Indoor Air Modeling for Furnace #2 with Blocked or Disconnected Vents

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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 an induced 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 a blocked or disconnected vent (Brown, Jordan, Tucholski, 2000). Further the furnace was operated at the manufacturer's rated fuel flow as well as at various fuel flow rates that exceeded the manufacturer's specifications.

The rate that CO "spilled" into the chamber 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 [8475 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 calculated 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 vent, combustion products exhausted properly and no measurable increase in the indoor air concentrations of CO occurred.

2. Although the standard does not specify a means to shut the furnace down when the vent is blocked, this furnace had such safety devices present. When the vent 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, and with 100 percent vent blockage, the maximum calculated maximum CO concentration did not exceed 9 ppm.

    - If the fuel flow was increased to 118 percent of the specified rate (112 percent of the "as received[1]" firing rate) the maximum CO concentration could be as high as 1911 ppm with 100% vent blockage and continuous furnace operation. If the furnace cycled on and off, the predicted maximum CO concentration range was 390 ppm to 889 ppm depending on the percentage of time the furnace was on (33 percent to 80 percent).

[1] "As Received" in this report represents the furnace being installed without making any adjustments to the manifold pressure. The furnace, as received, consumed gas at a rate of 106,000 Btu per hour.

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

    - At the manufacturer's specified gas flow and the furnace operating continuously, the maximum calculated concentration of CO was 14 ppm. If the furnace cycled, the calculated maximum concentration of CO ranged from 3 ppm to 7 ppm depending on the percentage of time the furnace was on (33 percent to 80 percent).

    - When the fuel flow was increased to 118 percent of the specified rate (112 percent of the "as received" firing rate) and the furnace operated continuously, the maximum calculated CO concentration did not exceed 156 ppm. If the furnace cycled on and off, the maximum calculated CO concentration ranged from 31 ppm to 71 ppm depending on the percentage of time the furnace was on (33 percent to 80 percent).

If the vent was blocked, the indoor air model indicates the potential of reaching a maximum calculated CO concentration as high as 1911 ppm. This would occur under very cold conditions when the furnace operated continuously for at least 10 hours at a firing rate 18% over the manufacturer's specification. When the furnace cycled at a rate of 80 percent of the time on and 20 percent of the time off, the test data showed the maximum calculated CO concentrations did not exceed 889 ppm. If the vent was disconnected, the indoor air model indicates the potential of reaching a maximum calculated CO concentration as high as 156 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 percent of the time on and 20 percent of the time off, the test data showed the maximum calculated CO concentration did not exceed 71 ppm. 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.

1. 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 was emitted when the vent pipe is partially blocked, totally blocked, or disconnected. These data provide the basis for using a mathematical model to predict potential concentrations of CO in houses where the furnaces may be installed. For an induced draft furnace, the current ANSI Z21.47 standard (1998) provides some degree of coverage for a totally or partially blocked vent. That is, the air free CO concentration in the vent gases can not exceed 400 ppm. The standard does not address the issue of a disconnected vent. The standard does not require the furnace to shut down in cases of vent blockage or disconnection of the vent. Further the standard specifies that the combustion air contains a "normal" concentration of oxygen or 20.9 percent. Thus, the standard's tests do not require testing under conditions that may occur in homes.

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 an induced draft furnace rated at 100,000 Btu/hr (Furnace #2). The modeling incorporated three different size houses (240 m^3 to 480 m^3) and three different ventilation rates that span the range from a weatherized, tight house (0.35 hr^{-1}) to a non-weatherized loose house (0.7 hr^{-1}). Further, the indoor air concentration calculations were made for both continuous and cyling operation of the furnace. This reflects operation under extremely cold conditions (continuous operation) and operation under moderate conditions (cyclical operation).

2. Emission Rates

The emission rates determined by the LS Staff are described elsewhere (Brown, Jordan, Tucholski, 2000). A mid-efficiency induced draft furnace 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 measured gas concentrations, the rates at which CO was released into the closet, chamber, vent, and the hot air supply were 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 vent blockage, location of the vent blockage, complete disconnection of the vent, and the locations of the vent disconnect. 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 Induced Draft Furnace Under Different Operating Conditions

Test Number	Firing Rate Btu/hr	% Duty Cycle During tests	Condition	Source cc/hr
13	100%	100%	Baseline	0
14	100%	80%	Baseline	0
1	106%	100%	Baseline	0
2	106%	80%	Baseline	0
46	112%	100%	Baseline	0
47	112%	80%	Baseline	0
3	118%	100%	Baseline	222
4	118%	80%	Baseline	0
Disconnect				
11	100%	100%	Disconnected, Closet	1,212
12	100%	80%	Disconnected, Closet	694
10	112%	100%	Disconnected, Closet	2,362
16	112%	80%	Disconnected, Closet	2,159
Avg 5& 29	118%	100%	Disconnected, Closet	13,139
Avg 6 & 15	118%	80%	Disconnected, Closet	7,436
Avg. 7 & 28	118%	100%	Disconnected, Chamber	8,562
8	118%	80%	Disconnected, Chamber	2,822
Blocked				
43	100%	100%	100%; Vent Outlet	774
34	100%	100%	95%; Diaphragm	185
33	100%	100%	90%; Diaphragm	0
Avg 42&44	106%	100%	100%; Vent Outlet	6,835
31	106%	100%	95%; Diaphragm	990
32	106%	100%	90%; Diaphragm	186
Avg 21&24	112%	80%	95%; Diaphragm	3,133
Avg 41&49	112%	80%	100%; Vent Outlet	17,473
Avg. 51& 39	118%	80%	100%; Vent Outlet	92,648
17	112%	100%	90%; Diaphragm	1,849
Avg 22&23	112%	100%	95%; Diaphragm	6,386
Avg 40,48&45	112%	100%	100%; Vent Outlet	42,773
25	118%	80%	90%; Diaphragm	2,344
Avg 20&30	118%	80%	95%; Diaphragm	18,972
35	118%	100%	85%; Diaphragm	2,007
Avg 18,27,37, 26	118%	100%	90%; Diaphragm	8,899
Avg 19,36	118%	100%	95%; Diaphragm	62,919
Avg 38,50	118%	100%	100%; Vent Outlet	160,520

3. Mathematical Model

The CO concentrations that may occur in a house where a furnace was connected to a blocked vent or where the vent became disconnected 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 an induced 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.

4. Discussion

The previously described equation was used to calculate the indoor CO concentrations over a period of 24 hours. The scenarios calculated represent the furnace being installed with an intact vent and no blockage of the vent, a blocked vent, and a disconnected vent. CO concentrations were calculated for the furnace not being over-fired, 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 rates 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 rate of flow of the incoming ambient air [S/(V*k)].

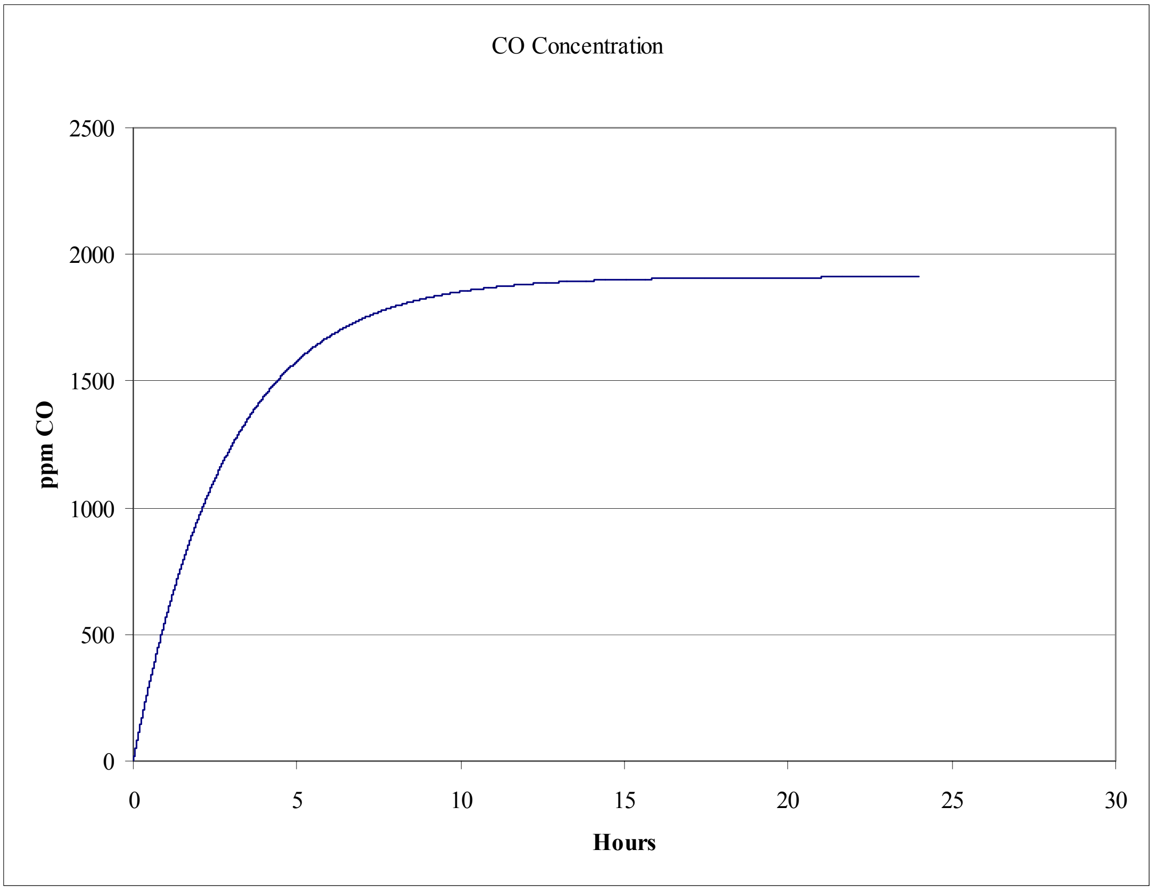

Figure 1. Continuous operation at 12 percent over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, 100% blocked vent outlet, emission rate 160,520 cc/hr.

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 CO emission rate, duty cycle, ventilation rate, and house volume determine those concentrations. The maximum average concentrations are similar regardless of the averaging period.

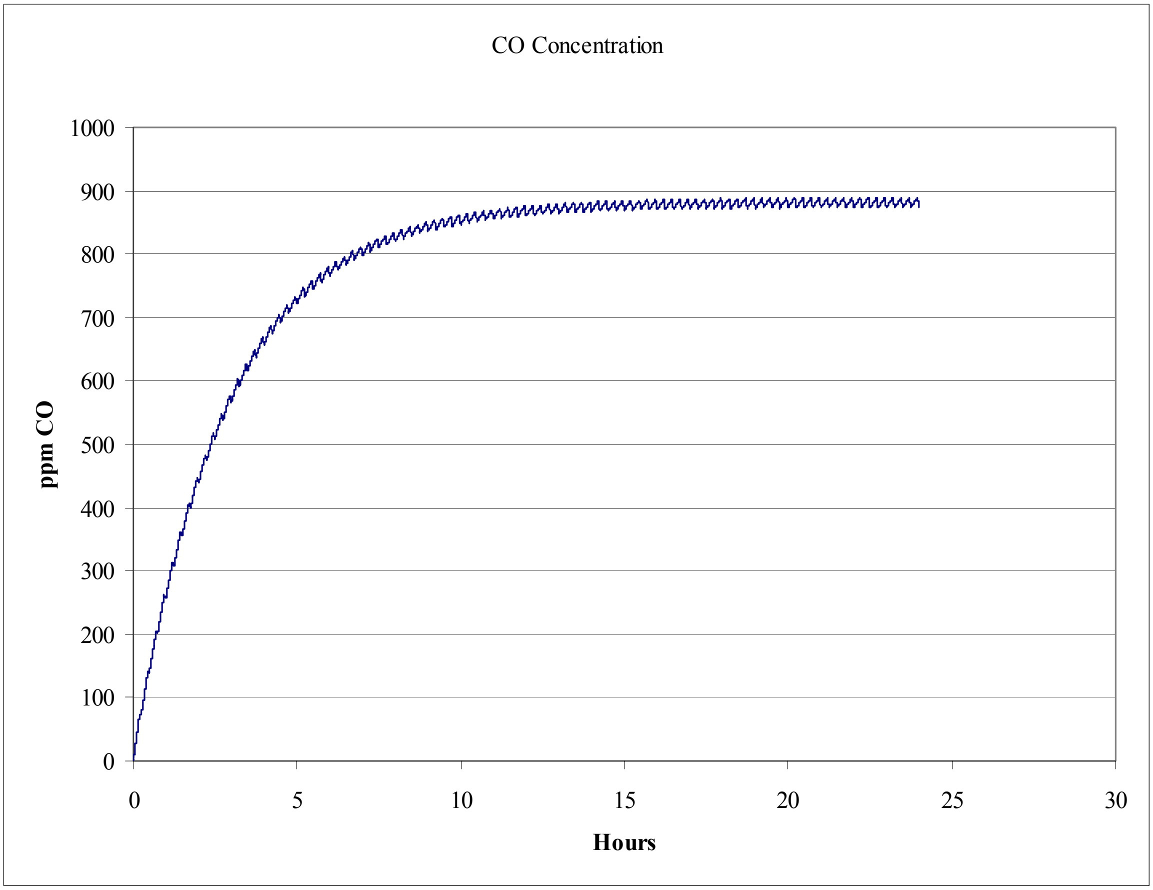

Figure 2. Cyclical operation, 80 percent duty cycle at 12 percent over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, 100% blocked vent outlet, emission rate 92,648 cc/hr.

5. Blocked Vent Predictions

For the baseline scenario, the CO emissions were either not measurable or so low that the maximum calculated CO concentrations were in the 0 ppm to 9 ppm range depending on the amount of vent blockage (90 percent to 100 percent blockage). For the "as received" installation, 6 percent over-fired or 106,000 Btu/hr, the maximum calculated CO concentrations ranged from 2 ppm to 81 ppm depending on the amount of vent blockage (85 percent to 100 percent blockage).

The highest calculated concentration of CO, 1911 ppm, was calculated with the 118 percent over-fired condition. For this calculation, the furnace was assumed to operate continuously with 100 percent vent blockage at the furnace outlet. At 95 percent vent blockage and the duty cycle ranging from 33 to 80 percent, the maximum calculated CO concentrations ranged from to 390 ppm to 889 ppm.

When vent blockage was achieved with a diaphragm located about 5 feet from the furnace, outside the closet, the calculated concentrations were lower. This may be due to leakage that occurred through the vent duct seams between the furnace outlet and diaphragm. The maximum calculated CO concentrations depended on the amount of blockage and whether the furnace operated continuously or cycled.

- At 95 percent vent blockage with the furnace operating continuously, the maximum calculated CO concentration was 749 ppm under the 118 percent over-fired condition.
    - When the furnace cycled, the maximum calculated CO concentrations ranged from 80 ppm to 182 ppm depending on the assumed duty cycle (33 percent to 80 percent).
- At 90 percent vent blockage with the furnace operating continuously, the maximum calculated CO concentration was 106 ppm under the 118 percent over-fired condition.
    - When the furnace cycled, the maximum calculated CO concentrations ranged from 10 ppm to 22 ppm depending on the duty cycle (33 percent to 80 percent).
- At 85 percent vent blockage with the furnace operating continuously, the maximum calculated CO concentration was 24 ppm.

These data are shown in Table 2.

Table 2. Calculated CO Concentrations with Vent Blockage

House size 100 m^2 (1076 ft^2) [1], ACH = 0.35 [2]

Test Number	Btu/hr	Model Duty Cycle %	Blockage %	Emission Rate cc/hr	Concentrations: Peak ppm	Max 4 hr ppm Avg.	max 8 hr ppm Avg.	max 12 hr ppm Avg.	24 hour ppm Avg.	Blockage Location
Adjusted to Mfr. Specs.										
43	100,000	100	100%	774	9	9	9	9	8	Vent Outlet
34	100,000	100	95%	185	2	2	2	2	2	Diaphragm
	100,000	100	90%	0	0	0	0	0	0	Diaphragm
As Received3										
Avg. 42&44	106,000	100	100%	6,835	81	81	81	81	72	Vent Outlet
31	106,000	100	95%	990	12	12	12	12	10	Diaphragm
32	106,000	100	90%	186	2	2	2	2	2	Diaphragm
12% over mfr. Specs										
Avg. 22&23	112,000	100	95%	6,386	76	76	76	76	67	Diaphragm
Avg. 21&24	112,000	80	95%	3,133	30	30	30	30	26	Diaphragm
Avg. 21&24	112,000	50	95%	3,133	19	19	19	19	16	Diaphragm
Avg. 21&24	112,000	33	95%	3,133	13	12	12	12	11	Diaphragm
17	112,000	100	90%	1,849	22	22	22	22	19	Diaphragm
Avg. 40,48&45	112,000	100	100%	42,773	509	509	509	507	449	Vent Outlet
Avg. 41&49	112,000	80	100%	17,473	168	166	166	166	147	Vent Outlet
Avg. 41&49	112,000	50	100%	17,473	107	104	104	103	92	Vent Outlet
Avg. 41&49	112,000	33	100%	17,473	74	69	69	68	61	Vent Outlet
12% over "as received"										
Avg. 18, 26, 27, & 37	118,000	100	90%	8,899	106	106	106	106	93	Diaphragm
25	118,000	80	90%	2,344	22	22	22	22	20	Diaphragm
25	118,000	50	90%	2,344	14	14	14	14	12	Diaphragm
25	118,000	33	90%	2,344	10	9	9	9	8	Diaphragm
35	118,000	100	85%	2,007	24	24	24	24	21	Diaphragm
Avg. 19,36	118,000	100	95%	62,919	749	749	748	746	660	Diaphragm
Avg. 20&30	118,000	80	95%	18,972	182	180	180	180	159	Diaphragm
Avg. 20&30	118,000	50	95%	18,972	117	113	113	112	100	Diaphragm
Avg. 20&30	118,000	33	95%	18,972	80	74	74	74	66	Diaphragm
Avg. 38,50	118,000	100	100%	160,520	1911	1910	1909	1904	1683	Vent Outlet
Avg. 39&51	118,000	80	100%	92,648	889	881	880	878	777	Vent Outlet
Avg. 39&51	118,000	50	100%	92,648	569	550	549	548	487	Vent Outlet
Avg. 39&51	118,000	33	100%	92,648	390	364	363	363	324	Vent Outlet

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

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

[3] "As Received" in this report represents the furnace being installed without making any adjustments to the gas manifold pressure. The furnace, as received, consumed gas at a rate of 106,000 Btu/hr.

6. Disconnected Vent Predictions

For tests at the manufacturer's specified fuel flow rate and with the furnace running continuously, the maximum calculated CO concentration was 14 ppm. Under cyclical conditions the maximum calculated CO concentrations ranged from 3 ppm to 7 ppm depending on the duty cycle (33 percent to 80 percent).

If the vent was disconnected in the closet that housed the furnace, the highest calculated CO concentration, 156 ppm, resulted from over firing the furnace by 118 percent (112 percent of the firing rate of the furnace "as received"). If the furnace operated in a cyclical mode, the maximum calculated CO concentrations ranged from 31 ppm to 71 ppm.

If the vent was disconnected in the chamber outside the closet that housed the furnace, the highest calculated CO concentration, 102 ppm, resulted from over firing the furnace by 118 percent (112 percent of the firing rate of the furnace "as received"). If the furnace operated in a cyclical mode, the maximum calculated CO concentrations ranged from 12 ppm to 27 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]

						Calculated CO Concentrations (ppm)				
Test #	**Firing Rate BTU/hr**	**Test Duty Cycle %**	**Model Cycle %**	**Disconnect Location**	**Emission Rate cc/hr**	**Peak**	**Max 4 hr. Avg.**	**Max 8 hr. Avg.**	**Max 12 hr. Avg.**	**24 hour Avg.**
Mfr. Specs										
11	100,000	100	100	Closet	1,212	14	14	14	14	13
12	100,000	80	80	Closet	694	7	7	7	7	6
	100,000	80	50	Closet	694	4	4	4	4	4
	100,000	80	33	Closet	694	3	3	3	3	2
12% over Mfr. Specs										
10	112,000	100	100	Closet	2,362	28	28	28	28	25
16	112,000	80	80	Closet	2,159	21	21	21	20	18
	112,000	80	50	Closet	2,159	13	13	13	13	11
	112,000	80	33	Closet	2,159	9	8	8	8	8
12% over "As Received[3]"										
Avg 5 & 29	118,000	100	100	Closet	13,139	156	156	156	156	138
Avg 6 & 15	118,000	80	80	Closet	7,435	71	71	71	70	62
`	118,000	80	50	Closet	7,746	46	44	44	44	39
	118,000	80	33	Closet	7,746	31	29	29	29	26
Avg 7 & 28	118,000	100	100	Chamber	8,562	102	102	102	102	90
8	118,000	80	80	Chamber	2,822	27	27	27	27	24
	118,000	80	50	Chamber	2,822	17	17	17	17	15
	118,000	80	33	Chamber	2,822	12	11	11	11	10

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

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

[3] "As Received" in this report represents the furnace being installed without making any adjustments to the manifold pressure. The furnace, as received, consumed gas at a rate of 106,000 Btu/hr.

7. Conclusions

The calculated CO concentrations clearly indicate that over firing the furnace leads to excessive CO production. This, coupled with a condition of a vent failure, either disconnection or blockage, 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 with 100% vent blockage, the highest calculated CO concentration was 9 ppm.

If the vent is 95 percent blocked in the chamber at 112 percent over firing (112,000 Btu/hr), the calculated CO concentration increased to 76 ppm when the furnace operated continuously. If the furnace cycled, the calculated CO concentrations ranged from 13 to 30ppm depending on the duty cycle (33 percent to 80 percent).

If the vent is 95 percent blocked in the chamber at 118 percent over firing (118,000 Btu/hr), the maximum calculated CO concentration was 749 ppm when the furnace operated continuously. If the furnace cycled, the maximum calculated CO concentrations ranged from 80 ppm to 182 ppm depending on the duty cycle (33 percent to 80 percent).

If the vent is 100 percent blocked at the furnace outlet at 118 percent over firing (118,000 Btu/hr), the maximum calculated CO concentration was 1911 ppm when the furnace operated continuously. If the furnace cycled, the maximum calculated CO concentrations ranged from 390 ppm to 889 ppm depending on the duty cycle (33 percent to 80 percent).

When the vent was disconnected, the maximum calculated CO concentrations for continuous furnace operation did not exceed 156 ppm. If the furnace cycled the maximum calculated CO concentrations did not exceed 71 ppm.

8. References:

Furnace CO Emissions Under Normal and Compromised Vent Conditions, Furnace # 2 - Mid-Efficiency Induced Draft, Brown C., Jordan, R. A., Tucholski, D. R., U.S. Consumer Product Safety Comission, Directorate for Laboratory Sciences, September 2000.