Indoor Air Modeling for Furnace #1 with Blocked or Disconnected Vents

Warren K. Porter, Jr.
Director, Chemistry Division
Directorate for Laboratory Sciences
U.S. Consumer Product Safety Commission
Gaithersburg, MD

Date: September 1, 2000

Executive Summary

During fiscal year 2000, the U.S. Consumer Product Safety Commission (CPSC) Laboratory Sciences staff conducted tests with a natural gas fueled furnace. The furnace was a natural draft furnace rated at 100,000 Btu/hr. The staff installed the furnace in a closet inside a room size chamber. These tests provided data on the rate that carbon monoxide (CO) "spilled" into the test chamber when the furnace had either blocked or disconnected vents (Brown, Jordan, Tucholski, 2000). The rate that CO spilled into the chamber ranged from not measurable to greater than 200,000 cubic centimeters per hour. The higher rates were associated with the furnace being fired continuously, at gas input rates that exceeded the manufacturer's specification, and with various degrees of flue blockage, or with the flue disconnected. Although the gas input rates exceeded the manufacturer's specification, the input rates were within testing guidelines specified by the American National Standards Institute (ANSI) standard (ANSI Z21.47). The input rates used in the test program were also at rates that occurred in the initial test of the "as received" furnace, 110,000 Btu/hr.

The furnace had a draft hood and spill switch that was intended to shut the furnace off in the event that the combustion products did not flow up the chimney but spilled into the room housing the furnace. In initial tests, the spill switch functioned, in later tests the switch failed to function. The spill switch did not fail in a "safe" mode. That is, after failing, the furnace continued to operate.

The testing data obtained allowed indoor air concentrations of CO to be predicted. The predictions represent exposures that might occur in a 1076 square foot house with an 8-foot high ceiling [8608 ft^3 (240 m^3)]. Further, the ventilation rate of 0.35 changes per hour is the rate specified by the American Society of Heating, Refrigeration, and Air Conditioning Engineers for new houses. In larger houses or at higher ventilation rates, the CO concentrations would be proportionately lower.

The estimated concentrations will be used by the Health Sciences staff to estimate the health effects of CO exposure associated with a disconnected, fully, or partially blocked vents.

The predictions show the following:

1. Under normal operation, that is with no vent blockage or disconnection of the flue, all combustion products exhausted properly and no increase in the indoor air concentrations of CO occurred.
2. When the flue was blocked to the point that the safety spill switch did not shut the furnace off, the following occurred:
    - At the manufacturer's specified input rate of 100,000 Btu/hr, with the furnace operating continuously, the maximum predicted CO concentration did not exceed 12 ppm. If the furnace cycled on and off, the predicted CO concentration range was 2 ppm to 4 ppm depending on the percentage of time the furnace was on.

- If the fuel flow was increased to 123% of the specified rate (112% of the "as received[1]" firing rate), the CO concentrations could be as high as 2,529 ppm when the furnace operated continuously. If the furnace cycled on and off, the predicted CO concentration range was 74 ppm to 396 ppm depending on the percentage of time the furnace was on (33% to 80%).

3. When the flue was disconnected from the furnace, allowing all combustion products to enter the closet in which the furnace was installed, the furnace continued to operate, discharging all combustion products to the closet or chamber. The following indoor air concentrations were predicted:

    - At the manufacturer's specified gas flow and the furnace operating continuously, no increased indoor air concentration of CO was predicted.

    - When the fuel flow was increased to 123% of the specified rate and the furnace operated continuously, the predicted CO concentration was 2,656 ppm. If the furnace cycled on and off, the predicted CO concentration range was 415 ppm to 947 ppm depending on the percentage of time the furnace was on (33% to 80%).

4. Reducing the flow of air into the closet by covering lower combustion air vent to the closet, the following indoor air concentrations of CO were predicted:
    - With 80% flue blockage and operating the furnace continuously at 110% of the rated input, the predicted CO concentration was 177 ppm. If the furnace cycled, the predicted CO concentration range was 20 ppm to 45 ppm (33% to 80%).

    - With a disconnected flue, the furnace cycling, and operating at 123% of the rated input the predicted CO concentrations ranged from 780 ppm to 1,780 ppm depending on the percentage of time the furnace was on (33% to 80%).

The indoor air model, using the test data indicates the potential of reaching CO concentrations as high as 2,656 ppm. This would occur under very cold conditions when the furnace operated continuously for at least 10 hours. When the furnace cycled at a rate of 80% of the time on and 20% of the time off, the test data showed the CO production rates decreased to between 12% and 62% of the CO production rates observed under continuous burning conditions. Generally furnaces are likely to operate in a cyclical manner. Thus, the concentrations that were calculated under cycling conditions are likely to be more commonly encountered. When operated in a cyclical manner, the calculated concentrations reach a maximum of 1780 ppm.

[1] "As Received" in this report represents the furnace being installed with the manifold pressure adjusted to the 3.5 inches gas pressure stated in the installation instructions. At that pressure the furnace consumed gas at a rate of 110,000 Btu per hour.

Introduction

CPSC began a test program in 1999 to evaluate the carbon monoxide (CO) exposure hazard posed to consumers when a furnace vent pipe is blocked or disconnected. This test program is part of CPSC's effort to reduce deaths and injuries related to carbon monoxide poisoning. The test program consisted of testing the furnace under controlled conditions and measuring the rate that CO is emitted when the vent pipe is partially blocked, totally blocked, or disconnected. These data provide the basis for using mathematical models to predict potential concentrations of CO in houses where the furnaces may be installed. The modeling results and health affects evaluations may be used to support revisions to the ANSI Z21.47 Gas Fired Central Furnace standard or for proposing mandatory rules for preventing CO poisonings. For a draft hood equipped furnace, the current ANSI Z21.47 standard (1998) provides some degree of coverage for a totally blocked vent, but does not address the issues of a partially blocked vent or a disconnected vent.

This report presents the CO concentrations predicted by a single compartment indoor air model. The input data for the model consisted of the emission rates of CO obtained from laboratory testing of a natural draft furnace equipped with a draft hood (Furnace #1). The modeling incorporated three different size houses, three different ventilation rates that span the range from a weatherized, tight house to a non-weatherized loose house.

Emission Rates

The emission rates determined by the LS Staff are described elsewhere (Brown, Jordan, Tucholski, 2000). A natural draft furnace with a vent hood was installed in a closet that met the general construction and clearances specified in the manufacturer's installation instructions. The closet was housed in a 27.3 m^3 (965 ft^3) environmental chamber. In these tests, they monitored CO, CO_2, O_2, temperature, pressures, and airflows. Based on the measurements, the rate at which CO was released into the closet, chamber, flue, and the hot air supply was calculated. Air exchange was measured by the use of SF_6 tracer gas. The air exchange within the chamber was kept high enough to prevent depletion of oxygen beyond that which could occur in a house. Emission rates were determined for various levels of flue blockage, complete disconnection of the flue, and with reduced combustion air entering the closet. The tests included operating the furnace continuously or having the burner cycling on and off. The emission rate data are shown in Table 1.

Table 1 Emission Rates for a 100,000 BTU/hr Natural Draft Furnace Under Different Operating Conditions

Firing Rate[1] BTU/hr	% Duty Cycle During tests	Condition	Source cc/hr	Test Number [2]
Rated Input		Blocked Vent		
100,000	100	100% blocked	1,046	58
100,000	80	100% blocked	373	69
10% overfire ("as received" installation)[3]				
110,000	100	100% blocked	63,178	54, 56
110,000	100	90% blocked	3,428	64
110,000	80	100% blocked	7,997 (7,957)	61
23% overfire				
123,000	100	90% blocked	212,500	52, 65
123,000	100	80% blocked	41,104	13, 36
123,000	80	90% blocked	41,297	37, 38
123,000	80	80% blocked	17,582	20
		Disconnected vent		
100,000	80	100% Disconnect	0	60
110,000	100	100% Disconnect	1,510	55
110,000	80	100% Disconnect	947	21, 30, 62
12% overfire				
112,000	100	100% Disconnect	3,136	48, 49
112,000	80	100% Disconnect	1,918	50
23% overfire				
123,000	100	100% Disconnect	223,170	23, 70
123,000	80	100% Disconnect	98,700 (96,772)	25, 29, 53, 63
Reduced Air to Closet				
		Blocked Vent		
110,000	100	80% Blocked Vent	14,884	12
110,000	80	80% Blocked Vent	4,643	11
		Disconnected vent		
123,000	80	100% Disconnect	185,404	26, 28

[1] Actual input rates are within ± 3 percent of the values listed in the table.
[2] Test numbers correspond to test numbers listed in the tables of Appendix G (Brown, Jordan, Tucholski, 2000). If more than one test number is listed, then the source value (cc/hr) is an average of those tests.
[3] "As Received" in this report represents the furnace being installed with the manifold pressure adjusted to the 3.5 inches gas pressure stated in the installation instructions. At that pressure the furnace consumed gas at a rate of 110,000 Btu per hour.

Mathematical Model

The CO concentrations that may occur in a house where a furnace was connected to a blocked flue or where the flue became disconnected from the flue were predicted with a single compartment mathematical model. This model calculates the room air concentration that would likely occur with a source that releases CO intermittently or continuously. Although houses have multiple rooms, the single compartment model is appropriate since the furnace is a forced air furnace that forces heated air into the various rooms and draws cooled air from those rooms back to the furnace. The rate at which the air flows from the furnace, approximately 2888 m^3/hr (102,000f^3/hr), is equivalent to the air in a 100 m^2 (1076 ft^2) house passing through the furnace twelve times each hour. The mixing at this flow rate would ensure that the CO concentration through out the house would be 95 percent of equilibrium in 15 minutes and 99.7 percent of equilibrium in 30 minutes. The model equation follows:

$$C_t = C_{initial} * e^{-k*t} + \left(\left(C_{ambient} + \left(\frac{S}{V * k} \right) \right) \left(1 - e^{-k*t} \right) \right)$$

where

C_t = Indoor CO concentration at time t, (ppm)
$C_{initial}$= Initial indoor air CO concentration at the start of the furnace burn time, (ppm)
$C_{ambient}$= Outdoor air CO concentration, (ppm)
k = Ventilation rate, (hr^{-1})
V = Volume of the house, (m^3) and
S = Emission rate of CO, (cc/hr).

The assumptions for modeling are that the ventilation rate remains constant and the house is well mixed.

Discussion

The previously described equation was used to calculate the CO concentrations over a 24 hour period. The scenarios calculated represent the furnace being installed with an intact flue and no blockage of the flue, a blocked flue, a disconnected flue, and with the lower vent to the closet being blocked. The final scenario represents the case where a piece of furniture may be pushed against the floor level air inlet to the closet. With the exception of the reduced air scenario, CO concentrations were calculated for the furnace not being over-fired (baseline), various degrees of over-firing, and for the furnace operating continuously or intermittently. The calculations for the intermittent firing of the furnace represent those situations where the weather is such that the furnace is not required to operate all of the time. The furnace tests were only done under conditions of continuous operation (100 percent duty cycle) or cycled at an 80 percent duty cycle. The emission rate for the calculation of CO concentrations at 50 and 33 percent duty cycles were based on emission rates from the 80 percent duty cycle test. The actual emission rates for the 50 percent and 33 percent duty cycles are likely to be lower than for the 80 percent duty cycle. Any error introduced from using the emission rates from the

80 percent duty cycle tests is conservative, tending towards prediction of higher CO concentrations.

A representative plot of concentration for continuous furnace operation is shown in Figure 1. As seen from this figure there is an initial rise in CO concentration during the first 5 to 10 hours. After the initial rise, the concentration approaches equilibrium for the remaining period of the burn. Had the burn continued on for more than 24 hours, the concentration would have remained at the equilibrium value. The net effect of this is that the maximum average concentrations for a given scenario are essentially equal, regardless of the averaging period (4, 8 or 12 hours). In effect, the modeling can be reduced to a steady state situation where the exponential terms approach zero. Thus, the concentrations approach the steady state condition that equals the emission rate divided by the volume of incoming ambient air [S/(V*k)].

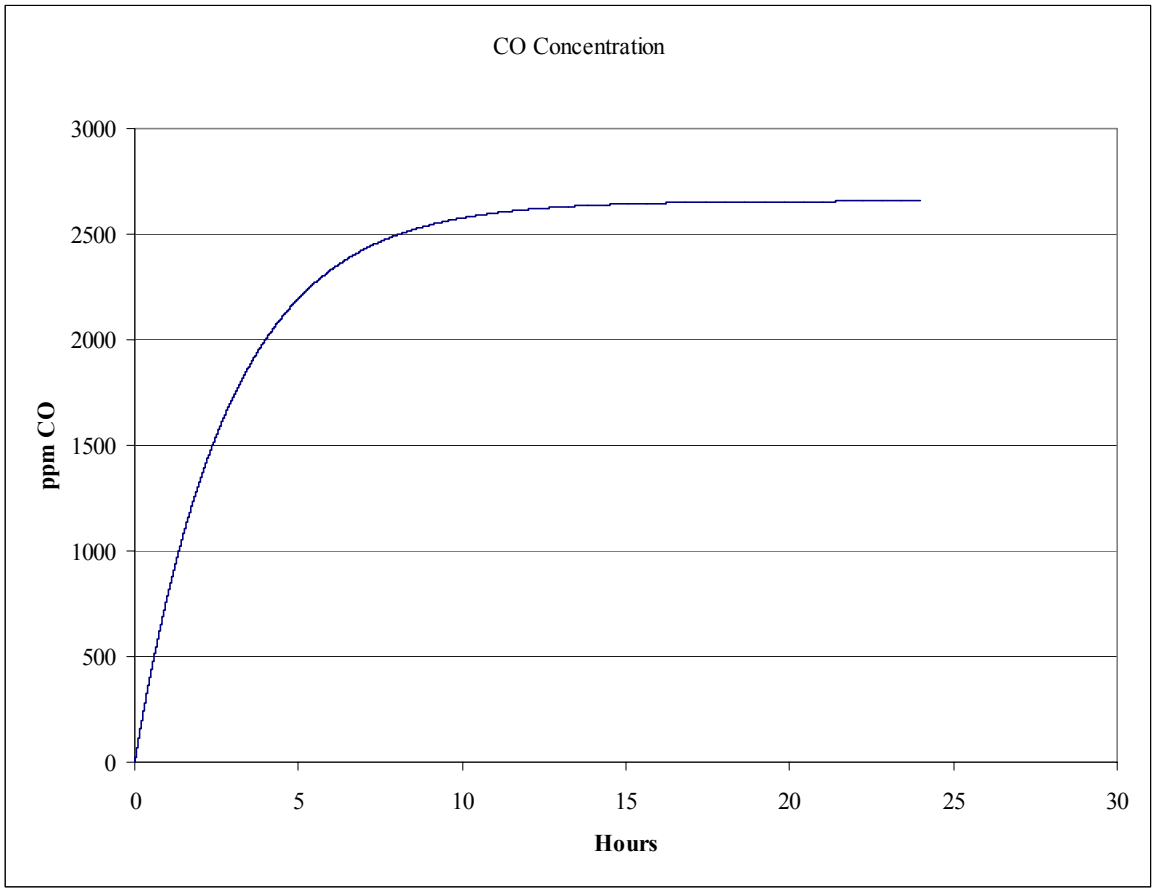

Figure 1. Continuous operation at 23% over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, disconnected vent, emission rate 223,170 cc/hr.

A representative plot for cyclic operation of the furnace is shown in Figure 2. The cyclic operation consisted of the furnace burning for 12 minutes and not burning for 3 minutes or an 80 percent duty cycle. The plot is similar to that for continuous furnace operation in that after an initial rise in concentration, the concentration then rises and falls between

two equilibrium concentrations. The maximum average concentrations are similar regardless of the averaging period.

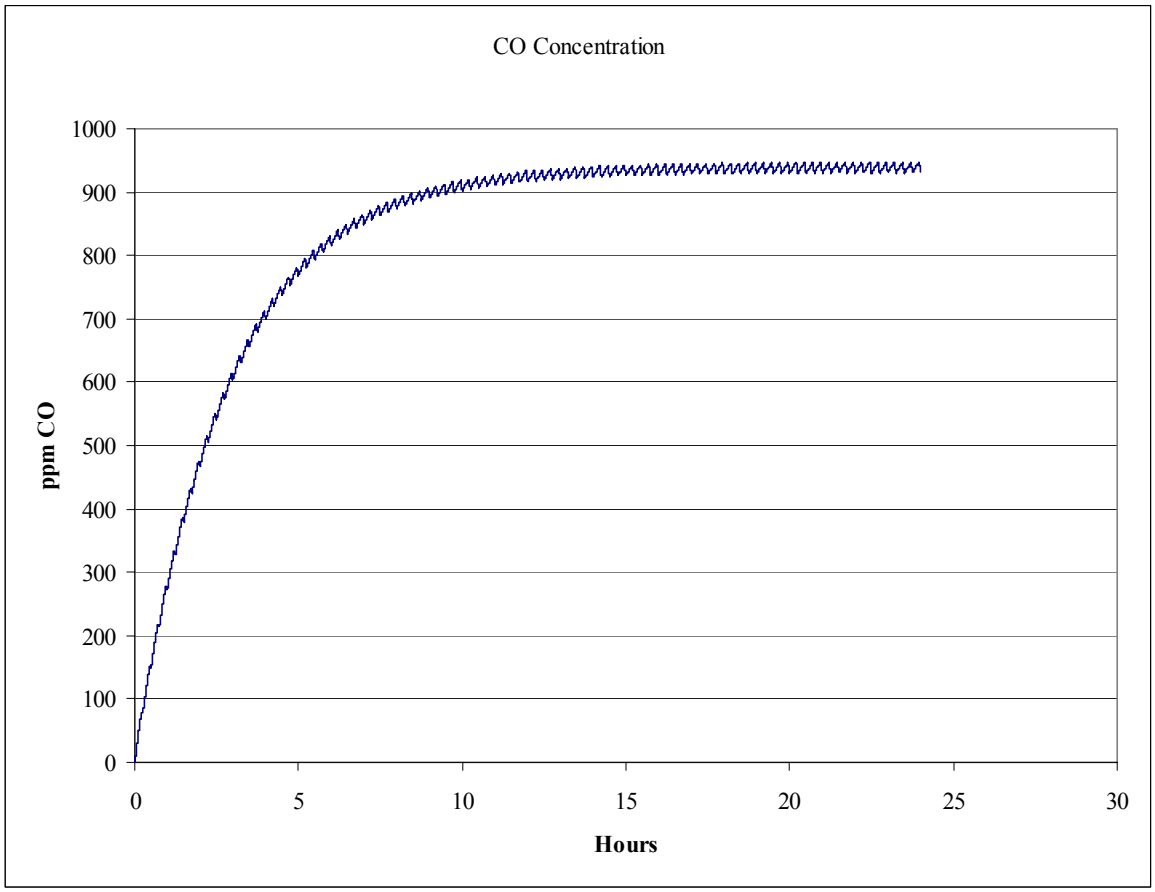

Figure 2. Cycling operation, 80% duty cycle at 23% over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2)house, disconnected vent, emission rate 98,700 cc/hr

Blocked Flue Predictions

For the baseline scenario the CO emissions were either not measurable or so low that the predicted house concentrations were in the 1.6 ppm to 12.4 ppm range. For the "as received" installation, 10 percent over-fired, the calculated elevation in CO concentration ranged from 34 ppm to 752 ppm. The highest calculated concentrations of CO were obtained with the 23% over-fired condition. At 90 percent flue blockage, the concentrations ranged from 174 to 2529 ppm, while at 80 percent blockage, the concentrations ranged from 74 ppm to 489 ppm. These data are shown in Table 2.

Table 2. Calculated CO Concentrations with Flue Blockage
House size 100 m^2 (1076 ft^2) [1]
ACH = 0.35 [2]

Firing Rate	Model Duty	Condition	Concentrations ppm				
BTU/hr	Cycle	Blocked Vent	Peak	max 4 hr avg	Max 8 hr avg	24 hour avg	Source cc/hr
Rated Input							
100,000	100	100% blocked	12.4	12.4	12.4	11.0	1046
100,000	80	100% blocked	3.6	3.5	3.5	3.1	373
100,000	50	100% blocked	2.3	2.2	2.2	2.0	373
100,000	33	100% blocked	1.6	1.5	1.5	1.3	373
10% overfire ("As received" installation)[3]							
110,000	100	100% blocked	751.9	751.7	751.2	662.6	63178
110,000	100	90% blocked	40.8	40.8	40.8	36.0	3428
110,000	80	100% blocked	76.8	76.1	76.0	67.1	7998
110,000	50	100% blocked	49.2	47.5	47.4	42.0	7998
110,000	33	100% blocked	33.6	31.4	31.4	27.9	7998
23% overfire							
123,000	100	90% blocked	2529.2	2528.5	2526.6	2228.5	212500
123,000	80	90% blocked	396.4	392.7	392.4	346.3	41297
123,000	50	90% blocked	253.8	245.1	244.9	216.9	41297
123,000	33	90% blocked	173.7	162.2	161.9	144.3	41297
123,000	100	80% blocked	489.2	489.1	488.7	431.1	41105
123,000	80	80% blocked	168.8	167.2	167.1	147.5	17582
123,000	50	80% blocked	108.1	104.3	104.3	92.4	17582
123,000	33	80% blocked	74.0	69.0	68.9	61.4	17582

[1] The concentrations for a house of 150 m^2 (1614 ft^2)area would be 66% of those shown in the table. For a house of 200 m^2 (2153 ft^2) area the concentrations would be 50% those shown in the table.

[2] The concentrations for a house with an air exchange rate of 0.5 hr^{-1} would be 74% of those shown in the table. The concentrations for a house with an air exchange rate of 0.7 hr^{-1} would be 50% of those shown in the table.

[3] "As Received" in this report represents the furnace being installed with the manifold pressure adjusted to the 3.5 inches gas pressure stated in the installation instructions. At that pressure the furnace consumed gas at a rate of 110,000 Btu per hour.

Disconnected Flue Predictions

For the baseline scenario the CO emissions were not measurable. For the "as received" installation (10 percent over fired) the calculated elevation in CO concentration ranged from 4.0 ppm to 18.0 ppm. The highest concentrations of CO resulted from over firing the furnace by 23 percent and ranged from 415.2 ppm to 2656.2 ppm. These data are shown in Table 3.

Table 3. Disconnected Vent Tests
House size 100 m^2 (1076 ft^2) [1]
ACH = 0.35 [2]

Firing Rate	Model Duty Cycle	Condition	Concentrations ppm Maximum					
BTU/hr		Disconnected Vent	Peak	4 hr avg	8 hr avg	12 hr avg	24 hr avg	Source cc/hr
Baseline								
100,000	80	100% Disconnect	0	0	0	0	0	0
10% overfire ("As received" installation)[3]								
110,000	100	100% Disconnect	18.0	18.0	18.0	17.9	15.8	1510
110,000	80	100% Disconnect	9.1	9.0	9.0	9.0	7.9	947
100,000	50	100% Disconnect	5.8	5.6	5.6	5.6	5.0	947
100,000	33	100% Disconnect	4.0	3.7	3.7	3.7	3.3	947
12% overfire								
112,000	100	100% Disconnect	37.3	37.3	37.3	37.2	32.9	3136
112,000	80	100% Disconnect	18.4	18.2	18.2	18.2	16.1	1918
112,000	50	100% Disconnect	11.8	11.4	11.4	11.3	10.1	1918
112,000	33	100% Disconnect	8.1	7.5	7.5	7.5	6.7	1918
23% overfire								
123,000	100	100% Disconnect	2656.2	2655.5	2653.5	2647.4	2340.4	223170
123,000	80	100% Disconnect	947.3	938.6	937.8	935.7	827.7	98700
123,000	50	100% Disconnect	606.7	585.7	585.3	584.0	518.5	98700
123,000	33	100% Disconnect	415.2	387.5	387.0	386.5	344.8	98700

[1] The concentrations for a house of 150 m^2 (1614 ft^2)area would be 66% of those shown in the table. For a house of 200 m^2 (2153 ft^2) area the concentrations would be 50% those shown in the table.

[2] The concentrations for a house with an air exchange rate of 0.5 hr^{-1} would be 74% of those shown in the table. The concentrations for a house with an air exchange rate of 0.7 hr^{-1} would be 50% of those shown in the table.

[3] "As Received" in this report represents the furnace being installed with the manifold pressure adjusted to the 3.5 inches gas pressure stated in the installation instructions. At that pressure the furnace consumed gas at a rate of 110,000 Btu per hour.

Reduced Air Predictions

Test data for the baseline firing rate were not available. This restricted calculations to those for 10 percent over firing (the "as received" condition of the furnace) and 23 percent over firing. For the "as received" installation, the calculated elevation in CO concentration for 80 percent vent blockage and continuous operation was 177.2 ppm. For cycling operation the CO concentrations ranged from 19.5 ppm to 44.6 ppm. In contrast, with a disconnected flue and cycling operation at 23 percent over firing, the CO concentrations ranged from 780.0 ppm to 1779.5 ppm. These data are shown in Table 3.

Table 4. Reduced Air to Closet
House size 100 m^2 (1076 ft^2) [1]
ACH = 0.35 [2]

Firing Rate	Model Duty	Condition	Concentrations ppm Maximum					
BTU/hr	Cycle		Peak	4 hr avg	8 hr avg	12 hr avg	24 hour avg	Source cc/hr
As Received[3]		**Blocked Vent**						
110,000[3]	100	80% Blocked	177.2	177.1	177.0	176.6	156.1	14884
110,000	80	80% Blocked	44.6	44.2	44.1	44.0	38.9	4643
110,000	50	80% Blocked	28.5	27.6	27.5	27.5	24.4	4643
110,000	33	80% Blocked	19.5	18.2	18.2	18.2	16.2	4643
12% Over-fire		**Disconnected vent**						
123,000	80	100% Disconnect	1779.5	1763.1	1761.7	1757.6	1554.9	185404
123,000	50	100% Disconnect	1139.6	1100.3	1099.4	1096.9	973.9	185404
123,000	33	100% Disconnect	780.0	728.0	726.9	726.0	647.7	185404

[1] The concentrations for a house of 150 m^2 (1614 ft^2) area would be 66% of those shown in the table. For a house of 200 m^2 (2153 ft^2) area the concentrations would be 50% those shown in the table.

[2] The concentrations for a house with an air exchange rate of 0.5 hr^{-1} would be 74% of those shown in the table. The concentrations for a house with an air exchange rate of 0.7 hr^{-1} would be 50% of those shown in the table.

[3] "As Received" in this report represents the furnace being installed with the manifold pressure adjusted to the 3.5 inches gas pressure stated in the installation instructions. At that pressure the furnace consumed gas at a rate of 110,000 Btu per hour.

Conclusions

The calculated CO concentrations clearly indicate that over firing the furnace leads to excessive CO production. This, coupled with a condition of a flue failure, either disconnection, blockage, or back drafting, can result in high CO concentrations. The importance of the over firing is illustrated by the fact that at the rated firing rate of

100,000 BTU/hr, the highest calculated CO concentration was 12.4 ppm. That occurred when the furnace operated continuously with 100 percent flue blockage. When the furnace was cycled, the maximum concentration of CO was only 3.6 ppm.

With as little as 10 percent over firing, the CO concentrations increased by 10 to 60 times reaching values of up to 751.9 ppm when the furnace operated continuously and 76.8 ppm when cycling occurred. Further, at 23 percent over firing, the concentrations further increased to as high as 2656 ppm with continuous operation and a disconnected flue. At 23 percent over firing in cycling operation the CO concentrations still achieved levels between 947 and 1780 ppm in disconnected flue tests and up to 396.4 ppm with 90 percent flue blockage.

References:

Furnace CO Emissions Under Normal and Compromised Vent Conditions, Furnace #1 Draft Hood Equipped, Brown C., Jordan, R. A., Tucholski, D. R., U.S. Consumer Product Safety Commission, Directorate for Laboratory Sciences, August 2000.