Indoor Air Modeling for Furnace #5 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 a recuperative 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 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 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 worst case exposures and assume a house of 100 m^2 (1076 ft^2) with a 2.43 m (8 ft) high ceiling or 240 m^3 (8475 ft^2). 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 staff of the CPSC Directorate for Health Sciences in estimating the health effects of CO exposure associated with disconnected and fully or partially blocked vents.

The predictions show the following:

1. With no vent blockage or disconnected flue, all combustion products exhausted properly and no increase in the indoor air concentrations of CO occurred.

2. When the vent was blocked up to 95% the furnace continued to operate but the forced draft feature provided sufficient flow to continue to exhaust the combustion products. At greater blockages the furnace shut down with little spilling of combustion products to the closet or chamber.

3. When the vent was disconnected from the furnace, allowing all combustion products to enter either the closet in which the furnace was installed, or the chamber that housed the closet, the following indoor air concentrations were predicted:

    - At the "as received" gas flow (~105,000 Btu/hr) and the furnace operating continuously with the disconnection located in the closet, the calculated indoor air concentration of CO was 125 ppm. With the furnace cycling, the calculated indoor air CO concentration ranged from 8 ppm to 18 ppm depending on the percentage of time the furnace was on (33 percent duty cycle to 80 percent duty cycle).

    - At the "as received" gas flow (~105,000 Btu/hr) and the furnace operating continuously with the disconnection located in the chamber, the calculated indoor

air concentration of CO was 45 ppm. With the furnace cycling, the calculated indoor air CO concentration ranged from 8 ppm to 19 ppm depending on the percentage of time the furnace was on (33 percent duty cycle to 80 percent duty cycle).

- When the fuel flow was increased to 112 percent of the "as received" flow rate (12 percent over-fire or ~118,000 Btu/hr) and the furnace operated continuously with the disconnection in the closet, the calculated CO concentration was 149 ppm. If the furnace cycled on and off, the calculated CO concentration was 11 ppm to 25 ppm depending on the percentage of time the furnace was on (33 percent duty cycle to 80 percent duty cycle).

- When the fuel flow was increased to 112 percent of the "as received" flow rate (12 percent over-fire or ~118,000 Btu/hr) and the furnace operated continuously with the disconnection in the chamber, the calculated CO concentration was 88 ppm. If the furnace cycled on and off, the calculated CO concentration was 7 ppm to 16 ppm depending on the percentage of time the furnace was on (33 percent duty cycle to 80 percent duty cycle).

The indoor air model, using the test data indicates the potential of reaching CO concentrations as high as 149 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 CO production rates decreased to between 18 percent and 51 percent 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 25 ppm.

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 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 high efficiency induced draft furnace, the current ANSI Z21.47 standard (1998) provides some degree of coverage for a partial or a total vent blockage, but does not address the issues of 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 recuperative, forced draft furnace (Furnace #5). The modeling incorporated three different size houses (240 m^3 to 480 m^3), 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 concentration calculations were made with the furnace running continuously or cycling. This reflects operation under extremely cold conditions, continuous operation, and operation under moderate conditions, cycling operation.

2. Emission Rates

The emission rates determined by the LS Staff are described elsewhere (Brown, Jordan, Tucholski, 2000). They installed a high efficiency induced draft furnace 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, they calculated the rate at which CO was released into the closet, chamber, flue, and the hot air supply. They measured the air exchange by 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. They determined the emission rates for various levels of flue blockage and complete disconnection of the flue. 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 recuperative forced draft furnace

Test Number	Firing Rate Btu/hr	Condition	% Duty Cycle During Tests	Condition	Source cc/hr
Baseline Tests-Flue connected, no flue blockage					
1	105,000	"As Received"	100%	Normal	0
3	105,000	"As Received"	80%	Normal	78
10	118,000	12% Over "As Received"	100%	Normal	0
11	118,000	12% Over "As Received"	80%	Normal	0
Blocked Vent					
4	105,000	"As Received"	100%	Blocked-Furnace shut down	63
17	118,000	12% Over "As Received"	100%	Blocked-Furnace shut down	15
Disconnected Vents					
5	105,000	"As Received"	100%	Disconnected - closet	10,520
7	105,000	"As Received"	100%	Disconnected - chamber	3,776
6	105,000	"As Received"	80%	Disconnected - closet	1,928
8	105,000	"As Received"	80%	Disconnected - chamber	1,958
13	118,000	12% Over "As Received"	100%	Disconnected - closet	12,533
16	118,000	12% Over "As Received"	80%	Disconnected - chamber	1,664
15	118,000	12% Over "As Received"	80%	Disconnected - closet	2,614
14	118,000	12% Over "As Received"	100%	Disconnected - chamber	7,434

[1] Test numbers correspond to test numbers listed in the tables of Appendix G (Brown, Jordan, Tucholski, 2000).

3. Mathematical Model

The CO concentrations that might 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 be likely to 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. Thus, it 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 throughout the house would be 95 percent of equilibrium in 15 minutes and 99.7 percent of equilibrium in ½ hour.

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 both 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 flue and no blockage of the flue, for the furnace having a blocked flue, and for the furnace having a disconnected flue. CO concentrations were calculated for the furnace operating "as received" (~5% over-fire or ~105,000 Btu/hr), 12 percent over-fire (~118,000 Btu/hr), 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 cyclic operation, 80 percent duty cycle. The emission rate from the 80 percent cycling test was used for calculation of CO concentrations at 50 and 33 percent duty cycles. 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 80 percent duty cycle test data 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 hours, or 8 hours). In effect the modeling can be reduced to a steady state situation where the exponential terms approach zero.

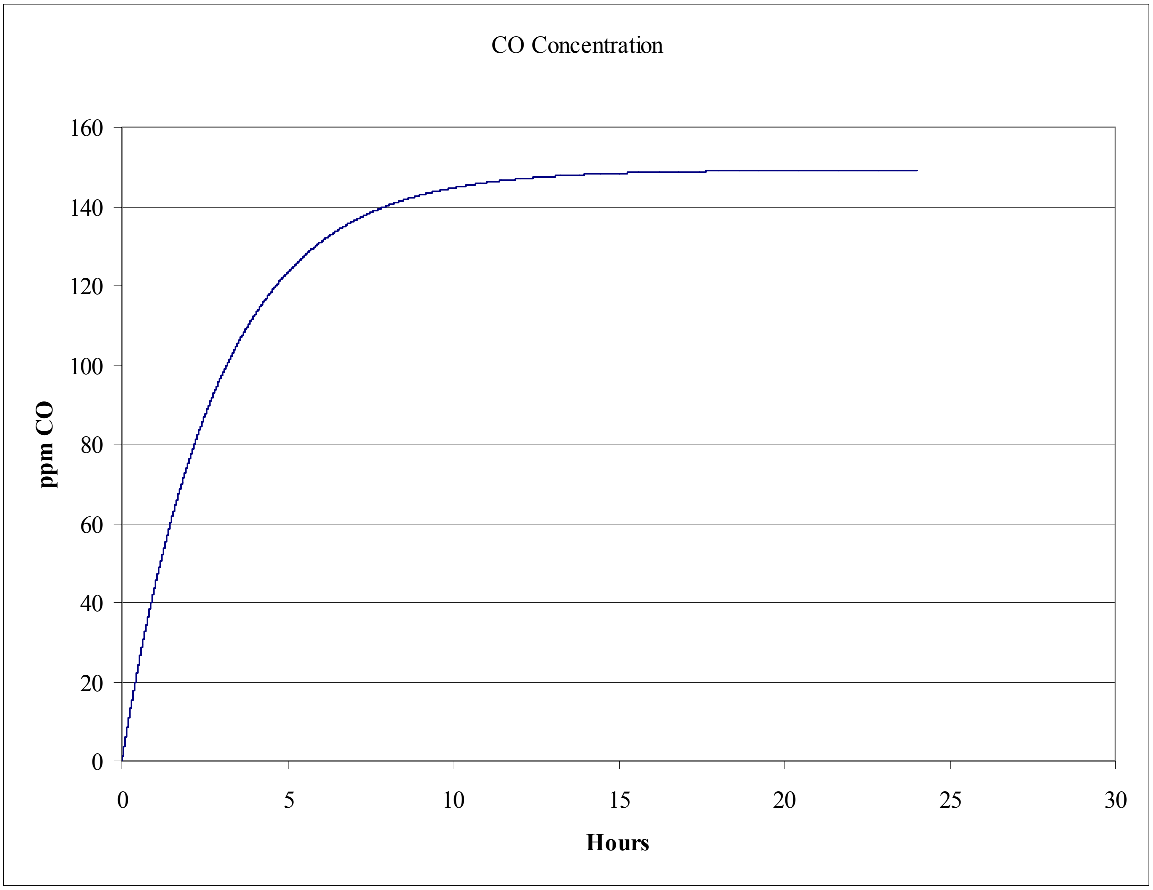

Figure 1. Continuous operation at 12% over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 house, disconnected flue in the closet, CO emission rate 12,533 cc/hr.

Thus, the concentrations approach the steady state condition that equals the emission rate divided by the volume of incoming ambient air (S/V*k).

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

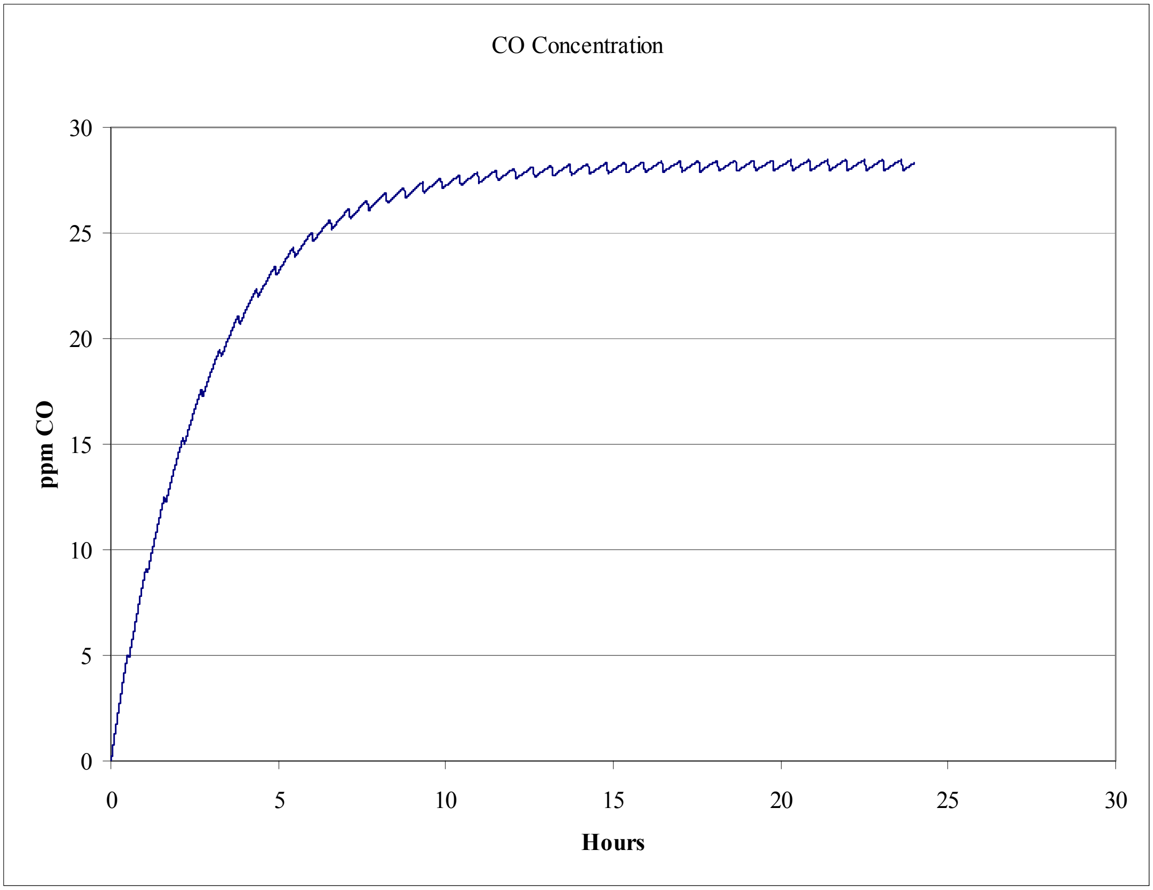

Figure 2. Cycling operation, 80% duty cycle at 12% over-fire, 0.35 hr^{-1} ventilation rate, 100 m^2 house, disconnected vent in the closet, emission rate 2,614 cc/hr

5. Blocked Flue Predictions

For the all blocked vent scenarios, the CO emissions were either not measurable or so low that the predicted house concentrations were less than 1 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]

Test Number	Firing Rate	Model Duty	Condition	Concentrations				
	Btu/hr	Cycle	Blocked Vent	Peak	Max 4 hr Avg.	Max 8 hr Avg.	24 hour Avg.	Source cc/hr
	Baseline "As received"							
1	105,000	100	No Blockage	0	0	0	0	0
3	105,000	80	No Blockage	1	1	1	1	78
	Over-Fire							
10	118,000	100	No Blockage	0	0	0	0	0
11	118,000	80	No Blockage	0	0	0	0	0
	Blocked Vent "As received"							
4	105,000	100	100% Blocked	1	1	1	1	63
	Over-Fire							
17	118,000	100	95% Blocked	0	0	0	0	15

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

6. Disconnected Flue Predictions

For the "as received" installation (~5 percent over-fired) the calculated elevation in CO concentration ranged from 8 ppm (33 percent duty cycle) to 125 ppm (continuous firing). The highest concentrations of CO resulted when the flue disconnect was inside the closet, the furnace was running continuously, and the furnace was being over-fired. Under those conditions the calculated peak concentrations ranged from 11 ppm (33 percent duty cycle) to 149 ppm (continuous firing). If the disconnect was outside of the closet, the calculated concentrations fell in the range of 7 ppm (33 percent duty cycle) to 88 ppm (continuous firing). 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]

Test Number	Firing Rate (Btu/hr)	Model Duty Cycle[3]	Vent Condition	Concentrations (ppm) Peak	Max 4 hr Avg.	Max 8 hr Avg.	24 hour avg.	Source cc/hr
	"As received"							
5	105,000	100	Disconnected-closet	125	125	125	110	10,520
6	105,000	80	Disconnected-closet	18	18	18	16	1,928
	105,000	50	Disconnected-closet	11	11	11	10	1,928
	105,000	33	Disconnected-closet	8	8	8	7	1,928
7	105,000	100	Disconnected-chamber	44	45	44	40	3,776
8	105,000	80	Disconnected-chamber	19	19	19	16	1,958
	105,000	50	Disconnected-chamber	12	12	12	10	1,958
	105,000	33	Disconnected-chamber	8	8	8	7	1,958
	Over-fire							
13	118,000	100	Disconnected-closet	149	149	149	131	12,533
15	118,000	80	Disconnected-closet	25	25	25	22	2,614
	118,000	50	Disconnected-closet	16	16	16	14	2,614
	118,000	33	Disconnected-closet	11	10	10	9	2,614
14	118,000	100	Disconnected-chamber	88	88	88	78	7,434
16	118,000	80	Disconnected-chamber	16	16	16	14	1,664
	118,000	50	Disconnected-chamber	10	10	10	9	1,664
	118,000	33	Disconnected-chamber	7	6	6	6	1,664

[1] The concentrations for a house of 150 m^2 (1615 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] Concentrations for continuous operation, 100% duty cycle, were calculated using the emission rate from continuous furnace operation tests. Concentrations for cycling operation, 80, 50, and 33% duty cycle, were calculated using the emission rate from 80% duty cycle furnace tests.

7. Conclusions

The calculated CO concentrations indicate that when the flue is completely blocked the furnace reliably shut down. With blockages as high as 95 percent the furnace continued to operate without spilling combustion products to the closet or chamber. This is undoubtedly because the forced draft blower on the furnace was powerful enough to force the combustion products through the blockage.

The furnace, however, did not shut off when the flue was disconnected. With a disconnected flue, elevated CO concentrations resulted in the chamber and closet. With the flue disconnected in the closet, and the furnace operating continuously, the emission rate of CO was 1.7 to 2.8 times the emission rate observed when the disconnect was outside the closet. This is likely to be a result of oxygen depletion being severe in the closet when the disconnection is also in the closet. The depletion of oxygen would lead to lowered combustion efficiency and an increase of CO emission rate. The calculated concentrations for continuous furnace operation ranged from 45 ppm, with the flue disconnected in the chamber to 149 ppm with the flue disconnected in the closet.

In the disconnected flue tests, when the furnace operated in the cycling mode, lower emission rates were observed. The emission rates, determined with the disconnect either in or outside the closet, were comparable when the furnace was fired at ~105,000 Btu/hr. When the furnace operated at a fuel flow 12 percent above the "as received" rate, the emission rate observed with the vent disconnected inside the closet was about 4 times the emission rate observed with the vent disconnected outside the closet. The calculated CO concentrations ranged from 7 ppm (33 percent duty cycle) to 25 ppm (80 percent duty cycle).

8. Reference:

Furnace CO Emissions Under Normal and Compromised Vent Conditions, Furnace #5 High Efficiency Induced Draft, Brown C., Jordan, R. A., Tucholski, D. R., U.S. Consumer Product Safety Commission, Directorate for Laboratory Sciences, August 2000.