Indoor Air Modeling for Furnace #4 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, high efficiency 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, and when the furnace operated continuously or was allowed to cycle on and off (Brown, Jordan, Tucholski, 2000). Further the furnace was operated at the manufacturers rated fuel flow as well as at various fuel flow rates that were more than the manufacturers 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 1059 square foot house with an 8-foot high ceiling [8608 ft^3 (240 m^3)]. Further, the ventilation rate used in calculation of indoor air concentrations, 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 or with the vent blocked, regardless of the rate of fuel flow, no calculated indoor CO concentration exceeded 18 ppm.

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

   - Between the manufacturer's specified gas flow and 12 percent of the specified fuel flow, with the furnace operating continuously or cycling, the calculated concentration of CO did not exceed 17ppm.

   - When the fuel flow was increased to between 18 and 28 percent of the specified rate and the furnace operated continuously, the calculated CO concentration reached a maximum of 493 ppm. If the furnace cycled on and off, the calculated CO concentration reached a maximum of 129 ppm.

The indoor air model, using the test data indicates the potential of reaching CO concentrations as high as 493 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, at 18 to 28 percent over fire, the calculated concentrations reach a maximum of 57 to 129 ppm. Generally furnaces are likely to operate in a cyclical manner. Thus, the concentrations that were calculated under cycling conditions are more likely to be encountered.

1. Introduction

The CPSC staff 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 mathematical models to predict potential concentrations of CO in houses where the furnaces may be installed. For a high efficiency 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 CO concentration in the vent gas should not exceed 400 ppm. The standard does not address the issue of a disconnected vent. Although the standard does not require the furnace to shut down in cases of vent blockage or disconnection of the vent, this furnace did have a provision for shutting down in the event of vent blockage. Further the standard specifies that the combustion air must contain a "normal" concentration of oxygen (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, high efficiency furnace (Furnace #4). The modeling incorporated three different size houses and three different ventilation rates that span the range from a weatherized, tight house to a non-weatherized loose house.

2. Emission Rates

The emission rates determined by the LS Staff are described elsewhere (Brown, Jordan, Tucholski, 2000). The induced draft, high efficiency 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, the investigators monitored CO, CO_2, O_2, temperature, pressures, and airflow. Based on the measurements, the rate at which CO "spilled" into the closet, chamber, vent, 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 vent blockage and complete disconnection of the vent at various locations. 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 high Efficiency Induced Draft Furnace Under Different Operating Conditions

Test Number	Firing Rate BTU/hr	% Duty Cycle During tests	Condition	Source cc/hr
As Received				
1	100,000	100	Normal	383
2	100,000	80	Normal	0
9	112,000	100	Normal	15
10	112,000	80	Normal	56
28	118,000	100	Normal	0
29	118,000	80	Normal	14
33	128,000	100	Normal	0
34	128,000	80	Normal	0
Disconnect				
5	100,000	100	Disconnected, Chamber	599
6	100,000	80	Disconnected, Chamber	1,241
3	100,000	100	Disconnected, Closet	1,085
4	100,000	80	Disconnected, Closet	1,550
14	112,000	100	Disconnected, Chamber	892
16	112,000	80	Disconnected, Chamber	1,229
13	112,000	100	Disconnected, Closet	1,137
15	112,000	80	Disconnected, Closet, and Chamber	1,795
26	118,000	100	Disconnected, Chamber	7,191
27	118,000	80	Disconnected, Chamber	2,481
32	118,000	100	Disconnected, Closet	21,736
42	118,000	80	Disconnected, Closet	2,556
25	128,000	100	Disconnected, Chamber	31,212
24	128,000	80	Disconnected, Chamber	8,818
23	128,000	100	Disconnected, Closet	41,423
43	128,000	80	Disconnected, Closet	13,487
Blocked				
7	100,000	100	86% Iris	58
8	100,000	100	88% Iris	Shut Down
41	100,000	80	86%, Iris	56
11	112,000	100	88%, Iris	Shut Down
12	112,000	100	86%, Iris	123
17	112,000	100	100%,Inducer Exhaust	Shut Down
38	112,000	80	86%, Iris	0
30	118,000	100	86%, Iris	722
18	128,000	100	86%, Iris	903
36	128,000	100	86%, Iris	1,397
19	128,000	100	86%, Iris	1,489

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 from the vent 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 because the furnace 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 CO concentrations over a 24 hour period. 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.

As noted in the tables, the data presented are for a house whose floor area is 100 m^2 (1076 ft^2) with a whole house ventilation rate of 0.35 air changes per hour. The calculated concentrations would be lower in larger houses and houses with higher ventilation rates.

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)].

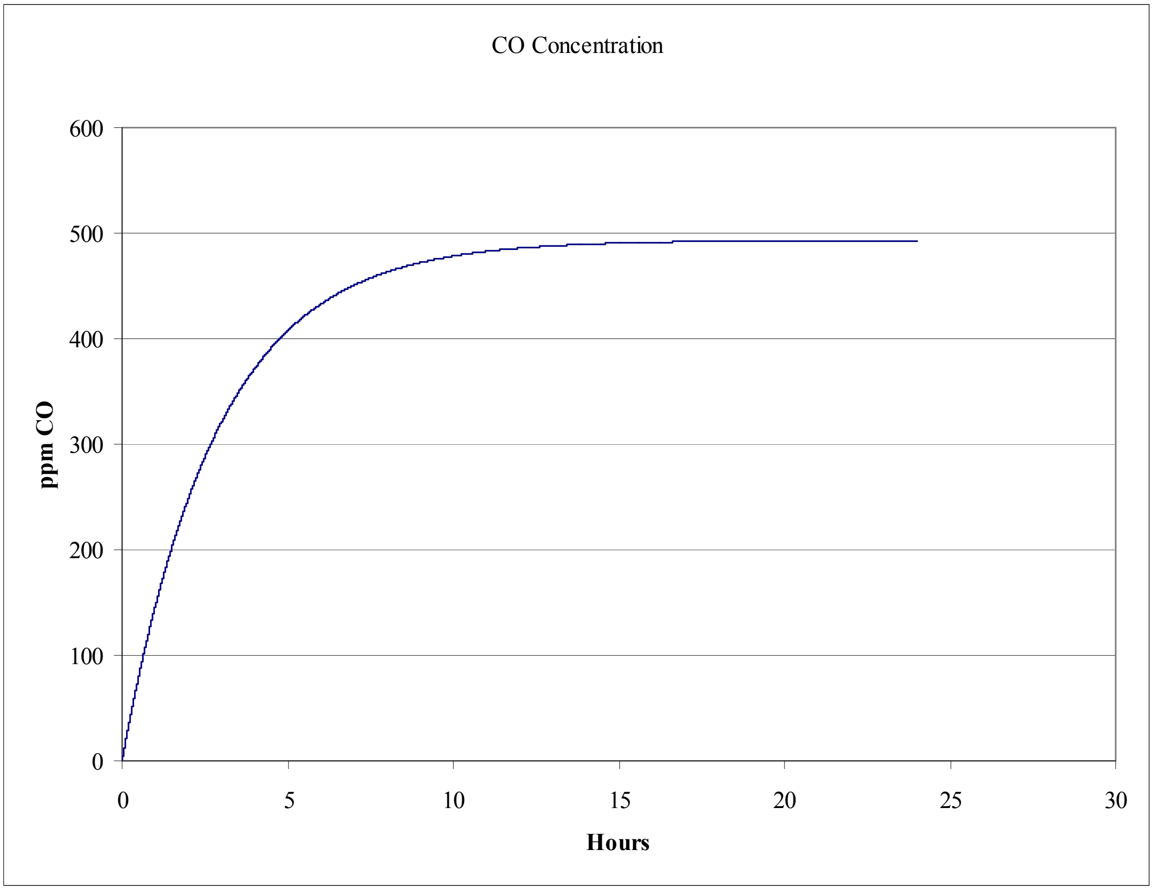

Figure 1. Continuous operation at 28 percent over-fire**,** 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, disconnected vent, emission rate 41,423 cc/hr.

A representative plot for cyclic operation of the furnace is shown in Figure 2. The cyclic operation, for modeling purposes assumed the furnace burned for 12 minutes and shut down 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.

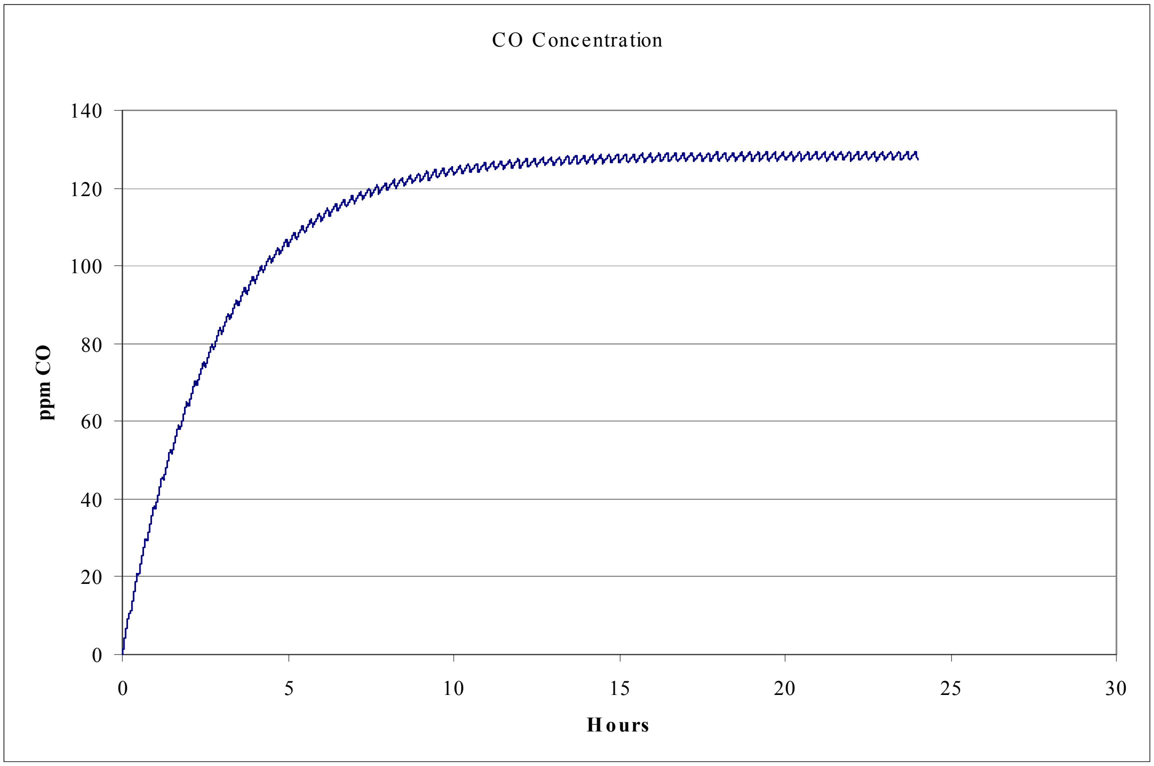

Figure 2. Cycling operation, 80 percent duty cycle at 28 percent over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, disconnected vent, emission rate 13,487 cc/hr.

4. Baseline Predictions

For the baseline scenario the CO emissions were either not measurable or so low that the predicted house concentrations were in the 0 ppm to 5 ppm range. For the 12, 18, and 28 percent overfire installations, with no vent disconnect or blockage, the calculated elevation in CO concentration ranged from 0 ppm to 1 ppm. These data are shown in table 2.

Table 2 Calculated CO Concentrations for Baseline Tests (no Blockage or Disconnects) House size 100 m^2 (1076 ft^2) [1], ACH = 0.35 [2]

File	Nominal Firing Rate Btu/hr	Duty Cycle Test	Duty Cycle Model	Emission Rate cc/hr	Concentrations (ppm) Peak	max 4 hr Avg.	max 8 hr Avg.	max 12 hr Avg.	24 hour Avg.
1	100,000	100	100%	383	5	5	5	5	4
2	100,000	80	80%	0	0	0	0	0	0
9	112,000	100	100%	15	0	0	0	0	0
10	112,000	80	80%	56	1	1	1	1	0
28	118,000	100	100%	0	0	0	0	0	0
29	118,000	80	80%	14	0	0	0	0	0
33	128,000	100	100%	0	0	0	0	0	0
34	128,000	80	80%	0	0	0	0	0	0

[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.

5. Blocked Vent Predictions

The highest calculated concentration of CO, 18 ppm, was calculated with the 28 percent over-fired condition. For this calculation the furnace was assumed to operate continuously with about 86 percent vent blockage. The concentrations ranged from 0 ppm to 18 ppm. The highest calculated concentration was based on the 28 percent over fired tests. These data are shown in table 3.

Table 3. Calculated CO Concentrations with Vent Blockage
House size 100 m^2 (1076 ft^2) [1], ACH = 0.35 [2]

File	Firing Rate BTU/hr	% Duty Cycle Test	% Duty Cycle Model	Location of Blockage	Emission Rate cc/hr	Concentrations (ppm) Peak	Max 4 hr Avg.	max 8 hr Avg.	max 12 hr Avg.	24 hour Avg.
100% Firing Rate										
7	100,000	100%	100	86% Iris	58	1	1	1	1	1
8	100,000	100%	100	88% Iris	Shut Down	0	0	0	0	0
41	100,000	80%	80	86% Iris	56	1	1	1	1	1
12% Over-fire										
11	112,000	100%	100	88% Iris	Shut Down	0	0	0	0	0
12	112,000	100%	100	86% Iris	123	1	1	1	1	1
17	112,000	100%	100	Inducer Exhaust	Shut Down	0	0	0	0	0
38	112,000	80%	80	86%, Iris	0	0	0	0	0	0
18% Over-fire										
30	118,000	100%	100	86%, Iris	722	9	9	9	9	8
28% Over-fire										
18	128,000	100%	100	86%, Iris	903	11	11	11	11	9
36	128,000	100%	100	86%, Iris	1397	17	17	17	17	15
19	128,000	100%	100	86%, Iris	1489	18	18	18	18	16

[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.

6. Disconnected Vent Predictions

For tests at the manufacturer's specified fuel flow rate with the furnace running continuously, the calculated CO concentration was 5 ppm. Under cycling conditions the calculated CO concentrations was 0 ppm.

If the vent was disconnected in the closet that housed the furnace, the highest calculated CO concentration, 493 ppm, resulted from over firing the furnace by 28 percent. If the furnace operated in a cycling mode, the calculated CO concentrations ranged from 57 ppm to 129 ppm.

If the vent was disconnected in the chamber outside the closet that housed the furnace, the highest calculated CO concentration, 371 ppm, resulted from over firing the furnace by 128 percent. If the furnace operated in a cycling mode, the maximum calculated CO concentrations ranged from 37 ppm to 85 ppm. These data are shown in Table 4.

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, disconnection or to a lessor degree blockage, can result in high indoor air CO concentrations. In most cases with a blocked vent, the furnace shut down or the amount of CO that spilled to the closet or chamber was low. The effect of over-firing is illustrated by the fact that at the rated firing rate of 100,000 BTU/hr with the vent disconnected, the maximum calculated CO concentration was 15 ppm versus 493 ppm at a firing rate of 128,000 Btu/hr.

With a disconnected vent and 12 percent over firing, the maximum calculated CO concentrations increased to 14 ppm when the furnace operated continuously. If the furnace cycled, the calculated CO concentrations ranged from 5 to 17 ppm depending on the duty cycle (33 percent to 80 percent).

With the vent disconnected and 18 percent over-firing, the maximum calculated CO concentrations was 259 ppm when the furnace operated continuously. If the furnace cycled, the calculated CO concentrations ranged from 10 ppm to 25 ppm depending on the duty cycle (33 percent to 80 percent).

With the vent disconnected and 28 percent over firing, the maximum calculated CO concentrations was 493 ppm when the furnace operated continuously. If the furnace cycled, the calculated CO concentrations ranged from 37 ppm to 129 ppm depending on the duty cycle (33 percent to 80 percent).

Table 4. Disconnected Vent Tests
House size 100 m^2 (1076 ft^2) [1], ACH = 0.35 [2]

Test Number	Nominal Btu/hr	Duty Cycle Test	Duty Cycle Model	Location of Disconnect	Emission Rate cc/hr	Concentrations (ppm) Peak	max 4 hr Avg.	max 8 hr Avg.	max 12 hr Avg.	24 hour Avg.
5	100,000	100	100%	Chamber	599	7	7	7	7	6
6	100,000	80	80%	Chamber	1241	12	12	12	12	10
6	100,000	80	50%	Chamber	1241	8	7	7	7	7
6	100,000	80	33%	Chamber	1241	5	5	5	5	4
3	100,000	100	100%	Closet	1085	13	13	13	13	11
4	100,000	80	80%	Closet	1550	15	15	15	15	13
4	100,000	80	50%	Closet	1550	10	9	9	9	8
4	100,000	80	33%	Closet	1550	7	6	6	6	5
14	112,000	100	100%	Chamber	892	11	11	11	11	9
16	112,000	80	80%	Chamber	1229	12	12	12	12	10
16	112,000	80	50%	Chamber	1229	8	7	7	7	6
16	112,000	80	33%	Chamber	1229	5	5	5	5	4
13	112,000	100	100%	Closet	1137	14	14	14	13	12
	112,000[3]	80	80	Closet						
26	118,000	100	100%	Chamber	7191	86	86	86	85	75
27	118,000	80	80%	Chamber	2481	24	24	24	24	21
27	118,000	80	50%	Chamber	2481	15	15	15	15	13
27	118,000	80	33%	Chamber	2481	10	10	10	10	9
32	118,000	100	100%	Closet	21736	259	259	258	258	228
42	118,000	80	80%	Closet	2556	25	24	24	24	21
42	118,000	80	50%	Closet	2556	16	15	15	15	13
42	118,000	80	33%	Closet	2556	11	10	10	10	9
25	128,000	100	100%	Chamber	31212	371	371	371	370	327
24	128,000	80	80%	Chamber	8818	85	84	84	84	74
24	128,000	80	50%	Chamber	8818	54	52	52	52	46
24	128,000	80	33%	Chamber	8818	37	35	35	35	31
23	128,000	100	100%	Closet	41423	493	493	493	491	434
43	128,000	80	80%	Closet	13487	129	128	128	128	113
43	128,000	80	50%	Closet	13487	83	80	80	80	71
43	128,000	80	33%	Closet	13487	57	53	53	53	47

[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] The disconnection of the vent was present in both the chamber and closet, modeling was not performed.

8. References:

Furnace CO Emissions Under Normal and Compromised Vent Conditions, Furnace # 4 - High-Efficiency Induced Draft, Brown C., Jordan, R. A., Tucholski, D. R., U.S. Consumer Product Safety Commission, Directorate for Laboratory Sciences, September 2000.