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EXECUTIVE SUMMARY

In 1995 Proctor Engineering Group (PEG) conducted a study of new homes in the Arizona Public Service (APS) territory. That study (Proctor et al. 1996) found that leaks in HVAC ductwork had a significant impact on cooling energy consumption (raising it by over 16%) and peak electric consumption. A program to reduce duct leakage could have significant benefit to the customers and to the utility. The same study also found that 82% of the homes in the study had building shells tight enough to cause concern about adequate ventilation (modeled ventilation rates were less than the ASHRAE standard). These tight building shells raise two concerns. First, any leakage imbalance (supply system vs. return system) will cause larger pressure effects in the home. If the supply leakage exceeds the return leakage the home will become depressurized, sometimes to the point that combustion appliances will spill combustion products into the living space. Second, reduced return leakage, if not accompanied by reduced supply leakage, can increase these effects.

Many of the new homes in the APS service territory have a variety of combustion appliances including gas ovens and ranges, gas fireplaces, gas water heaters, and gas dryers. This study investigated the interaction of these appliances with the building shell and duct system.

This study monitored a new residence, examining combustion product sources and their impact on indoor air quality. It provides recommendations based on the information from the monitored home, information from other investigations, and analysis of the physical principles governing ventilation and indoor air quality.

Natural gas is composed of mainly carbon and hydrogen. When natural gas is mixed with air in the presence of a flame the resulting combustion process produces heat, light, water vapor, and Carbon Dioxide (CO_2). Other gasses may also be present. These include Carbon Monoxide (CO), Oxides of Nitrogen (NO_x), Oxides of Sulfur, and Aldehydes. Of the potential gasses present CO poses the greatest risk in short term exposure. Carbon monoxide is created by a lack of available oxygen at the point of combustion. Malfunction of the combustion equipment coupled with the failure of the venting system to allow an escape path can result in CO levels in the house that can reach life threatening proportions. The long term effects of lower exposure are less apparent. There are risks of cardiovascular and respiratory damage from exposure above acceptable limits for a long term, for example, the length of the heating season (or several heating seasons).

NO_x also poses a health risk. Oxide of nitrogen is created by uncontrolled fuel burning (as in a residential furnace, oven, or range). Unvented combustion equipment and combustion equipment not venting properly will introduce NO_x into the living space. According to the California Environmental Protection Agency Air Resources Board: "NO_x can cause coughing, headache, and nausea. Short term exposures to NO_x at levels that can occur indoors can reduce breathing ability and increase the risk of respiratory infection, especially in young children. Long term exposure may result in permanent damage to lung tissues" (CEPA 1994). It is further noted that individuals with respiratory or heart problems and the elderly are especially sensitive to combustion pollutants.

In order to produce an indoor air quality problem from carbon monoxide (CO) three conditions must be met. First, the combustion equipment (stove, car, etc.) must be producing a significant amount of CO. Second, the combustion products must be released or brought inside the home. Third, the home must not have sufficient ventilation to dilute the CO to acceptable levels.

While lack of ventilation is often cited as the cause of indoor air quality problems, when the pollution is combustion products, ventilation is the least controllable variable. So called "natural" ventilation is dependent on many items: indoor/outdoor temperature differential, wind, building shell leakage, mechanical system interactions, building height, and location of building shell leaks. Since it is dependent on so many items it is quite variable even for a single home. Depending on "natural" ventilation to dilute combustion products is "asking for trouble". It is much safer to prevent the other two necessary conditions (CO production and combustion product delivery to the home)[1]. In short it is more reliable to reduce or eliminate the source of pollution than it is to dilute that that pollution.

Diagnostic testing performed in the study home indicated that the furnace, water heater and dryer were unlikely to pose serious threats of introduction of combustion products into the home without a catastrophic failure of some type (i.e., cracked heat exchanger). Testing indicated that the induced draft furnace was located in an attic that was completely decoupled from the home due to extensive ventilation of the attic. The water heater was located in a garage that was also decoupled from the house due to venting to outside and lack of large leakage areas to the house.

The primary source of combustion products in the occupied portion of the monitored home was the gas oven. The unvented gas oven produced both carbon monoxide (CO) and oxide of nitrogen (NOx) that were distributed throughout the home. This was seen by the elevated CO levels monitored above the oven, in the master bedroom, and on the fireplace mantle. Long term monitoring samples taken 2 feet above the stove/oven showed over 20 ppm during operation. Oven vent samples taken during the short term monitoring while on-site showed CO concentrations of 20-90 ppm with the oven in an as found condition. The oven experienced a CO spike at the beginning of the burn cycle but quickly fell to lower levels. Short term monitoring of NOx levels in the oven vent showed concentrations of 17 to 34 ppm. The NOx production of the oven has an inverse relationship with the production of CO. The NOx production decreased as CO production increased and increased as CO production decreased.

Fireplaces have a high potential for producing CO. Solid fuel (wood) burns incompletely producing high levels of CO in the combustion gasses. This incomplete combustion is one cause of the characteristic wood flame colors. Gaseous fuels (natural gas, propane, etc.) are less prone to incomplete combustion and production of CO. When gas fireplaces are designed and adjusted to provide flames that simulate a wood fire, they can produce elevated levels of CO.

The fireplace was evaluated in three conditions. The first condition was with the chimney open as found. The second condition simulated a damper in the chimney open to 1 inch. The third condition was with a mechanically induced backdraft of the fireplace.

Under the as-found condition, the CO sensor in the chimney detected 14 ppm after 20 minutes of burn. The chimney draft was 9 pascals at the end of the same time period.

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[1] Recent studies have shown that CO production and backdrafting are not always independent phenomenon.

When a 1" damper opening was simulated the sensor detected 23 ppm after 25 minutes. This was probably due to the reduction in dilution air entering the chimney rather than any effect on the quality of the burn. The chimney draft (measured above the simulated damper) was 17 pascals after 25 minutes. There was no combustion product spillage at any time during the "dampered" test.

When the house was depressurized by 19 pascals, the chimney spilled combustion products into the living space. This delivered nearly 100% of the combustion products into the house. This test raised the ambient CO levels to near 20 ppm near the fireplace within 20 minutes. Levels in the rest of the house ranged from 6 to 9 ppm This level of depressurization is unlikely to occur in this home under its current configuration. Other homes have different characteristics and will react differently.

Conclusions

Combustion appliances are a source of concern in residential new construction. These concerns are particularly relevant to homes with tight building shells and high neutral pressure planes. New residences in Phoenix, by virtue of their typical slab on grade construction and stucco exteriors, have both low leakage and high neutral pressure planes.

The Phoenix area is famous as an area for retirees. The elderly and individuals with respiratory or cardiovascular problems are particularly susceptible to combustion pollutants.

The short-term monitoring showed potential for indoor air quality problems from the gas appliances. The stove/oven, fireplace and water heater are all potential sources of both carbon monoxide and NOx. The indoor air quality is directly affected by the operation of unvented combustion appliances inside the building envelope. The oven produced CO and NOx in normal operation. These combustion products were delivered to the occupied areas of the home.

Recommendations

1) Do not use unvented combustion appliances in the home.

2) Do not use open combustion appliances in the home where the potential exists for depressurization.

3) Design and maintain all natural gas appliances to produce less than 100 ppm CO in the flue.

4) Install CO detectors in all homes with any combustion appliance or attached garage.

These recommendations are not made lightly and are controversial. Should Arizona Public Service decide to encourage duct sealing and other shell tightening measures, and if the political situation is such that the above recommendations are not followed, then all feasible measures should be undertaken to reduce the potential for health hazards associated with combustion appliances in tight homes. These measures could include:

1) Install CO detectors in all homes with any combustion appliance or attached garage.

2) Evaluate all combustion appliances for draft and venting both before and after duct sealing, shell sealing, or closed cavity insulation work. Compare the results to written standards and mitigate if necessary.

3) The CO production of all combustion appliances should be measured and mitigation completed both before and after duct sealing, shell sealing, or closed cavity insulation work.

4) Under no condition should the neutral pressure plane be higher than the top of the chimney or vent for a non-forced draft combustion appliance.

BACKGROUND

In 1995, Proctor Engineering Group (PEG) conducted a study of new homes in the Arizona Public Service (APS) territory. That study (Proctor et al. 1996) found that leaks in HVAC ductwork had a significant impact on cooling energy consumption (raising it by over 16%) and peak electric consumption. A program to reduce duct leakage could have significant benefit to the customers and to the utility. The same study also found that 82% of the homes in the study had building shells tight enough to cause concern about adequate ventilation (modeled ventilation rates were less than the ASHRAE standard). These tight building shells raise two concerns. First, any leakage imbalance (supply system vs. return system) will cause larger pressure effects in the home. If the supply leakage exceeds the return leakage the home will become depressurized, sometimes to the point that combustion appliances will spill combustion products into the living space. Second, reduced return leakage, if not accompanied by reduced supply leakage, can increase these effects.

Many of the new homes in the APS service territory have a variety of combustion appliances including gas ovens and ranges, gas fireplaces, gas water heaters, and gas dryers. This study investigated the interaction of these appliances with the building shell and duct system.

This study monitored a new residence, examining combustion product sources and their impact on indoor air quality. It provides recommendations based on the information from the monitored home, information from other investigations, and analysis of the physical principles governing ventilation and indoor air quality.

In order to produce an indoor air quality problem from carbon monoxide (CO) three conditions must be met. First, the combustion equipment (stove, car, etc.) must be producing a significant amount of CO. Second, the combustion products must be released or brought inside the home. Third, the home must not have sufficient ventilation to dilute the CO to acceptable levels.

While lack of ventilation is often cited as the cause of indoor air quality problems, when the pollution is combustion products, ventilation is the condition that is the most difficult to control. So called "natural" ventilation is dependent on many items: indoor/outdoor temperature differential, wind, building shell leakage, mechanical system interactions, building height, and the location of building shell leaks. Since it is dependent on so many items it is quite variable even for a single home. Depending on "natural" ventilation to dilute combustion products is "asking for trouble". It is much safer to prevent the other two necessary conditions (CO production and combustion product delivery to the home). In short it is more reliable to reduce or eliminate the source of pollution than it is to dilute that that pollution.

Combustion Contaminants

Natural gas is composed of mainly carbon and hydrogen. When natural gas is mixed with air in the presence of a flame the resulting combustion process produces heat, light, water vapor, and Carbon Dioxide (CO2). Other gasses may also be present. These include Carbon Monoxide (CO), Oxides of Nitrogen (NOx), Oxides of Sulfur, and Aldehydes. Of the potential gasses present CO poses the greatest risk in short term exposure. Carbon monoxide is created by a lack of available oxygen at the point of combustion. Combustion equipment that is not properly completing the burn process will create CO. If CO is introduced into the living space and the amount of ventilation in the house is low, CO levels can elevate to the point of exceeding short term exposure standards. ASHRAE has set a standard of 9 ppm short term exposure in living spaces. OSHA has set a standard of 35 ppm maximum exposure averaged over an 8 hour period. Malfunction of the combustion equipment coupled with the failure of the venting system to allow an escape path can result in CO levels in the house that can reach life threatening proportions. The long term effects of lower exposure are less apparent. There are risks of cardiovascular and respiratory damage from exposure above acceptable limits for a long term, for example, the length of the heating season (or several heating seasons).

NOx also poses a health risk. Oxide of nitrogen is created by uncontrolled fuel burning (as in a residential furnace, oven, or range) Typical NOx generation is in the order of 0.1 lb. per 1,000,000 Btu of heat input (ASHRAE 1997). Differences in emissions occur from the amount of nitrogen in the fuel and the flame temperature. Lower flame temperatures reduce NOx emissions but increase CO emissions. Unvented combustion equipment and combustion equipment not venting properly will introduce NOx into the living space. According to the California Environmental Protection Agency Air Resources Board: "NOx can cause coughing, headache, and nausea. Short term exposures to NOx at levels that can occur indoors can reduce breathing ability and increase the risk of respiratory infection, especially in young children. Long term exposure may result in permanent damage to lung tissues. NOx or some if its acidic by-products may also magnify the health effects of other air pollutants such as ozone and particles." (CEPA 19945). It is further noted that individuals with respiratory or heart problems and the elderly are especially sensitive to combustion pollutants.

The World Health Organization has set standards for NOx exposure of 0.08 ppm for a 24 hour period and 0.21 for a one hour period. Supplement to Indoor air Quality Guideline No. 2, Combustion Pollutants in your home May, 1994 p16 Table 2

Potential Sources of Combustion Contaminants

All combustion equipment can produce contaminants. Vented appliances, such as furnaces and water heaters can have a combination of problems: improper installation or adjustment, inadequate venting system design or operation, or sufficient negative pressure in the home to cause backdrafting of the vent system.

Installation of the combustion equipment outside the apparent building envelope does not ensure that the combustion products are irrelevant to the indoor air quality. Recent studies show that CO production in garages or attics can develop into an indoor air quality problem due to the connection between the space and house in conjunction with sufficient pressure imbalances. For example, a study of 50 houses with two or more CO alarm related service calls was completed for Minnegasco (Klossner 1996). Long term monitoring and short term testing confirmed the most likely source of CO in the study homes was the garage. Seventy-four percent of the homes were determined to have a potential for CO introduction from the garage (the second most likely source was gas cooking appliances). Pressure diagnostic testing confirmed that most houses had communication between the garage and house that would allow CO to enter the house if a driving force were present (i.e., a pressure imbalance).

Any appliance that is producing CO is a risk for contaminating the indoor air. The CO production lowers the efficiency of the appliance and decreases the temperature of the exhaust gases. Lower temperature combustion products are more susceptible to pressure fluctuations and downdrafts.

Background

Fireplaces have a high potential for producing carbon monoxide. Solid fuel (wood) burns incompletely producing high levels of CO in the combustion gasses. This incomplete combustion is one cause of the characteristic wood flame colors. Gaseous fuels (natural gas, propane, etc.) are less prone to incomplete combustion and production of CO. When gas fireplaces are designed and adjusted to provide flames that simulate a wood fire, they can produce elevated levels of CO.

Unvented appliances, such as gas stove/ovens are always contaminate sources. The amount of the contamination varies by use, adjustment and ventilation rate of the structure.

Concerns with Combustion Appliances in Residential Structures

There are four concerns with combustion appliances in residential structures. The first is incomplete combustion and the generation of CO. The second is the generation of other pollutants that occur even with a complete burn. The third is combustion products entering the house. The fourth is low ventilation rates. The lines of defense against indoor air quality and health problems are thus clearly drawn. First all combustion appliances should be designed and maintained to ensure a complete burn. Second, combustion products should not be allowed to enter the house. This approach provides two levels of protection against the most immediately deadly pollutant (CO) and a protection against other pollutants as well.

It has been assumed that venting combustion products and CO production were generally independent. Recent studies have found that otherwise clean burning appliances produce significant amounts of CO when backdrafting. For example, in the Klossner (1996) study 17% of the homes with multiple unexplained CO alarm incidents had furnaces or water heaters that "produced CO only during backdrafting".

A Gas Research Institute sponsored study (Grimsrud et al. 1995) reports:

> One of the ten houses investigated in this study had conditions which combined to create dangerously high levels of carbon monoxide in the indoor air. Very high levels of CO were observed to be produced by the furnace during the short-term tests and caused severe IAQ problems during the long-term measurement period due to stable backdrafting in the vent.

The furnace in the Grimsrud home did not produce excessive CO under normal draft, but did produce excessive CO under backdraft.

Venting Combustion Contaminants

Much of the work to date on residential combustion safety has centered on the design of the venting or chimney. The ability of the venting system to remove combustion products is related to the height of the vent, the amount of restriction in the venting system (diameter, turns, slope, etc.), the volume of products to be vented, and the temperature differential between the vented gas temperature and the outside temperature. This work has been incorporated into building codes that prescribe the height and "restrictiveness" for different types of appliances and different volumes of combustion products.[2]

[2] Combustion product and dilution air volumes are approximated by the input rate of the appliance.

Background

A portion of Table C-9 of Appendix C of the Uniform Mechanical Code (ICBO/IAPMO 1988) is reproduced in Table 1-1 as an illustration of these concepts.

Table 1-1 Code Venting Requirements

TABLE NO. C-9-B—CAPACITY OF TYPE B DOUBLE-WALL VENTS WITH TYPE B DOUBLE-WALL CONNECTORS SERVING A SINGLE APPLIANCE

Total Vent Height H (feet)	Total Vent Lateral L (feet)	Vent Diameter—(Inches)													
		3	4	5	6	7	8	10	12	14	16	18	20	22	24
		Maximum Appliance Input Rating in Thousands of Btu/h													
6	0	46	86	141	205	285	370	570	850	1170	1530	1960	2430	2950	3520
	2	36	67	105	157	217	285	455	650	890	1170	1480	1850	2220	2670
	6	32	61	100	149	205	273	435	630	870	1150	1470	1820	2210	2650
	12	28	55	91	137	190	255	406	610	840	1110	1430	1795	2180	2600
8	0	50	94	155	235	320	415	660	970	1320	1740	2220	2750	3360	4010
	2	40	75	120	180	247	322	515	745	1020	1340	1700	2110	2560	3050
	8	35	66	109	165	227	303	490	720	1000	1320	1670	2070	2530	3030
	16	28	58	96	148	206	281	458	685	950	1260	1600	2035	2470	2960
10	0	53	100	166	255	345	450	720	1060	1450	1925	2450	3050	3710	4450
	2	42	81	129	195	273	355	560	850	1130	1480	1890	2340	2840	3390
	10	36	70	115	175	245	330	525	795	1080	1430	1840	2280	2780	3340
	20		60	100	154	217	300	486	735	1030	1360	1780	2230	2720	3250
15	0	58	112	187	285	390	525	840	1240	1720	2270	2900	3620	4410	5300
	2	48	93	150	225	316	414	675	985	1350	1770	2260	2800	3410	4080
	15	37	76	128	198	275	373	610	905	1250	1675	2150	2700	3300	3980
	30		60	107	169	243	328	553	845	1180	1550	2050	2620	3210	3840
20	0	61	119	202	307	430	575	930	1350	1900	2520	3250	4060	4980	6000
	2	51	100	166	249	346	470	755	1100	1520	2000	2570	3200	3910	4700
	10	44	89	150	228	321	443	710	1045	1460	1940	2500	3130	3830	4600
	20	35	78	134	206	295	410	665	990	1390	1880	2430	3050	3760	4550
	30		68	120	186	273	380	626	945	1270	1700	2330	2980	3650	4390

The less researched side of combustion product venting is the interaction with the building. It is often true that a building offers less restriction to flow than the venting system. This is particularly true for open plan residences. Through a variety of interactions the home can become "a better chimney than the chimney".

House Interactions

Interaction between the house and the combustion appliances can be very complex. Multiple parameters interact to determine how combustion equipment will operate within a given structure. It is rare to see the appliance's generation of CO tied directly to the structure, for example, not having enough air supplied to the zone containing the combustion appliance. Most commonly CO is generated by the misadjustment of the appliance, for example, the burners being starved for primary air or the flame being allowed to impinge on a surface. It is not as rare however to see factors within the structure adversely affecting the venting system's ability to remove all the combustion products.

Factors that can influence the venting system include:

- Duct leakage - when ducts leak to outside the conditioned space, duct leakage dominated by either the supply or return creates a pressure imbalance within the house. Supply leaks expel air from inside to outside thereby creating a negative pressure in the house. Return leaks draw outside air in and pressurize the house. If the leakage on the supply and return side are equal no pressure imbalance is created.

- Door closure - Newer houses in the Phoenix area are commonly constructed with central return system. This type of system usually has one return for each air handler located in a central location within the house. When the door to a room is closed the room becomes pressurized and the main body of the house becomes depressurized. This occurs because the door restricts the pathway of the supply air to the return grille. The effect of door closure is controlled by the air flow from the supply register, the area under the door to allow air to escape from the room and the leakage area of the room.

- Shell leakage - Tight building envelopes make the house more susceptible to pressure imbalances. A tight shell keeps the house from being able to "self correct" to pressure imbalances. Tight building envelopes can increase combustion zone depressurization and interfere with proper venting.

- Neutral pressure plane - Buildings with high neutral pressure planes can promote a downdraft on the combustion venting when the appliance is off. Depending on the situation, when the appliance fires, the venting can be a bi-stable system that can become stable with the combustion products exiting through the building or through the vent system.

Neutral Pressure Plane

The ability of a chimney or vent to draw combustion products away from the combustion appliance and out of the home is dependent on a number of factors. One of the often overlooked factors is the neutral pressure plane of the home. In the winter, the neutral pressure plane is the level below which outside air will be drawn into the building if a leak is directly open to outside. Above the neutral pressure plane, direct leaks will exhaust air. The neutral pressure plane (NPP) is illustrated in Figure 1-1.

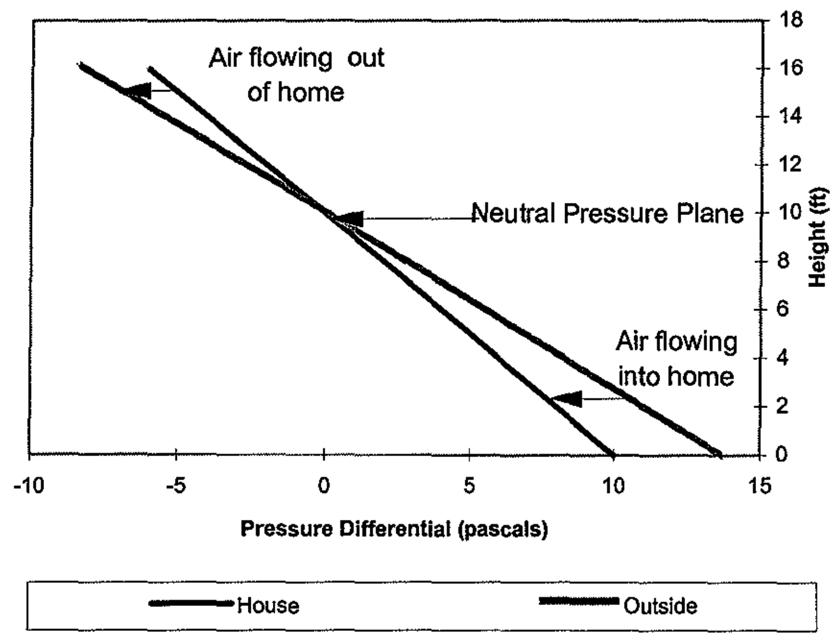

Figure 1-1. Neutral Pressure Plane Illustration (10 ft on a 16 ft high home)

Background

When a chimney is filled with hot gasses, the buoyant gasses rise through the chimney and pull in house air. The house air dilutes the combustion products and is exhausted outside with the combustion products. This is illustrated in Figure 1-2.

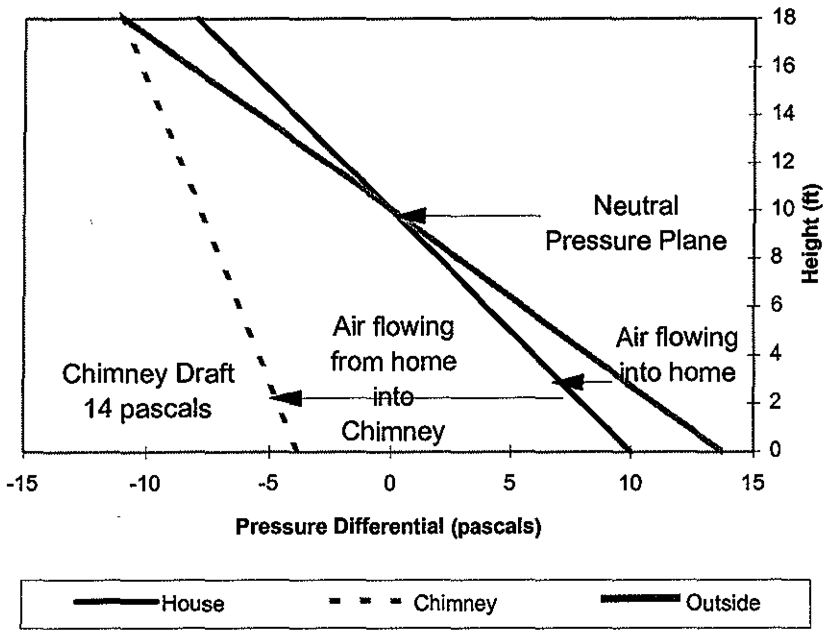

Figure 1-2 Chimney Function Illustration (18 ft. Chimney on a 16 ft. high home with a NPP at 10 ft.)

When a home is depressurized by exhaust appliances or dominant supply leaks, the neutral pressure plane rises often to above ceiling level. A depressurization of 4 pascals can raise the NPP by 10 ft. This reduces the Chimney draft as illustrated in Figure 1-3.

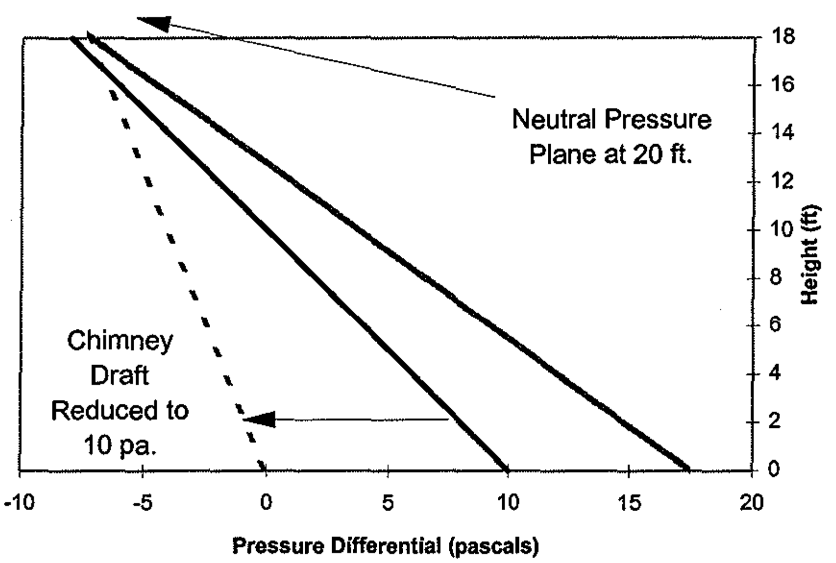

Figure 1-3. Effect of Exhaust Fans and Supply Leakage (18 ft. Chimney on a 16 ft. high home with a NPP at 20 ft.)

Background

If the Chimney is short (meets code, but is on the single story portion of a split level home) The top of the chimney can be below the Neutral Pressure Plane. This further reduces the Chimney draft as illustrated in Figure 1-4

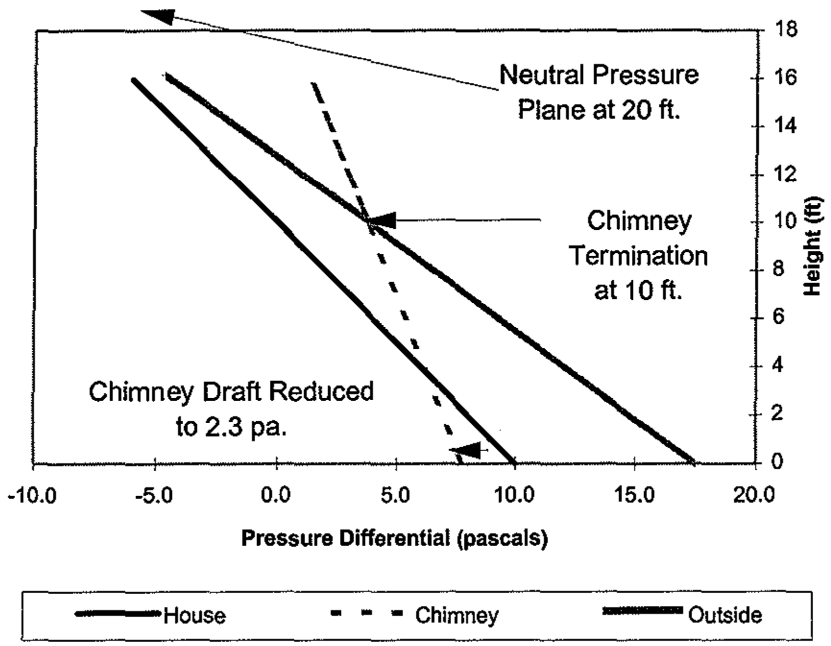

Figure 1-4. Effect of Exhaust Fans and Short Chimney (10 ft. Chimney on a home with a NPP at 20 ft.)

If the Chimney is shorter than the height of the Neutral Pressure Plane then when the chimney is cool it can reverse the flow (down the Chimney into the house). This is illustrated in Figure 1-5.

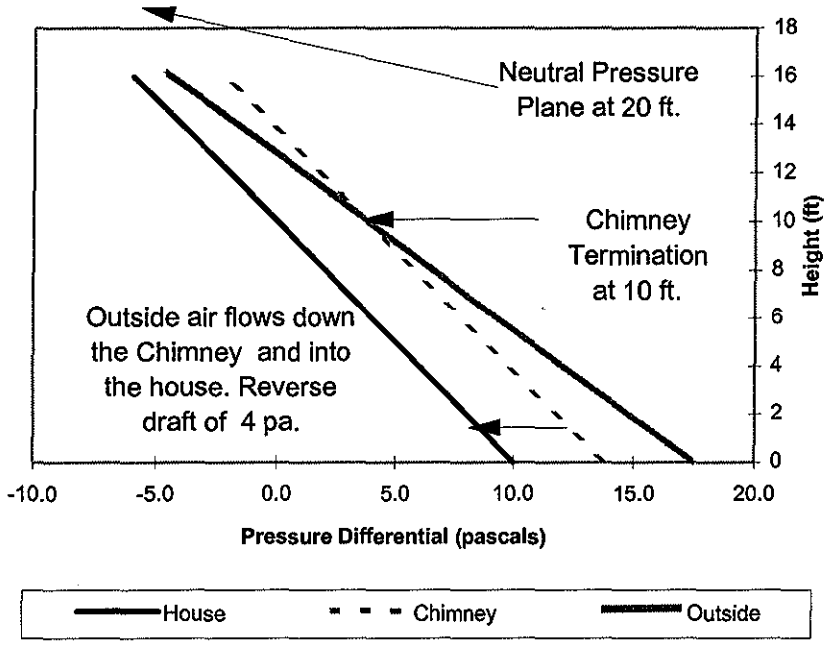

Figure 1-5 Effect of Exhaust Fans, Short Cool Chimney (10 ft. Chimney on a home with a NPP at 20 ft.)

If the combustion appliance starts and is unable to warm the descending air column in the Chimney, the chimney cools to outside temperature and a stable reverse draft can be established. This is illustrated in Figure 1-6.

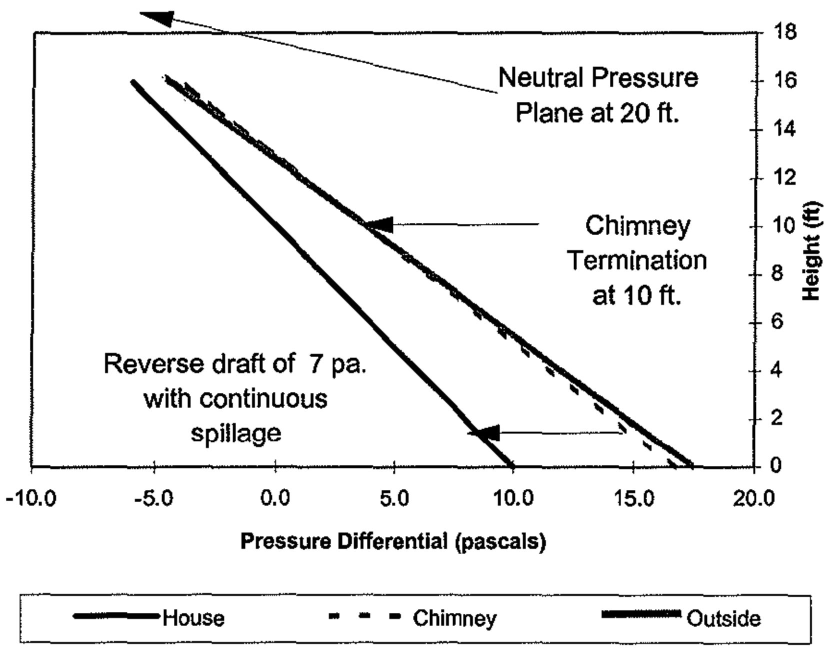

Figure 1-6. Effect of Exhaust Fans, Short Cool Chimney with Continuous Backdraft (10 ft. Chimney on a home with a NPP at 20 ft.)

Gas Fireplace

Fireplaces have a high potential for producing CO. Solid fuel (wood) burns incompletely producing high levels of CO in the combustion gasses. This incomplete combustion is one cause of the characteristic wood flame colors. Gaseous fuels (natural gas, propane, etc.) are less prone to incomplete combustion and production of CO. When gas fireplaces are designed and adjusted to provide flames that simulate a wood fire, they can produce elevated levels of CO.

In order to produce an indoor air quality problem from CO three conditions must be met. First, the combustion appliance must be producing a significant amount of CO. Second, the combustion products must be released inside the home. Third, the home must not have sufficient ventilation to dilute the CO to acceptable levels.

While lack of ventilation is often cited as the cause of indoor air quality problems, when the pollution is combustion products, it is the condition that is the most difficult to control. So called "natural" ventilation is dependent on many items: indoor/outdoor temperature differential, wind, building shell leakage, mechanical system interactions, building height, and the location of building shell leaks. Since it is dependent on so many items it is quite variable even for a single home. Depending on "natural" ventilation to dilute combustion products is "asking for trouble". It is much safer to prevent the other two necessary conditions (CO production and combustion product delivery to the home).

Gas Oven and Surface Units

It is almost universal practice for ovens and surface units to be vented directly into the home. As homes are built more tight, ventilation is decreased and the levels of combustion contaminants increases.

Gas stoves have been linked to elevated mean indoor Nitrogen Dioxide (NO_2) levels by numerous investigators. A study of 50 homes in Wisconsin (Quackenboss et al. 1984) monitored NO_2 levels in four locations throughout the homes. Both the magnitude and variability of NO_2 concentrations were higher in homes with gas stoves (mean 72 $\mu g/m^3$ std. dev. 71 $\mu g/m^3$) than in homes with electric stoves (mean 13 $\mu g/m^3$ std. dev. 7 $\mu g/m^3$).

In a 1987 Pennsylvania study of low income weatherization, NO_2 concentrations were measured in the fall (prior to air sealing) and mid-winter (after air sealing). There were three homes in Pittsburgh that had electric ranges. These three homes averaged 0.013 ppm NO_2 in both the fall and mid-winter. On the other hand, the 12 homes in Pittsburgh equipped with gas ranges had an average NO_2 concentration of 0.046 ppm prior to air sealing and 0.071 ppm after air sealing. A number of these units exceeded the 0.08 ppm World Health Organization for 8 hour exposure. The average measured mid-winter NO_2 concentrations in the Philadelphia gas range homes was 0.09 ppm (above the WHO standard). (GRI 1987)

INSTRUMENTATION AND LONG TERM OBSERVATION

A Campbell Scientific CR10 data acquisition system was installed to document the short term tests and observe the operation of the home over a portion of the heating season. The equipment captured data from all channels every 5 seconds and recorded the minimum, maximum and average reading every 15 minutes. Pressure, Carbon Monoxide, and Temperature sensors were used to monitor all of the combustion appliances and ambient conditions. Intensive data collection was completed for all channels during the first furnace or fireplace cycle of the day. The stored data was automatically collected by modem every day.

The data points gathered with the CR10 are summarized in Table 2-1.

Table 2-1. Sensor Locations

CR10 Input	Location	Parameter
Carbon Monoxide #1	Fireplace Mantle	Ambient CO level in vicinity of fireplace (living room)
Carbon Monoxide #2	Fireplace Vent	CO level 24" from the vent opening at the hearth
Carbon Monoxide #3	Stove/Oven	CO level approximately 24" above the stove surface (mounted under cabinet)
Carbon Monoxide #4	Master Bedroom	Ambient CO level in the master bedroom (at the night stand)
Carbon Monoxide #5	Outdoors	Ambient CO level measured 10' from the house (in the back yard)
Pressure #1	Fireplace Mantle	Pressure differential between living room and outdoors
Pressure #2	Master Bedroom	Pressure differential between master bedroom and outdoors
Pressure #3	Furnace Vent	Pressure differential between furnace vent and attic
Pressure #4	Furnace Return Plenum	Pressure differential between return plenum and attic
Pressure #5	Water Heater Vent	Pressure differential between water heater vent and garage
Temperature #1	Fireplace Mantle	Temperature of living room
Temperature #2	Fireplace Vent	Temperature of fireplace vent (detects burner operation)
Temperature #3	Master Bedroom	Temperature of master bedroom
Temperature #4	Outdoors	Temperature outdoors
Temperature #5	Furnace Vent	Temperature of furnace vent (detects burner operation)
Temperature #6	Water Heater Vent	Temperature of water heater vent (detects burner operation)

CO Sensors

City Technology Carbon Monoxide sensors were used to measure CO levels with the data acquisition system. The CO sensors have an operating range of 0 to 2000 ppm, with a resolution of 0.5 ppm. The Energy Conservatory supplied the sensors in a metal enclosure, outfitted with a standard phone jack for power and signal. PEG developed a pumped system for sampling high temperature locations (combustion appliance vents).

Pressure Sensors

SETRA model 264 pressure transducers were used to measure pressure differentials between the interior and outdoors as well as the combustion appliance venting systems and the combustion appliance space. The sensors have a full scale bi-directional operating range of 0 to 0.1"WC (25 Pascals) with an accuracy of +/- 0.25% full Scale (0.002"WC or 0.5 Pascals).

Temperature Sensors

Temperatures were measured using Omega Engineering 36 gauge beaded junction type K and T insulated thermocouples. Type K thermocouples were used in the high temperature vent systems. Type T thermocouples were used to measure lower temperature ambient conditions.

Other Equipment and Instrumentation

In addition to the CR10 and sensors, a selection of hand held equipment was available during the short term monitoring:

An Energy Conservatory blower door, Duct Blaster™ and two channel digital pressure gauge were used to determine house leakage, duct leakage, and to diagnose connections between various zones.

Gas service equipment was available to measure gas pressure, combustion efficiency, gas flow rates, etc. This equipment was used to determine the operating BTU/Hr input of the combustion equipment and make adjustments for the various scenarios tested during the short term testing.

Handheld Bacharach digital analyzers with electrochemical sensors were used to measure Carbon Monoxide (CO), Nitrogen Oxide (NOx), and Sulfur Dioxide (SO2). The analyzers provide continuous sampling and display. All three analyzers have a range of 0 to 2000 ppm and an accuracy of +/- 5% of the reading. The Sulfur Dioxide sensor malfunctioned early in the test protocol and did not provide any useful information.

SHORT TERM TESTS

This study took place from March 3, 1997, to April 9, 1997. A battery of tests was conducted on a new home in Phoenix, Arizona. The testing was divided into two segments: short-term intensive measurements, and longer term observation.

The first set of tests (baseline and short term) was completed while the team of investigators from Proctor Engineering Group were on-site. The homeowners were given an incentive to vacate their house for a week so the investigators could complete tests at various times of the day without inconvenience to the occupants.

The short-term tests examined the combustion appliances and how those appliances interacted with the dynamic parameters of the home. These tests characterized: the connections between combustion zones and the occupied portion of the home, the operation of the equipment under different conditions, and the depressurization potential of the home. Since the investigators were present in the home a wide variety of conditions could be tested, including conditions of high and low duct leakage, as well as mechanically induced house depressurization. The instrumentation for the long term testing was installed prior to the short term tests to help document the results. Results were recorded by both hand-held testing equipment and the data acquisition system. The data acquisition equipment remained after the short term tests to monitor the building operation under normal conditions.

Several data points were gathered in addition to the sensors connected to the CR10. The hand held Bacharach Monoxor II (Carbon Monoxide analyzer) was used to verify the City Technology CO sensors and to measure additional locations. CO reading locations included; the living room, the garage near the water heater, the fireplace vent, the oven vent, the furnace flue, the water heater flue, and the furnace return and supply plenums. The Bacharach Nonoxor II (Nitrogen Oxide) was used to measure NOx levels in the vent of the oven, the vent of the fireplace, the flue of the furnace, and the flue of the water heater. The Energy Conservatory two-channel digital pressure gauge was used to measure zone pressure differentials and draft in the vents of the fireplace, furnace, and water heater.

Depending on the house and its condition, several scenarios could be examined during short term testing. These scenarios included:

Baseline - the baseline tests determine how all of the appliances operate in their as-found condition.

Depressurization - these tests determine how all of the appliances operate under house depressurization in their as found condition. Tests were completed to determine the scenario that induced the greatest negative pressure in the living space of the home.

Appliances Clean - this test determines the effect on indoor CO concentrations when the appliances are adjusted to create the minimum levels of CO. The house configuration is the same as in the depressurization tests.

Short Term Tests

Appliances Dirty - this test determines the effect on indoor CO concentrations when the appliances are adjusted to produce more CO. The house configuration is the same as in the depressurization tests.

Fireplace Adjusted for Appearance - this test determines the CO concentrations at the fireplace vent and in the living space when the fireplace is adjusted for best flame appearance (most like a wood fire). The house configuration is the same as in the depressurization tests.

Fireplace Adjusted to Manufacturers Specifications - this test determines the CO concentrations at the fireplace vent and in the living space when the fireplace is adjusted to the manufacturer's installation instructions. The house configuration is the same as in the depressurization tests.

Building Shell to 0.30 ACH - this test determines the effect on the building when the shell leakage is reduced to 0.30 Air Changes per Hour. This is the level of ventilation observed in the testing completed on the Phoenix housing stock during the APS Assessment of HVAC Installations in New Homes (which is below the ASHRAE recommended 0.35 ACH level).

Minimum Return Duct Leakage, 20 % Supply Duct Leakage - this test determines the effect of operating the forced air heating system with high return leakage and low supply leakage. The test determined the effect of imbalanced duct leakage on the operation of the combustion appliances.

Pressure Induced Fireplace Backdraft - this test determines the amount of depressurization required to backdraft the fireplace, the effect of the backdrafting on CO levels, and the effects on the operation of the other combustion appliances.

Pressure Induced Water Heater Backdraft - this test determines the amount of depressurization required to backdraft the water heater (located in the garage), the effect of the backdrafting on CO levels, and the effects on other combustion appliances.

Attic Power Vent Water Heater - this test determines the effects of a powered attic ventilation fan on water heater venting and CO production. It also tests for the introduction of combustion products from the water heater into the living space.

Attic Power Vent Fireplace - this test determines the effect of a powered attic ventilation fan on the venting of the fireplace and the introduction of combustion products from the fireplace into the living space.

HOUSE DESCRIPTION

The test site was located in the northwestern section of the Phoenix metropolitan area in a relatively open area. The house was located on a quiet residential street with very little auto traffic and was backed by open space behind the property. The remote setting helped to keep outdoor ambient CO levels low. The house was a 2300 sq. ft., three-bedroom home, typical of the style currently being built in the Phoenix area. The house is of frame construction, is built on a slab, has a stucco exterior and a two-car attached garage. The majority of the interior is cathedral ceiling. The measured volume was 23,234 Cu. Ft.

Combustion Appliances In the Home

The test home had five combustion appliances: a gas cloths-dryer, a gas furnace, a gas water heater, a gas fireplace, and a gas range/oven.

The dryer is located in a laundry room directly off the garage. The combustion products are vented to the attic via a hard pipe vent from the dryer to a termination inside the attic near the peak of the roof. Enclosed spaces such as laundry rooms are often easy to depressurize but this room had a large undercut on the door.

The furnace, which has a rated input of 100,000 Btu/hr is located in a very well ventilated attic. Pressure diagnostic tests show the attic ventilation areas far exceed the leakage areas between the house and the attic.

The water heater, which has a rated input of 40,000 Btu/hr, is in the garage. The garage is also very well ventilated to the exterior and effectively isolated from the conditioned space of the home.

The fireplace is located in the living room in the center of the house. It has an 8" diameter triple wall metal chimney without a damper. The chimney extends to a height of approximately 16 foot without turns. This provides the appliance with a substantial on-cycle as well as off-cycle draft. The measured input was 60,000 Btu/hr.

The most likely source of combustion contaminates in this house is the gas oven/stove. The oven has a rated input of 16,000 Btu/hr and the stove burners (4) are all rated at 9,000 Btu/hr. The kitchen is open to the living room area, which contains the fireplace. The living room/kitchen area is connected to the master bedroom area by a hallway approximately 20' long.

Blower door testing

The home was set-up with exterior doors and windows closed and interior doors open. The blower door pressurized the home to 50 Pascals with an air flow of 2547 CFM. Using the LBL infiltration model, the natural infiltration is estimated to be 0.24 air changes per hour. This is slightly less than the average air change rate found in the 1995 APS study of 0.29.

House Description

Both the attic and garage were tested for leakage connections to the interior. These zones were 1.5 pascals with respect to outside when the house was at 50 pascals to outside. This indicates that the leakage areas from both the garage and the attic to outside were approximately 10 times larger than the leakage areas from the house to these spaces.

The investigators observed that the majority of the shell leakage was from the living space to the attic. With the slab-on-grade foundation and stucco exterior walls, the only real possibilities for leakage (other than at ceiling penetrations) were at the few exterior wall penetrations, the windows, and the doors.

Duct test procedure

The entire duct system was located in the attic. The return consisted of an 18" diameter single flex duct approximately 15' long. The flex duct supply consisted of 12 runs to individual registers located either in the ceiling or high on the sidewalls of areas with cathedral ceilings.

The duct leakage testing was conducted with a Duct Blaster™. The tests included: supply leakage, return leakage, total leakage, supply return leakage ratio, and leakage to the exterior. The standard leakage tests were conducted with the supply and return grilles sealed. The Duct Blaster™ was mounted at the air-handler blower-compartment door and tests were run with the system pressurized to 25 pascals.

Supply leaks accounted for 88% of the total leakage. The duct leakage was 296 CFM25. Supply leakage alone was 262 CFM25.

With the duct system located in the attic, most of the measured duct leakage is to the exterior. The only "interior" leaks are around the register seals and boot connections. Leakage to the exterior was measured with the blower door and Duct Blaster™. Both the ducts and the home were pressurized to 25 pascals with respect to the outside. The duct leakage to the exterior was 208 CFM25.

The system operating duct leakage is dependent on the actual pressure across the leakage site (as opposed to the test pressure of 25 pascals). When corrected for operating pressure, the baseline duct leakage was 171 cfm in the supply and 22 cfm in the return.

RESULTS

The short term testing gathered data from all CR10 sensors in 15 second intervals and measurements by on-site personnel. The house was left in the baseline condition for the long-term monitoring, except for a 22% supply duct leak.

Baseline Appliance Tests

Table 5-1. Combustion Products - "As-found"
(at 5 minutes of continuous burn)

Appliance	Test Location	CO (ppm)	NOx (ppm)
Fireplace	Chimney	21	5
Oven	Vent Termination	90	17
Furnace	Flue	2	35
Water Heater	Flue	3	83
Gas Dryer	Vent	2	0

The five minute test provides an indicator of the CO production after the initial warm-up stage has occurred. The oven had a CO production spike at the beginning of the cycle. Spikes are common at the start-up of ovens. The input, burner primary air setting and burner alignment were all checked and eliminated as options for reducing oven CO production.

Depressurization Tests

Depressurization tests were conducted with baseline combustion conditions. The maximum depressurization occurred with all exterior windows and doors closed, three of the four interior bedroom doors closed, all exhaust appliances operating (dryer, bath fans, and range hood) and all combustion appliances operating.

Turning on the furnace[3] resulted in a house depressurization of 1 pascal indicating the dominance of supply leakage over return leakage. The exhaust devices (two bath fans, cloths-dryer, and range hood) had no measurable house pressure effect under the test conditions and method. Closing three bedroom doors with the furnace on resulted in an additional house depressurization (beyond the supply dominant effect) of 2 pascals.

[3] House tested in the "as-found" condition prior to creating the 22% supply duct leak.

Appliances Clean and Dirty

Appliances Clean - None of the appliances could be adjusted to levels of carbon monoxide production levels below the as-found condition.

Appliances Dirty - Three of the five combustion appliances were adjusted to create higher levels of CO. The gas log fireplace had no adjustment for affecting CO production (neither a primary air shutter nor a gas pressure regulator was present). The oven, water heater and furnace were adjusted to create higher CO by reducing primary and secondary air sources. No attempt was made to create higher levels of CO on the dryer.

Table 5-2. Combustion Products - Appliances Adjusted (at 5 minutes of continuous burn)

		"Clean" Test		"Dirty" Test	
Appliance	Test Location	CO (ppm)	NOx (ppm)	CO (ppm)	NOx (ppm)
Fireplace	Chimney	21	5	23	5
Oven	Vent Termination	90	17	425	5
Furnace	Flue	2	35	22	42
Water Heater	Flue	3	83	2000+	78
Gas Dryer	Vent	2	0	2	0

The five minute test reports CO production after the initial spike typical at the beginning of the burn has dissipated. The water heater and the stove were the only appliances in the test house that produced significant amounts of CO under typical operating conditions. In almost all cases, the level of NOx production increased as the production of CO decreased. This is particularly important for appliances that are being "tuned" to reduce the amount of CO production.

Figure 5-1 shows the CO production pattern at the range hood with the oven adjusted to a "dirty" burn.

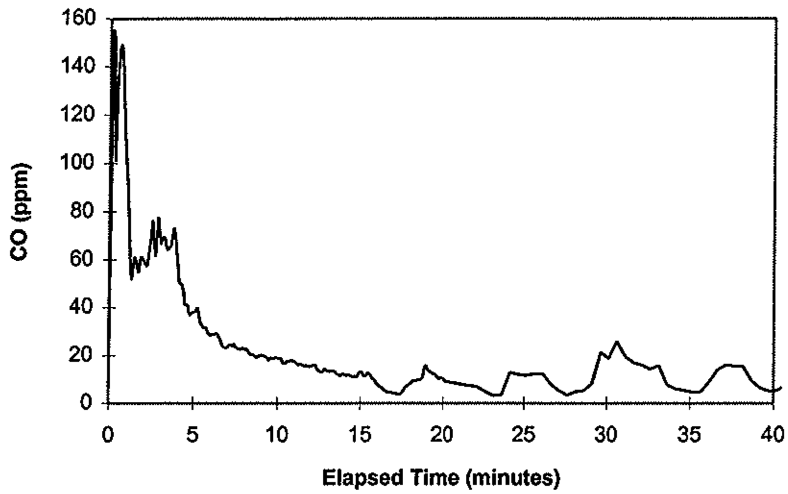

Figure 5-1. Range hood CO Readings - Oven "Dirty"

NOx was measured at each appliance. High excess air and high flame temperatures are conducive to complete combustion and the elimination of CO. NOx unfortunately is increased by these variables. (ASHRAE 1997) The NOx production by the gas oven was 17 ppm for a CO-clean oven and 5 ppm for a CO-dirty oven.

20% Supply Leakage, Minimum Return Leakage

The air flow through the forced air system was 1335 cfm as measured with a Duct Blaster™. The return leakage present was minimal (1.6% of operating leakage or 22 cfm). An 11 square inch hole was opened in the supply plenum to increase the supply leakage dominance. The operating supply duct leakage was increased from 171 cfm to 293 cfm (a 22% supply leak). This increased the total house depressurization to 4 pascals with the three bedroom doors closed and the furnace on.

Mechanically Induced Backdraft

Fireplace Backdraft - This test was completed by installing a blower door in an exterior doorway and depressurizing the house until the fireplace backdrafted. The fireplace did not backdraft until the house was depressurized by 19 pascals with respect to outside. The draft in the fireplace vent was monitored and maintained as near zero as possible. This delivered nearly 100% of the combustion products into the house. This test raised the ambient CO levels to 20 ppm at the fireplace mantle within 20 minutes. The CO levels at the range hood showed the influence of fireplace backdrafting and of the oven cycling. Levels in the rest of the house ranged from 6 to 9 ppm. The master bedroom sensor showed increasing CO levels even though the door was closed. CO from the oven and fireplace was being picked up by the furnace air handler and distributed to the rest of the house. Figure 5-2 displays these data. Figure 5-2 also illustrates the effect of oven cycling on the CO at the range hood.

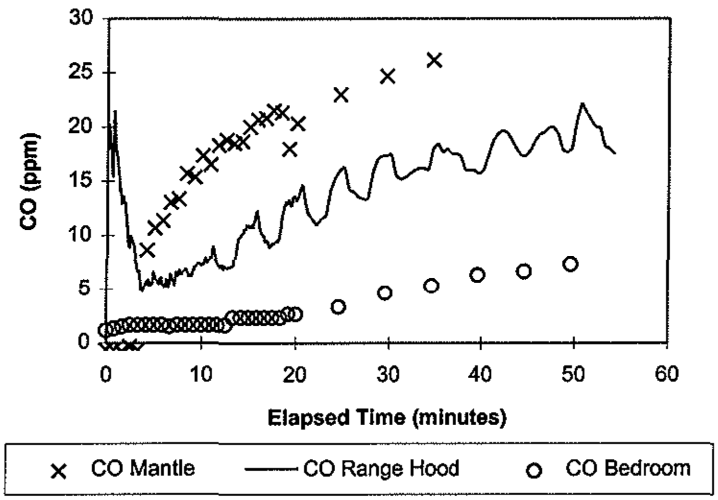

Figure 5-2. CO Measurements during the Fireplace Backdraft Test

This test illustrates the potential problems with pressure induced gas fireplace backdrafting. It is unlikely that this house would experience depressurization sufficient to cause fireplace backdrafting.

Furnace Backdraft - the furnace could not be backdrafted with either a power vent in the attic or a large depressurization of the home because of the large attic vent area.

Water Heater Backdraft - the furnace could not be backdrafted with a large depressurization of the home because the leakage from the house to garage is much smaller than the garage venting. This test was completed by installing a blower door in an exterior doorway of the garage and depressurizing the garage until the water heater backdrafted. The water heater backdrafted when the garage was depressurized by 8 pascals.

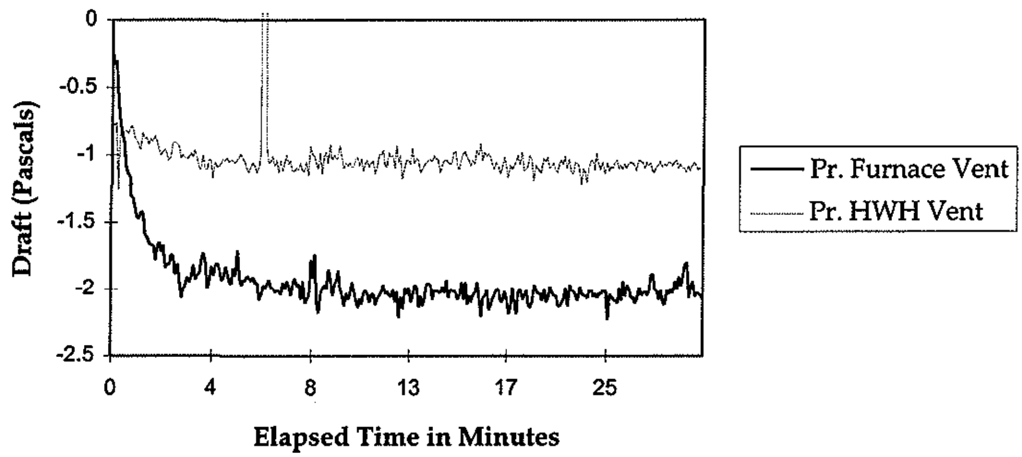

Figure 5-3. Furnace and Water Heater Draft during the Fireplace Backdraft Test

Results

The drafts on the furnace and water heater during the fireplace backdraft test were nearly identical to the drafts measured during the baseline test. This indicates that both the garage and attic are effectively decoupled from the interior of the house. The positive spike in the water heater vent is due to a door opening to the main body of the house.

Combustion Product Source for this Home

The only identified source of combustion products during long term testing was the gas oven/range. Elevated levels of CO were seen throughout the home when the stove/oven was operating. Air samples taken 2 feet above the stove/oven showed Carbon Monoxide (CO) concentrations ranging from 4-80 ppm during operation. During the long term monitoring the general concentration of CO in the home was lower than the 9 ppm - 8 hour maximum exposure limit.

CONCLUSIONS AND RECOMMENDATIONS

Conclusions

Combustion appliances are a source of concern in residential new construction. These concerns are particularly relevant to homes with tight building shells and high neutral pressure planes. New residences in Phoenix, by virtue of their typical slab on grade construction and stucco exteriors, have both low leakage and high neutral pressure planes.

The Phoenix area is famous as an area for retirees. The elderly and individuals with respiratory or cardiovascular problems are particularly susceptible to combustion pollutants.

The short-term monitoring showed potential for indoor air quality problems from the gas appliances. The stove/oven, fireplace and water heater are all potential sources of both carbon monoxide and NOx. The indoor air quality is directly effected by the operation of unvented combustion appliances inside the building envelope. The oven produced CO and NOx in normal operation. These combustion products were delivered to the occupied areas of the home.

Recommendations

1) Do not use unvented combustion appliances in the home.

2) Do not use open combustion appliances in the home where the potential exists for depressurization.

3) Design and maintain all natural gas appliances to produce less than 100 ppm CO in the flue.

4) Install CO detectors in all homes with any combustion appliance or attached garage.

These recommendations are not made lightly and are controversial. Should Arizona Public Service decide to encourage duct sealing and other shell tightening measures, and if the political situation is such that the above recommendations are not followed, then all feasible measures should be undertaken to reduce the potential for health hazards associated with combustion appliances in tight homes. These measures could include:

1) Install CO detectors in all homes with any combustion appliance or attached garage.

2) Evaluate all combustion appliances for draft and venting both before and after duct sealing, shell sealing, or closed cavity insulation work. Compare the results to written standards and mitigate if necessary.

3) The CO production of all combustion appliances should be measured and mitigation completed both before and after duct sealing, shell sealing, or closed cavity insulation work.

4) Under no condition should the neutral pressure plane be higher than the top of the chimney or vent for a non-forced draft combustion appliance.

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