Indoor Air Modeling for Furnace #3 with a Disconnected Vent

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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 110,000 Btu/hr. The staff installed the furnace in a closet inside a room-sized 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 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 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 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 disconnected vent, all combustion products exhausted properly and no increase in the indoor air concentrations of CO occurred. With or without vent blockage there was no build up of CO in the chamber. When the vent was blockage was greater than 47 percent, the furnace shut down. At lower levels of blockage, the furnace continued to operate but no CO spilled into the chamber or closet.

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

   - At the gas flow specified in the installation instructions (110,000 Btu/hr) or over-fired at 119,000 Btu/hr, the furnace operating continuously, and the disconnection located in either the closet or the chamber, the calculated indoor air concentration of CO did not exceed 88 ppm. With the furnace cycling, the calculated indoor air CO concentration did not exceed 54 ppm.

   - When the fuel flow was increased to 133,000 Btu/hr, the calculated CO concentration did not exceed 129 ppm when the furnace operated continuously. If

the furnace cycled on and off, the calculated CO concentration did not exceed 63 ppm.

The indoor air model, using the test data indicates the potential of reaching CO concentrations as high as 129 ppm. This would occur under very cold conditions with the furnace being over-fired and operating continuously for at least 10 hours at an input rate of 133,000 Btu/hr. 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 20 and 80 percent of the CO production rates observed under continuous burning conditions. When the vent was either partially or fully blocked, the furnace either shut down or continued to vent all of the combustion products to the outside. 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 63 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. For a mid-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 issue 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 an induced draft furnace (Furnace #3) rated at 110,000 Btu/hr. 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 calculations of indoor air CO concentrations were made with both continuously and cyclical 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 rate at which CO was released into the closet, chamber, vent, and the hot air supply was calculated. Air exchange was measured 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. Emission rates were determined for various levels of vent blockage and complete disconnection of the vent. The tests included operating the furnace continuously or having the burner cycling on and off. Table 1 presents emission rates only for the disconnected vent scenarios. Baseline tests with the vent attached and no vent blockage, and for tests with the vent partially or totally blocked showed no buildup of CO. In the case of the blocked vents, at less than 47 percent blockage, the induced draft provided enough pressure to exhaust the combustion products through the vent. When the vent was at least 56 percent blocked, the furnace shut down.

Table 1. Emission Rates for a 110,000 Btu/hr induced draft furnace

Test Number	Firing rate Btu/hr	Condition	% Duty cycle During tests	Vent disconnect Location	Source cc/hr
13	110,000	Specification	100	Closet	7,360
14	110,000	Specification	100	Chamber	6,711
44	110,000	Specification	80	Closet	4,915
45	110,000	Specification	80	Chamber	5,658
37	123,000	12% over Specification	100	Closet	5,906
35	123,000	12% over Specification	100	Chamber	6,058
36	123,000	12% over Specification	80	Closet	5,852
34	123,000	12% over Specification	80	Chamber	5,096
1	119,000	As Received	100	Closet	5,447
2	119,000	As Received	100	Chamber	5,253
18	119,000	As Received	80	Closet	4,591
42	119,000	As Received	80	Chamber	5,382
22	133,000	12% over As Received	100	Closet	10,816
23	133,000	12% over As Received	100	Chamber	8,340
27	133,000	12% over As Received	80	Closet	6,287
28	133,000	12% over As Received	80	Chamber	6,534

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 calculated 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 an induced 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 30 minutes. The model equation follows:

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

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 indoor air CO concentrations over a 24-hour period. As a result of the lack of CO buildup in normal and blocked vent tests, only calculations for the disconnected vent tests were made. Indoor air CO concentrations were calculated with the furnace operating at the manufacturer's specified rate (110,000 Btu/hr) and 12 per cent over-fired (123,000 Btu/hr). Further indoor air CO concentrations were also calculated for the furnace operating "as received," that is, no adjustment of manifold pressure or clocking of gas flow (119,000 Btu/hr), and 12 percent over the "as received" rate (~133,000 Btu/hr). The furnace was operated continuously and 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 cyclical operation, 80 percent duty cycle. The emission rate from the 80 percent cyclical 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. Thus, the concentrations approach the steady state condition that equals the emission rate divided by the volume of incoming ambient air (S/V*k).

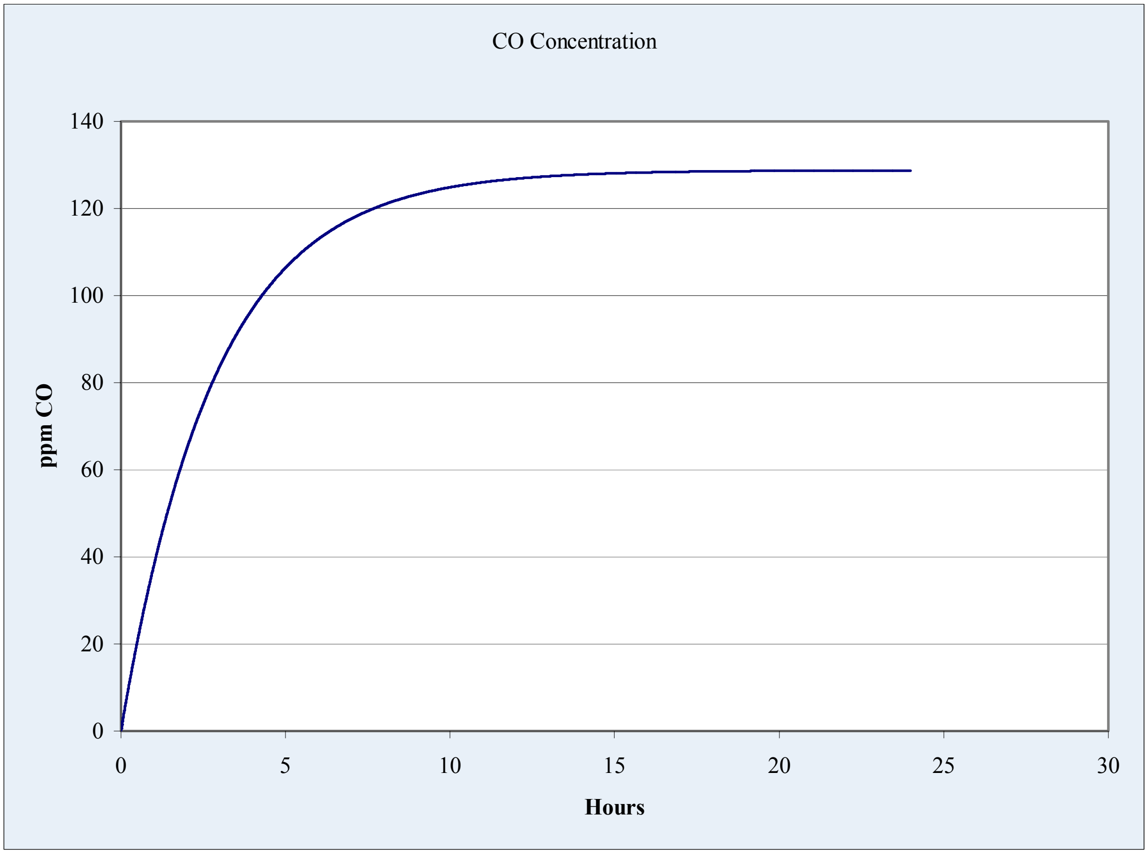

Figure 1 Continuous operation at 133,000 Btu/hr, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, vent disconnected in the closet, emission rate 10,816 cc/hr.

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. Again, the maximum average concentrations are similar, regardless of the averaging period.

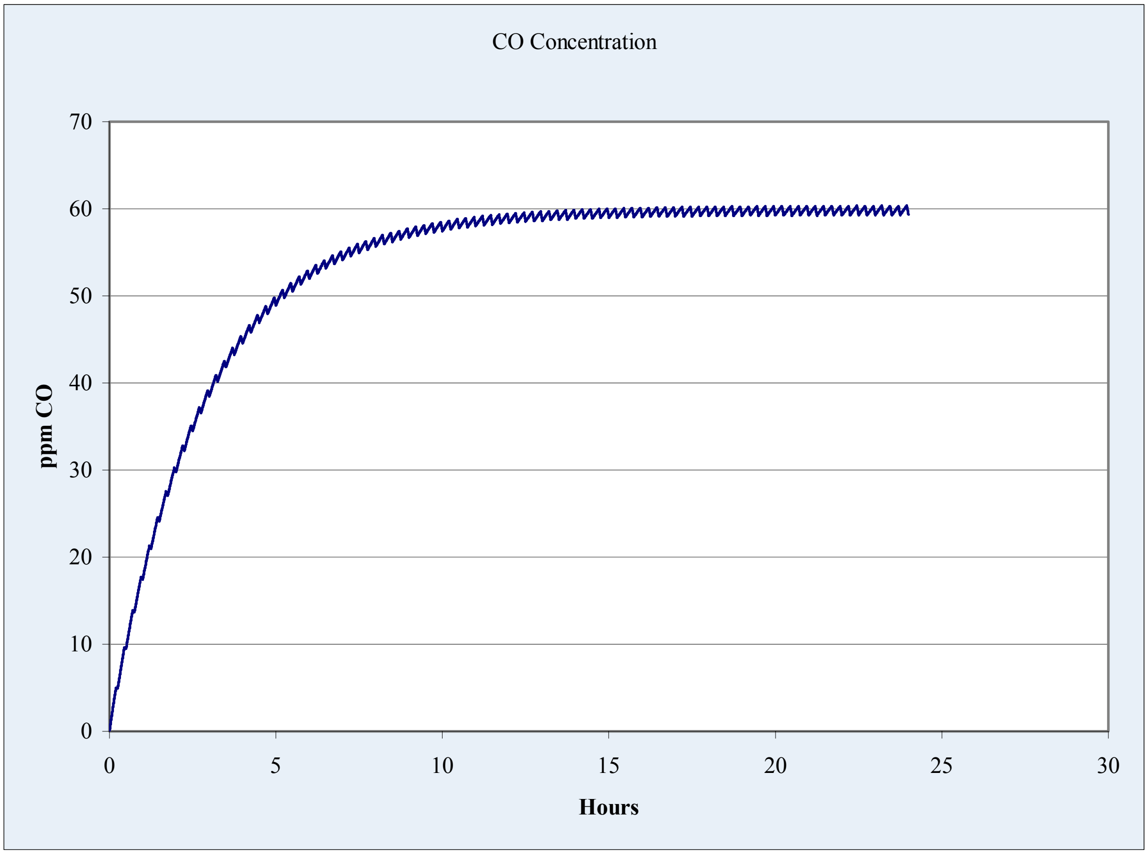

Figure 2 Cyclic operation (80 % duty cycle), at 133,000 Btu/hr, 0.35 hr^{-1} ventilation rate, 100 m^2 (1076 ft^2) house, vent disconnected in the closet, emission rate 6,287 cc/hr.

5. Disconnected Vent Predictions

When the furnace was installed at the specified firing rate (~110,000 Btu/hr), the calculated elevation in CO concentration ranged from 21 ppm to 88 ppm. The highest concentrations of CO resulted when the vent was disconnected inside the closet and the furnace was running continuously. Under those conditions the calculated peak concentration was 88 ppm. If the disconnect was in the chamber, the calculated concentrations was 80 ppm. With the furnace cycling at an 80% duty cycle and the vent disconnected in the chamber, the maximum concentration calculated was 47 ppm.

If the furnace was operated at 12 percent over the manufacturer's specified rate (~123,000 Btu/hr) the calculated concentrations ranged from 21 ppm to 72 ppm. The highest concentrations of CO resulted when the vent was disconnected in the chamber and the furnace was running continuously. Under those conditions the calculated peak concentration was 72 ppm. With the furnace cycling at an 80% duty cycle and the vent disconnected in the chamber, the maximum calculated concentration was 49 ppm. If the furnace ran continuously and the vent was disconnected in the closet, the calculated peak concentration was 70 ppm. With the furnace cycling at an 80% duty cycle and the vent disconnected in the closet, the maximum concentration calculated was 56 ppm.

For the “as received” installation (119,000 Btu/hr), the calculated elevation in CO concentration ranged from 19 ppm (33% duty cycle) to 65 ppm (100% duty cycle). The highest concentrations of CO resulted when the vent disconnect was inside the closet and the furnace was running continuously. Under those conditions, the calculated peak concentration was 65 ppm. If the disconnect was in the chamber, the calculated concentrations ranged from 23 ppm (33% duty cycle) to 63 ppm (100% duty cycle). With the furnace cycling at an 80% duty cycle and the vent disconnected in the chamber, the maximum concentration calculated was 52 ppm.

If the furnace was operated at 12 percent over the “as received condition” (~133,000 Btu/hr) the calculated concentrations ranged from 26 ppm to 129 ppm. The highest concentrations of CO resulted when the vent was disconnected in the closet and the furnace was running continuously. Under those conditions the calculated peak concentration was 129 ppm. With the furnace cycling at an 80% duty cycle and the vent disconnected in the closet, the maximum calculated concentration was 60 ppm. If the furnace ran continuously and the vent was disconnected in the chamber, the calculated peak concentration was 99 ppm. With the furnace cycling at an 80% duty cycle and the vent disconnected in the chamber, the maximum concentration calculated was 63 ppm. These data are shown in Table 2.

Table 2. Disconnected Vent Tests

House size 100 m^2 (1076 ft^2) [1]

ACH = 0.35 [2]

Firing Rate Btu/hr	Model Duty Cycle[3]	Vent Disconnect Location	Predicted Indoor Air Concentration (ppm) Peak	Max 4 hr Avg.	Max 8 hr Avg.	Max 12 hr Avg.	24 hr Avg.	Source cc/hr
Adjusted to the specified rate								
110,000	100	Closet	88	88	88	87	77	7,360
110,000	80	Closet	47	47	47	47	41	4,915
110,000	50	Closet	30	29	29	29	26	4,915
110,000	33	Closet	21	19	19	19	17	4,915
110,000	100	Chamber	80	80	80	80	70	6,711
110,000	80	Chamber	54	54	54	54	47	5,658
110,000	50	Chamber	35	34	34	33	30	5,658
110,000	33	Chamber	24	22	22	22	20	5,658
12% over specified rate								
123,000	100	Closet	70	70	70	70	62	5,906
123,000	80	Closet	56	56	56	55	49	5,852
123,000	50	Closet	36	35	35	35	31	5,852
123,000	33	Closet	25	23	23	23	20	5,852
123,000	100	Chamber	72	72	72	72	64	6,058
123,000	80	Chamber	49	48	48	48	43	5,096
123,000	50	Chamber	31	30	30	30	27	5,096
123,000	33	Chamber	21	20	20	20	18	5,096
"As Received", approximately 8% over fired								
119,000	100	Closet	65	65	65	65	57	5,447
119,000	80	Closet	44	44	44	44	39	4,591
119,000	50	Closet	28	27	27	27	24	4,591
119,000	33	Closet	19	18	18	18	16	4,591
119,000	100	Chamber	63	63	62	62	55	5,253
119,000	80	Chamber	52	51	51	51	45	5,382
119,000	50	Chamber	33	32	32	32	28	5,382
119,000	33	Chamber	23	21	21	21	19	5,382
12% over the "as received" rate								
133,000	100	Closet	129	129	129	128	113	10,816
133,000	80	Closet	60	60	60	60	53	6,287
133,000	50	Closet	39	37	37	37	33	6,287
133,000	33	Closet	26	25	25	25	22	6,287
133,000	100	Chamber	99	99	99	99	87	8,340
133,000	80	Chamber	63	62	62	62	55	6,534
133,000	50	Chamber	40	39	39	39	34	6,534
133,000	33	Chamber	27	26	26	26	23	6,534

[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.

6. Conclusions

When the vent was blocked between 47 and 56 percent, the furnace reliably shut down. The time to shut down was short enough that no build up of CO was observed in the chamber. With blockages equal to or lower than 47 percent, the furnace continued to operate without spilling combustion products into the closet or chamber.

The furnace cycled on and off when the vent was disconnected. With a disconnected vent, elevated CO concentrations resulted in the chamber and closet. With the vent disconnected in the closet, and the furnace operating continuously, the emission rate of CO averaged 10 percent greater than the emission rate when the vent was disconnected in the chamber. This is likely to be a result of oxygen depletion being more severe in the closet when the disconnection is also in the closet. The depletion of oxygen would lead to lowered combustion efficiency and increased CO emission rates. With the disconnection located in the chamber and the furnace operating continuously, the maximum calculated CO concentrations ranged from 63 ppm at 119,000 Btu/hr to 99 ppm at 133,000 Btu/hr. With the disconnection located in the closet and the furnace operating continuously, the maximum calculated CO concentrations ranged from 65 ppm at 119,000 Btu/hr to 129 ppm at 133,000 Btu/hr.

In the disconnected vent tests, when the furnace operated in the cycling mode (80% duty cycle), the emission rates were lower than when the furnace operated continuously. The calculated concentrations ranged from 44 ppm (119,000 Btu/hr, disconnection in the closet) to 63 ppm (133,000 Btu/hr, disconnection in the chamber).

7. Reference

Furnace CO Emissions Under Normal and Compromised Vent Conditions, Furnace #3 Induced Draft Furnace, Brown C., Jordan, R. A., Tucholski, D. R., U.S. Consumer Product Safety Commission, Directorate for Laboratory Sciences, September 2000.