowly builds up. Soot also affects the reliable operation of the burner. If soot covers the cad cell, or the soot builds up on the bimetal of the stack relay, it can simulate a flame failure and cause the control to lock out on safety, creating an unnecessary service call.

While older, obsolete equipment may not be able to operate with minimal smoke, today's burners are designed to operate at zero smoke. If the smoke reading is higher than zero, further adjustments or servicing

Figure 7-19: Smoke scale



is required. If a burner is incapable of operating at zero smoke, the customer should be advised to consider the installation of new equipment.

Smoke concentrations are measured by taking a sample of the flue gases and comparing the results to a calibrated chart to identify smoke concentrations on a scale, Figure 7-19. This scale has ten shaded spots.

An oily or yellow smoke spot on the filter paper is a sign of unburned fuel, indicating extremely poor combustion.

Common causes of smoke

1. **Poor fuel atomization**: smaller fuel droplets vaporize easier than large ones which allows them to mix better with the oxygen in the air. Large droplets lead to smoke creation and are caused by:
   - Damaged or worn nozzles
   - Low or improper fuel unit pressure
   - Cold fuel
2. **Inadequate combustion air:**
   - The burner air shutter is not open far enough
   - Accumulation of lint, hair, sawdust, and dirt on the air shutter and/or the burner fan
   - Improper set up of the burner
   - Buildup of soot and scale in the heat exchanger
   - Poor chimney draft
   - Restrictions of air flow to the combustion zone
3. **Air in the fuel:**
   - Air in fuel can lead to fuel dripping from the nozzle on shut-down, leading to an after burn
   - High vacuum can lead to fuel changing from a liquid to a foam

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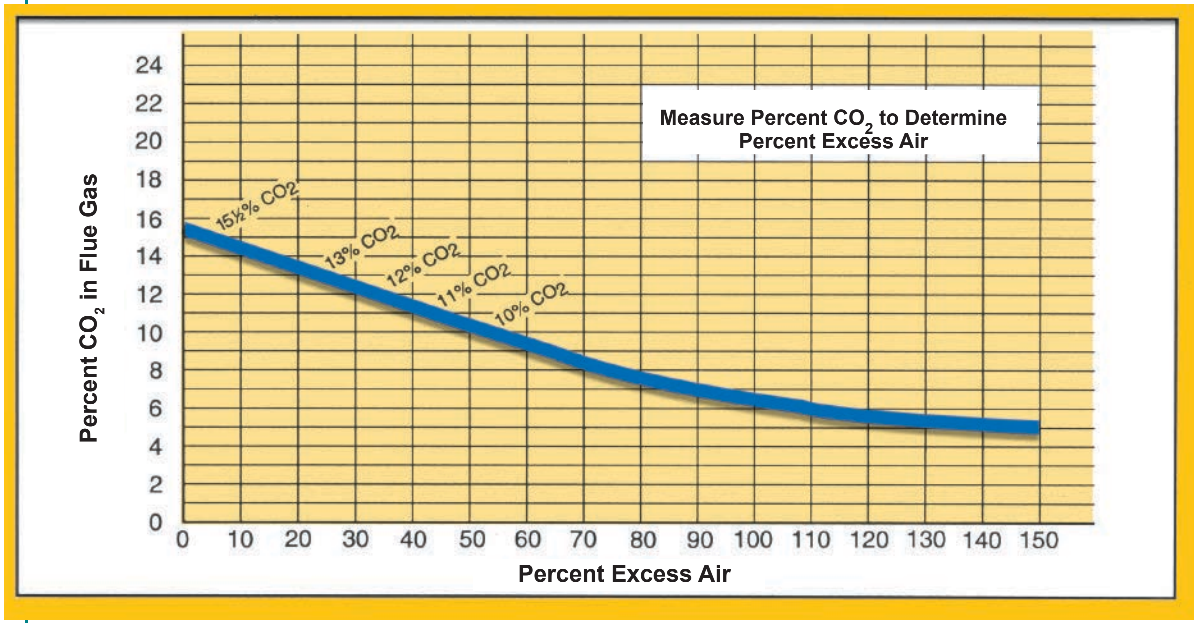
Figure 7-20: Relationship between excess air and CO_2



CO_2/O_2 – Excess air

Typical ranges:

CO_2: 11.5 to 12.5%

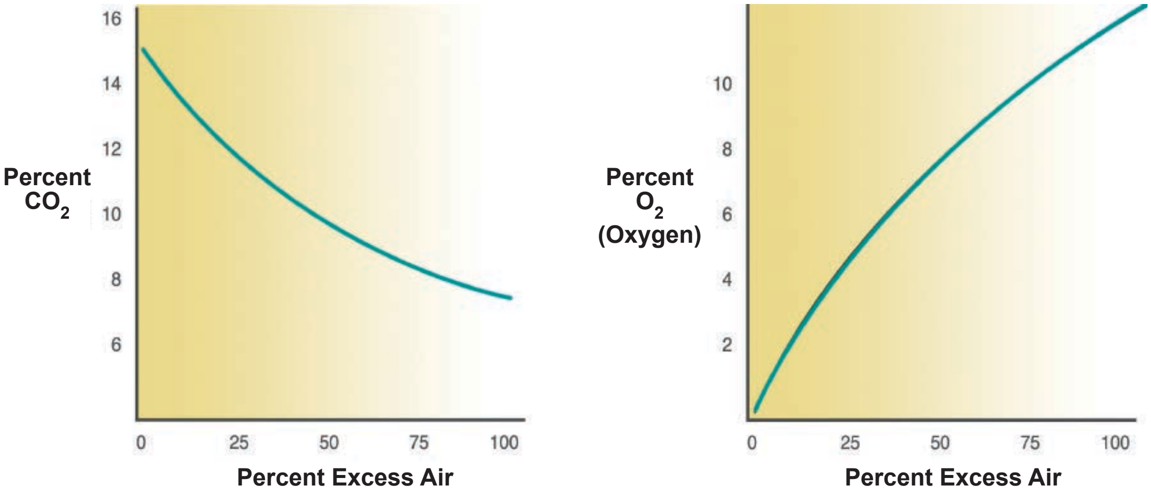
O_2: 4.0 to 5.3%

Excess air: 25 to 35%

Although CO_2 and O_2 readings are commonly used to calculate combustion efficiency, they are just indicators of how much "excess air" is being provided to the combustion process.

Since perfect (*aka stoichiometric)* combustion cannot be achieved, a managed amount of excess air must be provided to provide a safety margin to compensate for environmental conditions.

Figure 7-21: Relationship of CO_2, O_2 and excess air



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As excess air is added, the percentage of oxygen (O_2) in the combustion gases increases, while the percentage of carbon dioxide (CO_2) decreases (Figures 7-20 and 7-21). By measuring either the percentage of CO_2 or the percentage of O_2 in the exhaust, one can determine the quantity of excess air.

Correlation of Percent of CO_2, O_2 and Excess Air

Carbon Dioxide	Oxygen	Excess Air (Approx.)
15.4	0.0	0.0
15.0	0.6	3.0
14.5	1.2	6.0
14.0	2.0	10.0
13.5	2.6	15.0
13.0	**3.3**	**20.0**
12.5	**4.0**	**25.0**
12.0	**4.6**	**30.0**
11.5	**5.3**	**35.0**
11.0	**6.0**	**40.0**
10.5	6.7	45.0
10.0	7.4	50.0

The ranges that you will use most frequently are bold-faced and in color.

Figure 7-22: 0% Excess air

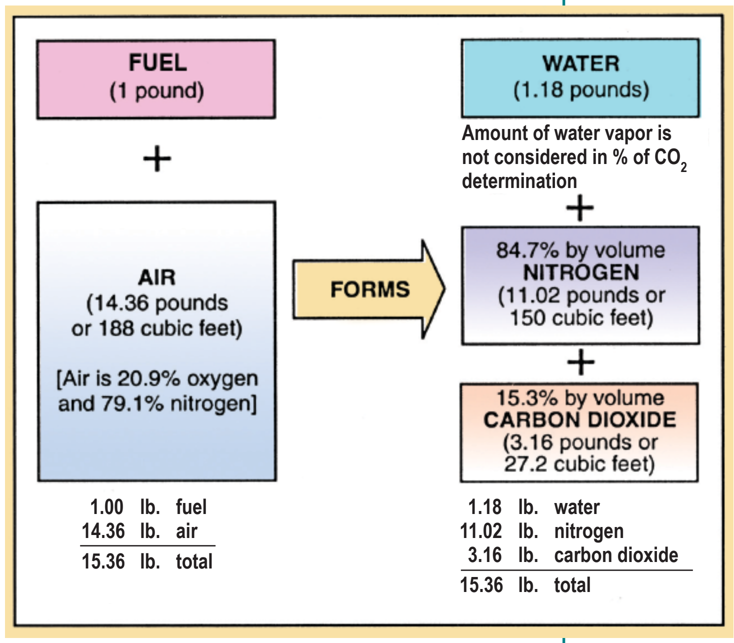
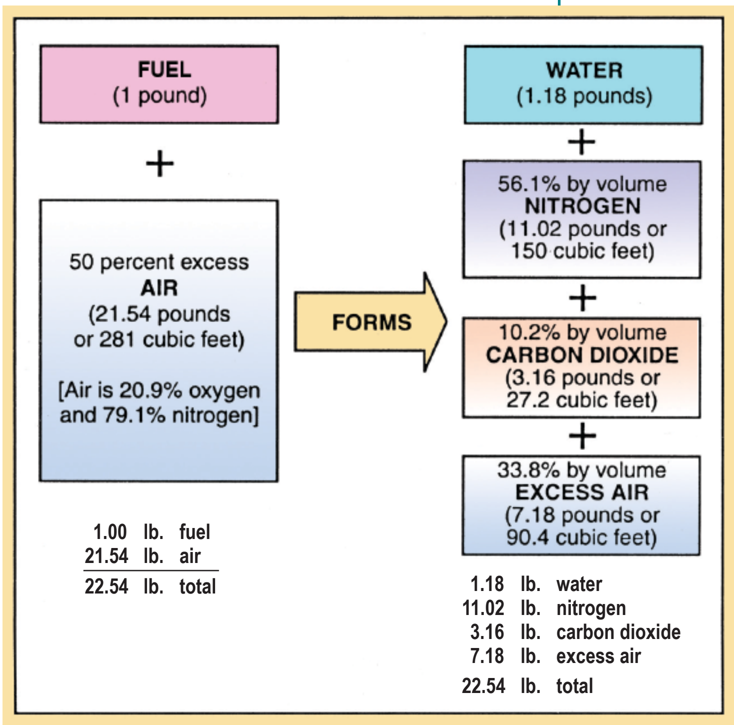


Figure 7-23: 50% Excess air



Why excess air must be controlled

Burners require a controlled amount of excess air to assure proper combustion and smoke free operation. Properly adjusting excess air is a compromise between too little air and too much air. See Figures 7-22 and 7-23.

The excess combustion air serves as a safety margin to assure enough air is always available to compensate for variables such as air, fuel temperature, draft, clogged air fan, etc.

While excess air is needed for reliable clean operation, it also reduces efficiency. Too much excess air increases the amount of combustion gases that must be vented and causes them to travel through the heat exchanger faster. This gives the heat

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49:02

exchanger less time to extract heat which leads to higher stack temperatures and lower efficiency.

Too much excess air also cools the flame. This further reduces combustion efficiency and can cause carbon monoxide levels to rise. Finally, too much excess air can cause "flame detachment" which pushes the flame away from the retention head and leading to:

- Smoke
- Soot
- Primary control lockout
- Heat exchanger fouling
- Burner head coking

Therefore, the amount of excess air allowed into the combustion process must be properly set. The only practical way to achieve this is by using combustion test equipment.

Carbon monoxide (CO)

Typical ranges:

In flue gas: Single digits to 30 ppm

Ambient: 0 – 5 PPM

Carbon monoxide (CO) is a result of incomplete combustion. During combustion, carbon in the fuel oxidizes through a series of reactions to form carbon dioxide (CO_2). However, 100% conversion of carbon to CO_2 is rarely achieved under field conditions and some carbon only oxidizes to the intermediate step, CO. CO can be produced by both insufficient or too much combustion air. Mismatched fuel and air patterns and ratios as well as flame impingement can also lead to high CO production.

CO is a toxic gas that can occur in homes and buildings where combustion by-products are generated, not properly vented and allowed to accumulate. CO is a colorless, odorless, tasteless gas that is readily absorbed in the body and can impair the oxygen-carrying capacity of the blood. This can result in less oxygen to the brain, heart, and tissues. Even short-term exposure to carbon monoxide can be critical or fatal, especially to people with heart and lung diseases, and to the young or the elderly. It may also cause headaches and dizziness and other significant medical problems in healthy people. At low concentrations, CO can go undetected and contribute to nagging illnesses, and can compound pre-existing health problems.

Safety should be the primary goal of all technicians. The production of CO in the flue gases should be kept below 100-ppm air-free, even though the allowable limit in the flue is 400-ppm air-free. Higher CO levels in the appliance or flue do not typically affect ambient measurements of CO. Extra attention should always be given to determine that proper CO levels are contained in the flue gases and all appliances should be carefully checked for flue gas spillage.

CO warning signs

If smoke is seen near the burner or coming from the chimney, or if a sharp raw fuel smell is noticeable, the burner is probably producing unacceptable levels of carbon monoxide. With insufficient combustion air, burners can produce elevated smoke levels before high CO levels are reached. It is important to realize that this smoke is a warning signal.

Burners that are operated with too much combustion air can lower the temperature of the flame and create CO with no smoke. Any time a technician works on the burner components of a fuel fired appliance; an electronic combustion analyzer should be

Never leave a jobsite operating with elevated CO!

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52:33

used to measure CO levels. Never leave a jobsite operating with elevated CO.

What to watch out for

In addition to performing a combustion analysis, the technician should inspect for the following:

- **Fuel odors** - *locate and repair any fuel leaks, inspect for proper ventilation and adequate combustion air*
- **Soot, rust, or scale build-up on or around appliances and vents** - *determine the cause, correct and clean, as necessary*
- **Loose or disconnected chimney or vent connections** - *repair immediately*
- **Debris or soot falling from chimney, fireplace, or appliance** - *inspect and repair*
- **Excessive moisture on the inside of windows or walls** - *this is often an indication of flue gas spillage. Test ambient air and the appliance*
- **Chalky white powder forming on the chimney or vent** - *can indicate flue gases condensing through cracks in the chimney. Inspect and repair*
- **Visible smoke in the living space** - *locate source of smoke, check the appliance and exhaust connections, check for "whole house fans" or any other devices that could cause negative pressure in the building*

Light off CO levels: CO levels at light off are typically higher, but quickly drop and stabilize. Unusually high CO levels may be an indication of rough or delayed ignition, warranting further investigation. CO readings should stabilize quickly and should never be rising during operation.

Mechanical problems and CO: If the appliance being tested has sufficient combustion air and is still producing higher than acceptable CO levels, it could be a mechanical problem. Inspect the burner and appliance for cleanliness, proper firing assembly alignment and adjustment, missing burner covers, missing or damaged burner components, improper air adjustment or incorrect fuel pressures, defective or incorrect nozzle. Check the appliance, inspect the combustion chamber for damage or excessive debris. Look for evidence of flame impingement, which occurs whenever the flame is hitting a surface.

Initial start-up CO levels: When a new appliance is installed, manufacturing residue often causes temporarily elevated CO levels. These levels typically drop after approximately 15 minutes of operation.

CO ambient air testing

(Combustion air zone & living space)

Carbon monoxide (CO) is always a potential hazard when combustion is taking place. Ambient CO levels should also be checked, and the appliance should be run through a complete cycle if any combustion problems are suspected.

High ambient CO levels in a home are most often the result of auto exhaust in an attached garage, depressurization of the home or insufficient air in the combustion zone. If CO is detected, all possible sources should be checked, including but not limited to water heaters, gas appliances, non-electric space heaters, and vented or unvented appliances like gas logs. A furnace with a cracked heat exchanger, a blocked flue or appliance can also cause improper combustion and allow flue gases with higher-than-normal CO levels to spill into the living space.

To check ambient CO levels start the analyzer and let it run through its start up cycle, typically about 60 seconds. When the presence of CO is detected in a build-

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56:07

ing, it's essential to also measure the CO outside the building to determine where the carbon monoxide is being generated.

For example, if you measure 25 PPM of CO inside and 17 PPM outside, the main problem may be caused by something outdoors, but there could still be 8 PPM being generated by an indoor source.

Ambient CO limits (Recommended) Figure 7-24

0 ppm. This level is most desirable, but not always achievable. Levels where cigarette smoke, candles, and appliances such as gas stoves are present can sometime be slightly higher.

1-9 ppm. Normal acceptable level

10-35 ppm. Advise occupants, check for symptoms (slight headache, tiredness, dizziness, and nausea or flu like symptoms). Check all appliances, including the furnace, water heater and boiler, check for other sources including internal combustion engine operation in attached garages.

36-99 ppm. Recommend fresh air, check for symptoms, ventilate the space, recommend medical attention.

100+ ppm. Evacuate the home (including yourself!) and contact the fire department or emergency medical services (911). Do not attempt to ventilate the space. Short-term exposure to these levels can cause permanent physical damage.

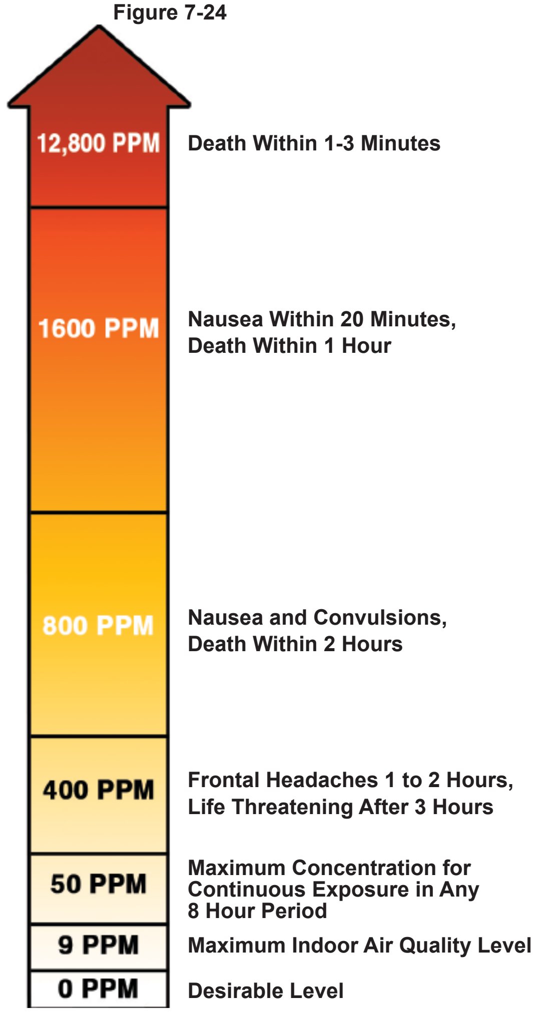
Typical combustion challenges?

This section addresses four combustion issues:

1. **Insufficient combustion air**
2. **Improper air-fuel mixing**
3. **Flame impingement**
4. **Smoky shut-down**

Carbon Monoxide (CO) Levels

Figure 7-24



1. Insufficient combustion air

For the proper operation and venting of appliances, sufficient air must be supplied to the combustion zone.

For years, it has been assumed that when a heating appliance is located in an open area there would be sufficient air for combustion. In many situations today that is not true. New construction standards often confine heating equipment to a very small space such as a utility room that may include other appliances such as clothes dryers which also require large amounts of air.

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58:31

Insufficient air problems are most noticeable on the coldest days when the heat loss is the greatest, the windows or doors are closed for extended periods of time and the burner consumes more oxygen because it runs for extended periods. These conditions can lead to dangerous carbon monoxide levels being generated by the appliance

NFPA 31 requires that there must be 50 cubic feet of open space per 1,000 BTU input rating of all appliances installed in the combustion zone. So, any space that provides less than 50 cubic feet per 1,000 BTU's of total appliance input is considered a confined space and additional air must be provided.

To determine the maximum total firing rate allowable in a room, the total cubic feet must be known.

To determine the total cubic feet of the room, multiply the length times the width times the height:

L x W x H = Total cubic feet

So, if the combustion zone is in a room that is 20' long, 24' wide with a 8' ceiling:

20 x 24 x 8 = 3,840 cubic feet

To determine the maximum BTU firing rate allowable in this room, multiply:

3,840 x (1,000 BTU/50) (3,840 x 20)

3,840 x 20 = 76,800 maximum BTU input

A gallon of #2 fuel contains approximately 138,690 BTUs, to determine the maximum allowable firing rate, divide 76,800 by 138,690

76,800/138,690 = .55 GPH

The maximum firing rate for this room is .55GPH. Any appliance, or appliances, with a higher firing rate requires that additional air must be made available.

This air can be added by installing:

- Permanent openings, one near the top of the combustion zone and one near the bottom, sized in accordance with NFPA 31 requirements
- Ducts to bring in air from other parts of the building or from the outside, sized in accordance with NFPA 31 requirements
- Mechanical devices such as a "fan in a can" to bring outside air into the combustion zone (https://www.fieldcontrols.com/fan-in-a-can-cas-3-combustion-air-system/)
- An "outside air intake kit" which brings outside air directly to the burner air intake. Most burner manufacturers offer information online:

beckettcorp.com/support/tech-bulletins/combustion-air-requirements-for-oil-burners/

carlincombustion.com/wp-content/uploads/CAP-System-Kit-Instructions-021320.pdf

s3.amazonaws.com/s3.supplyhouse.com/product_files/Riello%20-%203002761%20-%20Install%20Instructions.pdf

For further information regarding combustion air requirements see *NFPA 31, Standard for the Installation of Oil-Burning Equipment,* Chapter 5.

Testing for insufficient combustion air

NFPA has developed a "worst case draft test" that enables technicians to determine if there is a combustion air problem or if one might arise in the future. The test simulates what happens if all of the air stealing appliances, except for a whole house cooling exhaust fan, are on at the same time.

"The technician should perform the following tasks to determine if the appliance can operate in accordance with the draft requirements specified by the equipment manufacturer."

1. Close fireplace dampers and fireplace

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1:02:32

doors, close all exterior doors and windows in the building, and close all interior doors in the building.

2. Turn on building air exhaust systems, including clothes dryers, range hoods, bathroom exhausts, and mechanical ventilation and forced-air heating or cooling system blowers and operate them at their highest speed setting. **Do not operate a whole-house cooling exhaust fan.**
3. Operate the burner in the smallest oil heating appliance first, and then other appliances in order of increasing capacity. Measure and record the breech draft and over-fire draft of each appliance, and check for flue gas spillage.
4. Check that the breech and over-fire draft are at a level that is required by the oil heating equipment manufacturer as specified in the installation and operating manuals for the appliance. Over-fire draft in oil appliances is usually negative 0.01 to negative 0.02 in. of water column.
5. If the draft is maintained at the manufacturer's recommended level, return doors, windows, exhaust fans, fireplace dampers, and appliances to their previous conditions of use.
6. If the draft is NOT maintained at the manufacturers recommended level, take action as needed to correct excessive depressurization of the appliance combustion air zone and return the flue draft and over-fire draft to the requirements of the oil heat equipment manufacturer. If additional steps are necessary, shut the appliance down until the situation can be corrected.

Notify the homeowner, building owner, or occupant if combustion air zone depressurization impacts the operation of the oil heating equipment and of all actions and modifications that are required to allow the flue draft and over-fire draft to be maintained at the level required by the oil heating equipment manufacturer."

It is important to understand that this test, or an equivalent, is required by NFPA 31, 2020 edition, in Section 5.2.1.1:

"After installing a new or replacement oil-burning appliance and before placing the equipment into service, the equipment installer shall perform testing of the worst-case depressurization of the room where the appliance is located and shall determine, by measuring the flue draft and over-fire draft, that the appliance can operate in accordance with the draft requirements of the appliance manufacturer."

2. Improper air-fuel mixing

Improper mixing creates "fuel rich" (too much fuel) and "fuel lean" (too little fuel) pockets in the combustion area and prevents complete burning. Some of the causes are:

- Mismatch pattern of the fuel spray and the burner air pattern. *Suggestion: check the manufacturers guide to determine the correct nozzle spray, angle and pattern*
- Using a nozzle that is either too small or too large for the burner head and combustion area. *Suggestion: Verify that the nozzle and fuel unit pressure are correct*
- Inadequate air swirl and turbulence. *Suggestion: Check air handling components including the retention head size/setting, set burner to manufacturer specs*

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1:06:04

- Improper burner head size or mismatched burner components. *Suggestion: Replace with correct components and set to specs*
- Improper adjustment of air handling parts of the burner. *Suggestion: Check settings*
- Irregular or unbalanced fuel spray. *Suggestion: Check for a defective or partially plugged nozzle*
- Off center installation of the nozzle assembly. *Suggestion: Set to specs*
- Dirt or soot accumulation on burner air handling parts including air shutter and fan. *Suggestion: Clean if necessary*
- Defective or damaged burner parts. *Suggestion: Check the retention head, air tube, fan, and motor coupling. Replace if applicable*
- Fuel pump pressure set too low or too high. *Suggestion: Check and adjust to specs*
- Cold fuel producing larger fuel droplets, and increasing the firing rate beyond the air setting: *Suggestion: Consider a nozzle line heater or fuel de-aerator*

3. Flame impingement

The flame must not touch any solid surfaces of the burner, the retention head, the combustion chamber or the heat exchanger. If this happens, the flame will be cooled and the unburned carbon becomes smoke and soot. Possible causes of flame impingement are:

- Overfiring-too large a nozzle or excessive fuel unit pressure
- Incorrect nozzle (for example, wrong spray angle or pattern)
- Collapse or deterioration of combustion chamber, incorrect combustion chamber size or shape, or debris has collected at base of chamber
- Partially clogged nozzle
- Cold fuel

4. Shut down issues (after-burn)

If the burner rumbles, or if smoke comes from the chimney on shut-down, it is most likely from air accumulation in the nozzle assembly. Install a suction line analyzer in the suction line close to the burner and observe for any visible bubbles, Figure 7-25. Check the vacuum, if it is too high, clean the fuel lines with a push pull pump. If the fuel unit is connected as 2-pipe, consider abandoning the return line and installing a deaerator. If the vacuum is too low, check for a suction leak.

Figure 7-25: Suction line analyzer showing air bubbles in the fuel

Alternately the fuel cutoff may be to blame. Perform a pressure check at cutoff test as described in Chapter 4 to check the cut-off of the fuel unit.

Other causes of afterburn are:

- An accumulation of soot in the chamber
- Flame impingement

Chapter 7: Additional Resources

NORA has compiled a library of additional technical resources for your continued education. Scan the QR code or go the the web address. Check back often as NORA will contnually add content as it becomes available.

You will find:
- Videos
- Technical Bulletins
- Instructions
- and More

https://Learning.NORAweb.org/combustion