

Carbon monoxide: A mechanic's approach

Application Note

It's not always technical maid service. Sometimes HVAC professionals are rewarded with a mystery and given the opportunity to put our technical detective skills to work. How accurately we solve combustion related mysteries is directly related to our fundamental understanding of the science and technologies in effect, our choice of tools and test equipment, our previous experiences, and even our imagination.



The answers lie beyond the obvious

Carbon monoxide consumer awareness is still on the increase. More and more consumers are installing CO detectors in their homes and workplaces. This is good. It offers occupants a level of safety they did not have previously, and offers the expert (you) an opportunity for in-depth site analysis.

So how does it usually unfold? An occupant calls the fire department after a CO alarm. The firemen may not see an obvious source of the CO, so they recommend having the furnace (or boiler) checked by a heating contractor: the combustion expert. It's your job to find the source of the CO under current conditions, or to try to duplicate variable conditions under which CO could be produced. This is a tall order, requiring a process of elimination of possible malfunctions and a keen awareness of variables, such as building depressurization and gasses (air and vent products), that could behave unexpectedly.

While you're driving to the jobsite, turn off the radio and think about the abundant possibilities. Think of the structure in its entirety as a system. Combustion appliances are only a part of the integrated whole. What else is competing for or interfering with combustion air, fuel supply, vent function? How can contaminants such as chlorides, sulfides, VOC's, dust, and dirt affect component integrity and operation?

Think about some of the questionable creative engineering you've seen from end users trying to save on energy costs. Think about all of the different fossil fuel appliances and products, wood fireplaces and stoves that may be in play: some fixed, some portable, some that drive away. Think about what could be external to the structure that could produce combustion products and be drawn into the occupied space: idling school buses or trucks, standby generators in exercise mode, poorly placed or improperly installed vent terminations.

The list of possibilities is seemingly endless, and more often than not, it's two or more processes gone wrong. One process may have been operating on the edge of acceptability since day one, and a second process changes enough to throw the first process over the edge. Every job is different and valuable lessons can be learned from each. Be observant and allow your mind to explore the possible system failure modes and their interacting effects.

Exterior survey

When you arrive at the jobsite, observe the exterior of the system (the building and its immediate surroundings). Before entering the building, turn on your environmental air meter (such as Fluke 975) and give it time to warm up and zero outdoors. This will give you time for a walk-around.

Notice chimneys, vertical vents, sidewall vents, air intakes and exhausts, exhausts that could become intakes (such as drier vents that stick open from lint build-up), building penetrations proximity to doors and windows, and meter locations. Look underneath decks and porches, at the garage location, inside corners for vents, and notice shrubberies and trees, prevailing wind direction and possible effects, and foundation type (slab, crawlspace, basement). Look in window wells and crawlspace access wells, and just generally notice things.

Later, as you focus on individual components such as the furnace or boiler, water heater, venting and ventilation, you will return to the outdoors to pay more attention to the details and interactions of functions. You might be surprised by how a seemingly unrelated outdoor feature can affect the indoor function of a process.

Check more than just CO

Before you leave the outdoors, record the outdoor ambient CO₂ so you can compare it to indoor levels. Outdoor levels could be as low as 380 ppm CO₂ or less in rural and seacoast locations, or above 500 ppm CO₂ in congested urban locations. Then, as you start your indoor survey, record CO₂ ppm, CO ppm and humidity on your air meter.

LEED-EB IEQ2⁽¹⁾ Credit 1 CO₂ concentrations can range from less than 1,000 ppm CO₂ to over 2,000 ppm CO₂ depending on per person ventilation requirements and Met (metabolic) rate activity levels.⁽²⁾ Elevated CO₂ (from respiration) can be an indicator of a poorly ventilated structure, but unvented (spilling) combustion products will elevate CO₂ and humidity levels in the occupied space as well. Increased CO₂ levels in kitchens may be due to decomposing organic material (garbage).

CO₂ and water (vapor) are produced in the complete combustion of fossil fuels, and CO

Questions to ask

Once inside the structure, consider yourself as a combination of police detective and crime scene investigator.

Here are some questions to ask:

- What kind of CO alarm sounded?
- When did the alarm sound?
- Was it a standard CO detector designed according to UL 2034 that specifies that alarm must sound within 1 to 4 hours at 70 ppm CO, or do they have a low level alarm model that sounds after 5 minutes when CO reaches 15 ppm to 34 ppm?
- Can you retrieve the maximum CO level retained in the alarm memory?
- What CO level did the firemen find?
- What other comments did the firemen have besides suggesting to call the heating contractor?
- Did the alarm sound during early morning hours when all were asleep indicating possible ventilation and venting problems?
- Did any of the occupants exhibit any physical symptoms?
- Did it sound after everyone was awake indicating a possible occupant created condition from space heaters or automobile warm up in an attached garage?
- Did it sound on Sunday afternoon when friends or relatives came for dinner?
- Did they burn the roast, burn the biscuits, or burn the food in the pan on a burner they forgot about?
- Is there an exhaust fan in the kitchen over the stove and is it used?
- Was an outdoor cooking grill used and at what location?
- What about gasoline powered tools and equipment?
- Is smoking allowed indoors?
- Did it sound shortly after everyone retired for the night and was the fireplace used on that night?

and water (vapor) are produced from incomplete combustion. A furnace, boiler or water heater typically produce 80,000 ppm to 30,000 ppm (8 % to 13 %) CO₂ depending on fuel type, and about a gallon of water per 100,000 Btu input. If a category I vent is spilling combustion products, the first change an occupant may notice is increased condensation on windows due to elevated humidity that hadn't occurred previously.

The first rule of fire

Fire must be safely confined and controlled while maintaining correct fuel supply, oxygen supply, and ignition temperature. When we build a fire indoors, we must know that the combustion products will vent to the outdoors. Appliances designed to operate over extended periods of time like a furnace, boiler or water heater must be vented directly to the outdoors. Products with limited operating times such as residential stoves, ovens

and space heaters are usually expected to have products of combustion in quantities low enough to be vented by normal building ventilation, which may be relying entirely on the natural infiltration of air through structural leaks. As oxygen is consumed and vent products exit the building, fresh air from outdoors must be continuously supplied or disaster will follow.

Combustion analysis

- Warm up and zero your combustion analyzer outdoors.
- Combustion products must be sampled undiluted before any draft hoods, barometric draft dampers, or any dilution air injection. (Some high efficiency direct vent boilers may draw air from the air intake into the combustion air blower prior to the exhaust pipe.)
- Sample the O₂ and CO on startup and monitor as the process settles in to steady state operation. CO may be high on startup and reduce to

normal values as steady state operation is reached. Allow at least 15 minutes for steady state operation to be achieved.

- Think about what you are measuring. To find the amount of excess air (air that has not been used in the combustion process), we measure O₂ or CO₂. To discover the quality of combustion, we measure CO.
- Since before any of us started in this trade, the national standard for maximum CO in the vent of vented products has been 400 ppm CO air free.⁽³⁾ Air free means: if we remove the excess air from the sample, what would the CO be? Or, what would the CO reading be with stoichiometric air: Only enough air for perfect combustion without any excess air whatsoever. No product may legally exceed this value, but some older equipment may operate on the threshold of this value.
- Target values for modern natural gas, LP gas and #2 fuel oil equipment steady state maximum CO sample levels should not exceed 100 ppm CO. Setup values for efficiently operating equipment is considered to be between 10 ppm CO and 100 ppm CO. These values are actual sample levels not corrected to "air free" levels. This is a good rule of thumb and is recommended unless specifically overridden by the equipment manufacturer.
- O₂ and CO₂ are excess air measurements and vary widely between products. O₂ is measured by modern electronic analyzers and is basically a direct indicator of excess air. Six percent O₂ equates to about 40 % excess air whether the fuel is natural gas, LP gas, or # 2 fuel oil. For comparison, 6 % O₂ and 40 % excess air is equivalent to (using typical ultimate CO₂

6 % to 9 % O₂ 11 ppm to 99 ppm CO for Bunsen type (primary air and gas mixed injection) burners

- 6.8 % to 8.6 % CO₂ for natural gas
- 7.8 % to 9.8 % CO₂ for LP gas

3 % to 6 % O₂, 11 ppm to 99 ppm CO for power or specialty burners (oil or gas)

- 8.6 % to 10.3 % CO₂ for natural gas
- 9.8 % to 11.7 % CO₂ for LP gas
- 11.1 % to 13.4 % CO₂ for #2 fuel oil with flame retention head burners

values) 8.6 % CO₂ for natural gas, 9.8 % CO₂ for LP gas, and 11 % CO₂ for #2 fuel oil.

- Set up burners and air or water flow volumes to manufacturer's specifications. You may need to consult the product service manual or contact the manufacturer directly for excess air and CO values.
- In the absence of manufacturer's excess air specifications, the following abbreviated guidelines may be used as typical values.⁽⁴⁾
- Excluding the laws of physics, every rule has exceptions. Packaged rooftop gas equipment may have unexpectedly high O₂ (14 % O₂, or 4 % CO₂ natural gas) in order to control side vented vent temperatures (flame temperature is inversely proportional to excess air quantities).⁽⁵⁾ Variable capacity burners can fire at over 10 % O₂ at low fire. Older 1725 RPM burners without flame retention heads may have a setup range of 8 % to 10 % CO₂. Do not try to force a burner to operate at typical values if it does not want to willingly comply.
- As in any diagnostic procedure, no one thing is used as a stand-alone proof. We use our senses, instruments, knowledge and common sense to gather as much information as we can in order to support our

theory that a process is, or is not, functioning as it should.

- If a natural gas appliance is installed that requires field conversion to LP gas, do not operate the appliance until the conversion has been completed. If equipment set up for operation with natural gas is operated with LP gas, abundant CO will be produced, sooting is likely, and more than one kind of headache will be created. If the LP conversion cannot be done at the time of installation, disable the appliance so it cannot be operated until the conversion has been completed.
- The equipment, components and passageways must be clean. Components must be in good mechanical condition, physically and operationally, and properly aligned. High CO in the vent products usually points to shortcomings of one or more of those factors.
 - Heat exchanger passages must be clean and clear. Look for metal flaking, scale or soot especially at reduced dimensions around baffles.
 - Don't overlook the importance of injection (Bunsen type) burner venturi cleanliness. If the interior of the burner accumulates lint, develops rust or scale, or is coated with anything





that creates friction in the venturi, then less than normal primary air will be entrained and a dirty fire will develop that secondary air cannot clean up.

- Cold oil from an outdoor tank will cause increased oil flow through an oil nozzle and resists atomization and proper fuel/air mixing. Reduce nozzle size and increase pump pressure to clean up the fire.
- CO that steadily increases as the burner operates usually indicates combustion air and/or venting problems.

The furnace heat exchanger

The culprit is always a leaking heat exchanger, and leaking heat exchangers are deadly. The firefighters said so. But we know it ain't necessarily so. We know that restricted (and non-leaking) heat exchanger passages draw in less secondary air and elevate CO levels. We know that if the passageways in a non-leaking heat exchanger are restricted enough, then floating flames, increased CO and roll-out can occur. But unless a heat exchanger leak interferes with combustion or draft, the production of CO is likely to remain unchanged.

Even a new heat exchanger can leak. One of the requirements for heat exchanger manufacture stipulates in ANSI standard Z21.47 that a new furnace must have a leakage rate of no more than 2 percent of the total volume of flue gases. It may leak when it's new. Still, heat exchanger integrity is something that we try to monitor on an annual basis. Visual confirmation of a heat exchanger leak is usually one of our more difficult tasks. Before breaking out the visual inspection tools, or tearing down the furnace, **try some old tricks:**

- Close supply registers to increase static pressure. If there are no significant changes before and after the blower starts, then the heat exchanger is probably fine.
- Check O₂ (or CO₂) before and after the blower starts. Increased O₂ (or decreased CO₂) would indicate air leakage into the heat exchanger.
- With oil burners, compare stack O₂ to overfire O₂. Higher O₂ (lower CO₂) in the stack than overfire points toward a leaking heat exchanger.
- With direct-vent products, tee into the more positive ("+") pressure sensing tubes and see if there is a pressure change when the blower starts. A change in pressure differential can indicate a heat exchanger leak.

What not to rely on:

- Don't use a CO reading at a supply register to determine heat exchanger integrity. That only proves that the blower is operating. But two CO readings that show a difference between the return at the furnace (provided there are no return leaks) and the supply could point to a leaking heat exchanger.
- Don't rely on a change in CO readings in the vent when the blower starts up to determine a leaking heat exchanger. A leak in the heat exchanger might not have any effect on the quality of combustion and CO production.

Combustion air

Increasing CO and decreasing O₂ (or increasing CO₂) levels in the vent point to combustion air problems and possible venting problems.

We know that adequate combustion air must always be available for the operation of fossil fuel products. Just because provisions are made that meet code requirements doesn't mean combustion air is indeed adequate. Even spaces that are not considered confined (greater than 50 cubic feet per 1,000 BTU input) still may not have adequate infiltration for combustion air and venting.

We think nothing of creating access holes in ductwork for air measurements (dry and wet bulb temperature, velocity readings), but before we allow fossil fuel products to operate, shouldn't we make a hole in the building envelope to verify that we are not depressurizing the interior space?

All we need is a 3/16" or 1/4" hole to connect to the "+" side of our micro-manometer (Fluke 922 Airflow Meter) for checking pressure differential between the equipment room and outdoors. Start all products that vent to the outdoors: furnaces, boilers, water heaters, exhaust fans, clothes driers.

Close doors to the equipment room. Monitor the pressure differential between the equipment room and outdoors. Then open the equipment room door (if it is an interior door) and monitor the pressure differential again. Any indoor depressurization means you need more combustion air.

Venting

Increasing CO and decreasing O₂ (or increasing CO₂) levels in the vent indicate combustion air problems and possible venting problems. Most of the efforts to ensure adequate combustion air will apply to venting as well. But sometimes proper venting requires more than the provisions that were provided for combustion air.

Whatever leaves the equipment room through venting to the outdoors must be replaced by air from the outdoors. In the case of Category I vents, proper draft pressure is very low (-0.01" to -0.03" wc) and easily overcome by opposing forces such as return-duct leaks. Too much draft is also a problem because it can reduce product efficiency, lower vent temperatures and increase building depressurization.

Vent design and make up air must be carefully considered in order to ensure proper venting under all possible conditions. Vent gasses that spill from a draft diverter can ultimately lead to insufficient combustion air and high CO production. Combustion products from carelessly placed sidewall vents can be drawn into the occupied space due to building depressurization, or cause damaging condensation on structural surfaces or other equipment and cause operational problems with meters and regulators located in the vicinity.

Category I venting

- Use a draft gauge or your Fluke 922 Airflow Meter to check draft.
- If a cold vent with the appliance off can create a -0.03" wc draft, then the vent is probably adequate.

- Operating draft should be -0.01" wc for both natural draft and fan assisted products. Oil burners may require -0.03" wc draft to overcome heat exchanger internal pressure drops in order to maintain -0.01" wc overfire draft. Operating drafts over -0.03" wc should be avoided.
- A poorly venting chimney will spill flue products from the draft hood or draft diverter. CO₂ is slightly heavier than air and, as concentrations increase in the still air of the equipment room, will settle at floor level where the water heater burner is located. The burner is the first to be starved for combustion air and produce high levels of CO.
- If draft is poor, here are some key reminders:
 - Seal any and all return side duct leaks and filter access leaks.
 - Add a small register in the supply plenum to overcome equipment room depressurization.
 - Get as much vertical height off the flue collar as possible before the first elbow.
 - Draft is lost in any vent section that is less than vertical. Avoid sloped vent connectors. Use vertical for rise, then 1/4" per foot rise for lateral.
 - Increase vent connector size at the flue collar. The code allows for up to two sizes of vent connector upsizing when vent tables allow the selected size.
 - Seal vent leaks such as leaking cleanouts, poor vent connector fit in thimble, and poor thimble fit to clay tile liner.
 - If a masonry chimney has poor draft, installing a stainless steel corrugated reliner will increase friction and make the draft worse.
- Fan-assisted gas equipment is directly coupled to the vent without any means of draft control. A dual action



barometric draft control can be installed and adjusted to control draft.

- Draft hoods, including draft diverters integral to equipment, are vent de-couplers. This means furnace draft and chimney draft are separate. A good vertical vent draft will vent the equipment room and usually vent the appliance also, but an air curtain can be created at the draft hood and cause flue gas spillage, even when the vent draft is good. When this occurs, replacing the draft hood with a dual-action barometric draft control makes the appliance an integral part of the vent and allows draft to be controlled—just like oil burner vents, except oil vents require only single-action, not dual-action, barometric draft controls.

We began thinking about what characteristics of the system can affect the quality of combustion. In closing, maybe we should think about what characteristics of the system cannot affect the quality of combustion? Which list is longer?

Combustion air tips

Any return ducts located in the same space as the fossil fuel equipment must be sealed airtight.

Filter access panels must be sealed airtight.

Returns and filter access panels located in garages must be sealed airtight, airtight, airtight.

When combustion air openings to the outdoors are used, always use two: one high, one low. If ducts are used to connect to the outdoors, use two ducts, one for each opening. If only one combustion air supply or duct is used, it may act like a vent in the space and try to remove air, rather than make it available.

Add a small register to the supply trunk in the equipment room and make sure there are no return leaks. This will make available in the equipment room the same air that's available to the entire structure. Supplying 33 cfm per 100,000 BTU input allows for 50 % excess air.

When natural draft venting is used, double this amount. While you're at it, add the poor man's ventilation system. A duct with a balancing damper between a hood installed outdoors and the return duct will ensure an "on demand" pressurizing whole-house ventilation system.

Remember that any outdoor air access must not use a screen covering with less than 1/4" mesh. Smaller mesh screens can become lint traps which block the supply of outdoor air.

Various after-market combustion air systems are available for quick and easy installation.

A heat recovery ventilator could satisfy the requirement for combustion air, along with providing healthy indoor air.

See how much money is available for ensuring adequate ventilation, venting, and combustion air; then see how much is left over for the furnace or boiler purchase. If we didn't think our brakes would work,

we wouldn't even want to start our car. Don't even think about starting a fossil fuel product until you're sure that there is adequate ventilation air.

One would think that direct vent gas and oil products would not have combustion air problems. Yet improper design and installation or poor location can cause exhaust gas recirculation into the air intake and create elevated CO and even sooting. Chances of lingering direct-vent exhaust gasses increase with low velocity discharge, mild weather, dampness, low barometric pressure conditions, or any combination thereof. Follow the manufacturer's direct-vent application and installation requirements very carefully and don't use one manufacturer's guidelines for another manufacturer's product.

Footnotes

- (1) LEED-EB IEQ
LEED = Leadership in Energy Efficiency and Design
EB = Existing Building
IEQ = Indoor Environmental Quality
- (2) Rate of CO₂ generation per person = 0.0084 cfm x met rate
Resting met rate = 1.0
Light activity met rate = 1.2
Cooking met rate = 1.8
House cleaning met rate = 2.7
Callisthenics met rate = 3.5
Basketball met rate = 6.3
- (3) Calculating CO Air Free
(Oxygen in Air / (Oxygen in Air - Oxygen in Vent Products)) x CO in Vent Products
(21 / (21 - O₂ Sample)) x CO Sample
(Ultimate CO₂ / (Ultimate CO₂ - CO₂ Sample)) x CO Sample
Natural Gas: (12 / (12 - CO₂ Sample)) x CO Sample
LPG: (13.7 / (13.7 - CO₂ Sample)) x CO Sample
#2 Fuel Oil: (15.6 / (15.6 - CO₂ Sample)) x CO Sample
O₂ example: (21 % O₂ / (21 % O₂ - 6 % O₂ Sample)) x 100 ppm
CO Sample = 140 ppm CO Air Free
CO₂ example: (15.6 % CO₂ / (15.6 % CO₂ - 12.5 % CO₂ Sample)) x 100 ppm CO Sample = 124 ppm CO
- (4) Values based on National Comfort Institute recommendations developed from many years of research data
- (5) Gas Engineers Handbook

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Printed in U.S.A. 1/2010 3611250A A-EN-N

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