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Memorandum

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SUBJECT: Carbon monoxide (CO) emissions from a high-efficiency, induced-draft furnace (Furnace #5): health concerns related to projected consumer exposure.

Introduction

The U.S. Consumer Product Safety Commission (CPSC) has an ongoing effort to reduce deaths and injuries resulting from accidental, non-fire related carbon monoxide poisoning (CO). Part of this effort considers the need for improvement in the safety of combustion appliances. To this end, staff initiated a project to evaluate the effects of compromised furnace vents on: furnace CO emissions, projected residential CO levels that could result under such circumstances, and, the likelihood that these projected CO levels could adversely impact consumers' health. Several furnace designs are being evaluated as part of this test program.

The current ANSI standard for Gas Fired Central Furnaces, ANSI Z21.47, requires that direct vent furnaces comply with certain blocked vent provisions (Section 4.4.6, 1998). These provisions specify that for conditions of partial to complete blockage of the flue outlet, the CO concentration in an air-free sample of flue gases shall not exceed 0.04 percent (400 ppm) when the furnace is tested in an atmosphere with a normal oxygen supply. However, there are no specific requirements for a mechanism to shutoff the furnace if the flue gas CO limit is exceeded. The CPSC's Directorate for Laboratory Sciences (LS) recently issued a report concerning CO emissions from a natural gas-fueled, high-efficiency, induced draft furnace under various "compromised-vent" test scenarios (Brown, Jordan, and Tucholski, 2000). LS staff then used selected CO emission rates derived from the LS test data to model residential CO levels that could result under different furnace use scenarios (Porter, 2000). Health Sciences (HS) staff was asked to determine whether these CO concentrations have any likely adverse impact on consumer health.

Background

The subject product of this report, a natural gas-fueled, high-efficiency, induced draft furnace with an energy input rate of 100,000 Btu/hr, was tested by CPSC LS staff in a controlled environmental chamber. This furnace is equipped with two pressure switches, one of which monitors the differential pressure within the combustion chamber and the inlet side of the inducer motor. This differential pressure switch can sense the change in static pressure that can result when the furnace vent becomes blocked (see page 2, Brown et al., 2000). In addition to establishing baseline performance, CPSC LS staff investigated how furnace operation was affected by varying degrees of vent blockage (56-100% blockage), vent blockage location, and by a totally disconnected vent. Other important variables in the test matrix included the fuel input rate (from 100,000 to 134,000 Btu/hr, i.e., up to 34% overfire), and the furnace operating conditions which varied between an 80% "burner on" cycle and the worst-case scenario of continuous firing of the burner. The chamber test conditions were intended to replicate conditions that can occur in the field. The CO emission rates for each test run were calculated from the respective equilibrium CO concentration in the test chamber and are reported elsewhere (see Brown, Jordan and Tucholski, 2000).

Subsequently, CPSC LS staff conducted modeling analyses to predict indoor air levels of CO, based on CO emission rates derived from CPSC's empirical furnace test data. A single compartment mass balance computer model was used to estimate residential CO concentrations that could likely result from use of the furnace over a 24 hour use period, under various "compromised vent" test scenarios (Porter, 2000). LS staff's projections focus on the worst case scenario of a furnace operating in a small, airtight home (100 m^2 [240 m^3] with 0.35 air changes per hour [ACH]), however, they allow for the effects of increases in room size and/or ACH to be derived from modeled CO concentrations. The computer model also allows the user to input the cycling time of the furnace; thus, although 33% and 50% "burner-on" cycles were not specifically tested in the chamber, predicted indoor CO concentrations are presented in the modeling report. It should be noted that LS staff has acknowledged that these latter CO concentrations are calculated using CO emission rates derived from the 80% "burner on" test data, and, as such, represent conservative safety predictions, since lower CO emission rates would be expected at reduced "burner on" cycles. LS staff's projected residential CO levels for baseline, blocked vent and disconnected vent scenarios, are presented in tabular form in the lab report (see Tables 2 and 3, Porter, 2000)

Health Sciences' Perspective

It is clearly established that CO interferes with oxygen uptake, delivery, and utilization by combining at least 200 times more avidly than oxygen with hemoglobin, the body's oxygen transport protein, to form carboxyhemoglobin (COHb). COHb formation is primarily a function of the CO level and duration of exposure. After 10 to 12 hours of sustained exposure to a given CO level, the % COHb level will reach an equilibrium level that is limited by that CO exposure level. Before equilibrium conditions are reached, COHb formation is greatly influenced by an exposed individual's activity level which affects the amount of air and CO taken into the lungs. As the activity level increases, the time to reach the equilibrium COHb level decreases. At high levels, CO can be a lethal asphyxiant. Levels above 20% COHb are generally considered to pose an immediate threat of permanent neurological impairment, even death, to all consumers. Sustained exposure to approximately 150 ppm CO will result in about 20% COHb at equilibrium. As a general rule, HS staff considers that keeping COHb levels from reaching 10% is protective of the majority of healthy consumers. The lowest CO exposure that can result in 10% COHb is about 65-70 ppm for at least 4-5 hours, depending on the exposed individual's activity level. However, at even lower levels, CO is reported to have more subtle effects on cardiac function, such as decreasing the onset times of exercise-induced electrocardiogram ST-segment changes and angina symptoms in some patients with coronary artery disease (CAD).

These changes are indicative of myocardial ischemia and can be associated with lethal myocardial infarcts. Thus, HS staff considers CAD patients to be the population most susceptible to adverse health effects of CO exposure (Burton, 1996).

CPSC staff believes that consumer exposure to CO should be kept to a minimum, whenever feasible. Staff develops recommendations for CO limits for specific consumer products on a case-by-case basis. Staff takes into consideration the intended use of the product, consumer use patterns, relevant affected populations, technical feasibility, and overall impact of their recommendations. Previously, in association with the unvented gas space heater (UVGSH) and kerosene heater (KH) projects, CPSC's HS staff recommended that indoor CO levels should be limited to 15 ppm for 8 hours, or 25 ppm for 1 hour, as time-weighted averages. These CO exposures can potentially elevate COHb levels to approximately 2.4%, about the level associated with the earliest subtle effects of CO on cardiac function in some CAD patients. The staff's recommendations for indoor air CO limits associated with use of individual CO source products (such as UVGSHs and KHs) are generally more stringent than the limits for mandatory alarm activation of residential CO alarms[1]. The CPSC staff considers that the primary way to combat the CO hazard is to limit CO emissions from source products, particularly products that are expected to be used for extended durations, such as furnaces.

Health Science's Assessment of Projected CO Exposures

For this exposure assessment, HS staff examined LS staff's projections for the maximum 8h and 24 h-average CO exposures in the worst case modelling scenarios. The latter averages are generally slightly less than the former over the 24h modelling period used by LS staff. However, they would ultimately increase to reach the respective maximum 8h averages if the modelling period was sufficiently extended to reflect actual in-field use of furnaces. Thus, HS staff elected to base all the following CO hazard assessments on LS staff's maximum 8h averages. The LS data 8h and 24h projections are presented within this current report in Tables 1 and 2. Table 2 also presents additional data to show how less extreme conditions for home size and ventilation rates can greatly reduce the projected residential CO exposure. A 75% reduction in projected CO exposures occurs when both larger sized homes (200 m^2 [480 m^3] v 100 m^2 [240 m^3]) and increased ventilation rates (0.7 ACH v 0.35 ACH) are used to model CO emission data.

Baseline and Blocked Vent Conditions

When the furnace was operated with intact, unoccluded vents, CO emission rates were extremely low, and there was negligible impact on projected residential CO concentrations, even if the furnace was 18% overfired and running continuously. Even when the furnace was overfired by 5% to 18%, was running continuously, and had between 95-100% vent blockage, projected indoor air concentrations of CO were less than 1ppm under the most extreme conditions of a small, tightly weatherized home. No adverse health effects of CO would be expected under these scenarios (Table 1).

[1] Current voluntary standards (UL 2034 and IAS 696) specifications for CO alarm activation are 70 ppm for 189 minutes, 150 ppm for 50 minutes, and 400 ppm for 15 minutes. Alarm resistance is required at 30 ppm for 30 days, 70 ppm for 60 minutes, 150 ppm for 10 minutes, and 400 ppm for 4 minutes. CO alarms are considered a secondary means of protecting against the CO hazard. The higher limits for CO alarm activation reflect the fact that the CO alarm is not a source product, and, that in order to maintain confidence in CO alarms, consumers/emergency responders need to be able to readily trace and address the source of CO elevations that activate an alarm signal. The CO alarm will react to CO from all sources, thus, it needs to be able to resist activation by transient elevations in outdoor CO levels and/or CO emissions from more than one normally-operating CO source product.

Table 1. Predicted maximum 8h average indoor CO concentrations for intact unoccluded vent (baseline) and partially and totally blocked vent scenarios at different furnace operating conditions.

ACH	0.35		Home size	100 m^2 (240 m^3)
Firing rate Btu/hr	VENT % block	cycle % burner on	CO source cc/hr	CO ppm
105,000	0	100	0	0.0
105,000	0	80	78	0.7
118,000	0	100	0	0.0
118,000	0	80	0	0.0
105,000	100	100	63	0.7
118,000	95	100	15	0.2

Disconnected Vent Conditions

Table 2 shows data on projected CO exposures that would occur when the furnace was overfired up to 18% and the vent was disconnected in either the furnace closet or the chamber. The greatest hazard would occur when the vent disconnect occurred in the closet and the furnace was firing continuously. Under these operating conditions and in the most extreme scenario of the tightly weatherized small home, the projected indoor CO levels of 125 ppm (~5% overfire) to 149 ppm (~18% overfire) could result in COHb levels of about 17 to 20%. Although these COHb levels are unlikely to result in lethal effects in healthy individuals, they can cause mild to severe headaches and nausea, and lasting neurological impairment is believed to be possible if the exposures are sustained for long durations. Serious life-threatening compromise of susceptible individuals, such as CAD patients, is possible at these exposures. However, HS staff notes that home size and ventilation rates significantly impact projected health effects; for the same CO emission rates modelled in larger, well ventilated homes, the projected indoor CO levels are between 31 and 37 ppm, equivalent to about 5 to 6% COHb. While these levels are not likely to cause perceptible effects in healthy individuals, they would still be of concern to susceptible populations such as CAD patients.

The CO hazard associated with the vent disconnect in the closet decreases as the furnace firing time decreases. At both 5% and 18% overfire, there is minimal health concern at furnace firing times between 33 and 50%, since 8 to 16 ppm CO is equivalent to about 1 to 2.7% COHb. At 80% firing times, the projected CO levels rise to between 18 and 25 ppm for 5% and 18% overfire scenarios respectively, and are very slightly above staff recommendations for other heating appliances (UVGSH and KHs). The corresponding estimated COHb levels of about 3 to 4% would not likely have any perceptible effects in healthy individuals, but would be of concern to susceptible populations.

For vent disconnects in the chamber, only the overfire scenario was of health concern, with about 7% COHb projected at 5% overfire (45 ppm CO) and about 13% COHb at 18% overfire (88 ppm CO). The latter level could cause mild headaches and possibly nausea in healthy individuals, and both scenarios would be of concern to susceptible populations, such as CAD patients.

Conclusions

For the given test conditions, this particular furnace appears unlikely to present a CO hazard to healthy or compromised individuals when installed and operated as intended, even when the furnace vents are partially or fully blocked. Disconnected vents can result in hazardous CO exposures depending on the location of the vent disconnect and on the amount of time that the furnace burners spend in the firing mode. If the furnace vent is disconnected within the furnace closet, significant CO exposures can occur if the furnace is continuously fired. While these are unlikely to cause lethal effects in healthy individuals, serious neurological impairment could possibly result. When the vent is disconnected in the chamber area, there is a relatively reduced risk of serious CO exposure when the furnace is fired continuously.

The likelihood of serious health effects associated with vent disconnects decreases progressively as the furnace firing time decreases. Under the given test conditions, when the furnace burners are firing for 80% of the furnace cycle time, there is minor health concern for vent disconnects within the closet space or chamber. At burner firing times less than, or equal to, 50% of the furnace cycle, there is no significant health concern. The risk of any health concerns associated with CO exposure from furnaces is greatest in small, tightly weatherized homes. In larger homes and/or more well ventilated homes, when the furnace burners operate in a cyclical mode (<80% duty cycle), the projected indoor CO exposure rarely achieve a level that would be of concern to healthy or susceptible populations.

References

American National Standard/National Standard of Canada for Gas-Fired Central Furnaces, ANSI Standard No. Z21.47-1998, American Gas Association, New York, NY (1998).

Brown CJ, Jordan RA and Tucholski DR. CPSC LS memo, Furnace CO Emissions Under Normal and Compromised Vent Conditions. Furnace #5 – High Efficiency Induced Draft (September, 2000).

Porter WK Jr, CPSC LS memo. Indoor Air Modeling for Furnaces with Blocked or Disconnected Vents (Furnace # 5) (October, 2000).

Burton LE, CPSC HS memo. Toxicity from Low Level Human Exposure to Carbon Monoxide (7/1/96)

Table 2. Predicted 8h and 24h average indoor CO concentrations for disconnected vents in closet or chamber and various furnace operating conditions: effects of home size and ventilation rate

			Home size	100 m^2 ($240 m^3$)			150 m^2 ($360 m^3$)			200 m^2 ($480 m^3$)		
			ACH	0.35	0.5	0.7	0.35	0.5	0.7	0.35	0.5	0.7
Firing rate Btu/hr	Site of Vent Disconnect	cycle % burner on	CO source cc/hr	Maximum 8h average CO ppm								
105,000	closet	100	10,520	125	93	63	83	61	41	63	46	31
105,000	closet	80	1928	18	14	9	12	9	6	9	7	5
105,000	closet	50	1928	11	8	6	8	6	4	6	4	3
105,000	closet	33	1928	8	6	4	5	4	3	4	3	2
105,000	chamber	100	3776	45	33	22	30	22	15	22	17	11
105,000	chamber	80	1958	19	14	9	12	9	6	9	7	5
105,000	chamber	50	1958	12	9	6	8	6	4	6	4	3
105,000	chamber	33	1958	8	6	4	5	4	3	4	3	2
118,000	closet	100	12533	149	110	75	98	73	49	75	55	37
118,000	closet	80	2614	25	18	12	16	12	8	12	9	6
118,000	closet	50	2614	16	11	8	10	8	5	8	6	4
118,000	closet	33	2614	10	8	5	7	5	3	5	4	3
118,000	chamber	100	7434	88	65	44	58	43	29	44	33	22
118,000,	chamber	80	1664	16	12	8	10	8	5	8	6	4
118,000,	chamber	50	1664	10	7	5	7	5	3	5	4	2
118,000,	chamber	33	1664	7	5	3	4	3	2	3	2	2
				Maximum 24h average CO ppm								
105,000	closet	100	10,520	110	82	55	73	54	36	55	41	28
105,000	closet	80	1928	16	12	8	11	8	5	8	6	4
105,000	closet	50	1928	10	7	5	7	5	3	5	4	3
105,000	closet	33	1928	7	5	3	4	3	2	3	2	2
105,000	chamber	100	3776	40	29	20	26	19	13	20	15	10
105,000	chamber	80	1958	16	12	8	11	8	5	8	6	4
105,000	chamber	50	1958	10	8	5	7	5	3	5	4	3
105,000	chamber	33	1958	7	5	3	4	3	2	3	3	2
118,000	closet	100	12533	131	97	66	87	64	43	66	49	33
118,000	closet	80	2614	22	16	11	14	11	7	11	8	5
118,000	closet	50	2614	14	10	7	9	7	5	7	5	3
118,000	closet	33	2614	9	7	5	6	4	3	5	3	2
118,000	chamber	100	7434	78	58	39	51	38	26	39	29	20
118,000,	chamber	80	1664	14	10	7	9	7	5	7	5	4
118,000,	chamber	50	1664	9	6	4	6	4	3	4	3	2
118,000,	chamber	33	1664	6	4	3	4	3	2	3	2	1