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Memorandum

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SUBJECT: Carbon monoxide (CO) emissions from a high-efficiency, induced-draft furnace (Furnace #4): 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 induced draft furnaces comply with certain blocked vent provisions (Section 2.22, 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 a pressure switch that monitors the static pressure at the inlet side of the unit's inducer fan. If the switch opens, the furnace will shut off and will enter a "lockout" mode; this prevents it from restarting until the pressure switch closes.

To restart after a lockout, the furnace must be de-energized and re-energized (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 (86-100% blockage) and the vent blockage location, and by a totally disconnected vent and the vent disconnect location. Other important variables in the test matrix included the fuel input rate (from 100,000 to 128,000 Btu/hr, i.e., up to 28% 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, 3, and 4, 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 a 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 modeling scenarios. The latter averages are generally slightly less than the former over the 24h modeling period used by LS staff. However, they would ultimately increase to reach the respective maximum 8h averages if the modeling 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 projections are presented within this current report in Tables 1 and 2. These tables also present 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 either not measurable or were so extremely low that there was negligible impact on projected residential CO concentrations (between 1 and 5 ppm CO), even if the furnace was 28 % overfired and running continuously. When the furnace was overfired by 118 % and was running continuously with between 86 and 100 % vent blockage, the projected indoor air concentrations of CO were >9 ppm under the most extreme conditions of a small, tightly weatherized home. Indeed, the lab test report found that the furnace automatically shut off within 20 seconds when

[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.

the exhaust vent was completely blocked at either the vent outlet, the inducer fan outlet, or midway along the vent. No adverse health effects of CO would be expected under these scenarios. When overfired by 28 % and running continuously with 86 % vent blockage, the projected 8 hour CO exposures from this furnace ranged between 11 and 18 ppm. Exposures above 15 ppm/8 hours are very slightly above HS staff recommendations for other heating appliances (UVGSH and KHs). The corresponding COHb estimates of about 2 to 3 % would not likely have any perceptible effects in healthy individuals, but would be of slight concern to susceptible populations (see Table 1).

Disconnected Vent Conditions

Table 2 shows data on projected CO exposures that would occur under the given test conditions when the furnace was overfired by up to 128 % and the vent was disconnected in either the furnace closet or the chamber. The projected CO exposures increased as the fuel input rate increased, and the location of the vent disconnect affected the projected CO exposures. When overfired by up to 12%, the projected CO exposures did not exceed 15 ppm/8 hour, (CPSC's recommended limit for other residential combustion heating devices such as KHs and UVGSHs) regardless of where the vent disconnect was located. No adverse health effects of CO would be expected in the most susceptible individuals under these scenarios. At a fuel input rate of 118,000 Btu/hr, a cyclically operated furnace (<80 % duty cycle), used in the most extreme scenario of a small, tightly weatherized home, was projected to result in CO exposures of about 24 ppm. This is equivalent to about 4 % COHb and might be of concern to susceptible persons (e.g., CAD patients), but would not be expected to result in any perceptible effects in healthy individuals. However, if the furnace was continually fired at this 118,000 Btu/hr input rate, the projected CO exposures reached 86 ppm when the vent disconnect was located in the chamber and 258 ppm when located in the closet. The former value corresponds to about 12.5 % COHb, at which mild headaches might start to be perceived in healthy individuals. In contrast, the latter value would be equivalent to about 30% COHb; this COHb level, if sustained, would cause severe headaches, nausea, vomiting, dizziness, and cognitive impairment in healthy individuals, and lasting neurological impairment is also possible. Serious life-threatening compromise of susceptible individuals, such as CAD patients, is possible at these exposures. At 128,000 Btu/hr, projected CO exposures from continuously fired furnaces reached catastrophic levels, regardless of the vent disconnect location. About 371 ppm/8 hours was projected for the chamber disconnect location compared to 493 ppm/ 8 hours for the chamber disconnect location. The corresponding COHb levels of about 39 % and 45 % could both result in unconsciousness, coma, and possibly death, especially in compromised individuals. Lasting neurological impairment is likely in all victims who survive sustained exposures at these CO levels. HS staff notes that home size and ventilation rates significantly impact projected CO exposures and their related health consequences. For the same CO emission rates modeled in larger, well ventilated homes, the projected indoor CO exposures are significantly lower at 93 ppm/8 hours and 123 ppm/8 hours, respectively. However these exposures are equivalent to about 13% and 17% COHb, and are still of low to moderate concern to healthy individuals, and of greater concern to susceptible populations such as CAD patients. As would be expected, the projected CO hazard associated with disconnected vents decreased as the burner firing times (cycle duty) decreases and is generally negligible when the furnace burners operate for less than 50% of the time (see Table 2).

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 vents are partially or completely blocked and the furnace operated at up to 28 % overfire, the projected CO hazard is negligible.

In contrast, the test data indicates that this furnace can present a serious CO hazard, to both healthy and susceptible individuals, when overfired by at least 18% and operated in a continuous firing mode with a disconnected vent. The CO hazard is potentially catastrophic if the furnace is operated with disconnected vents in a continuously firing mode at 28% above the manufacturer's specified fuel input rate.

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 50 to 80% of the furnace cycle time, there is a low to moderate health concern for vent disconnects within the closet space or chamber. There is little health concern in healthy individuals at burner firing times less than 50% of the furnace cycle. The risk of any health concerns associated with CO exposure from furnaces is greatest in small, tightly weatherized homes. In larger homes and/or well ventilated homes, when the furnace burners operate in a cyclical mode (<80% duty cycle), the projected indoor CO exposures rarely achieve a level that would be of concern to healthy individuals, though susceptible populations may have some slight health concerns.

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 #4 – High Efficiency Induced Draft (October, 2000).

Porter WK Jr, CPSC LS memo. Indoor Air Modeling for Furnaces with Blocked or Disconnected Vents (Furnace # 4) (October, 2000).

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

Table 1. Predicted 8h average indoor CO concentrations for various baseline and blocked vent scenarios, and 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	Vent % block	Vent Blockage Location	cycle % burner on	CO source cc/hr	Maximum 8h average CO ppm								
BASELINE													
100,000	0	N/A	100	383	5	4	3	3	2	2	3	2	1
100,000	0	N/A	80	0	0	0	0	0	0	0	0	0	0
112,000	0	N/A	100	15	0	0	0	0	0	0	0	0	0
112,000	0	N/A	80	56	1	1	1	1	0	0	1	0	0
118,000	0	N/A	100	0	0	0	0	0	0	0	0	0	0
118,000	0	N/A	80	14	0	0	0	0	0	0	0	0	0
128,000	0	N/A	100	0	0	0	0	0	0	0	0	0	0
128,000	0	N/A	80	0	0	0	0	0	0	0	0	0	0
BLOCKED VENT													
100,000	86	Diaphragm	100	58	1	1	1	1	0	0	1	0	0
100,000	88	Diaphragm	100	shut off	0	0	0	0	0	0	0	0	0
100,000	86	Diaphragm	80	56	1	1	1	1	0	0	1	0	0
112,000	88	Diaphragm	100	shut off	0	0	0	0	0	0	0	0	0
112,000	88	Diaphragm	100	123	1	1	1	1	0	0	1	0	0
112,000	100	Inducer exhaust	100	shut off	0	0	0	0	0	0	0	0	0
112,000	86	Diaphragm	80	0	0	0	0	0	0	0	0	0	0
118,000	86	Diaphragm	100	722	9	7	5	6	4	3	5	3	2
128,000	86	Diaphragm	100	903	11	8	6	7	5	4	6	4	3
128,000	86	Diaphragm	100	1397	17	13	9	11	8	6	9	6	4
128,000	86	Diaphragm	100	1489	18	13	9	12	9	6	9	7	5

Table 2. Predicted 8h 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	Site of Vent	cycle	CO source	Maximum 8h average CO ppm								
Btu/hr	Disconnect	% burner on	cc/hr									
100,000	chamber	100	599	7	5	4	5	3	2	4	3	2
100,000	chamber	80	1,241	12	9	6	8	6	4	6	4	3
100,000	chamber	50	1,241	7	5	4	5	3	2	4	3	2
100,000	chamber	33	1,241	5	4	3	3	2	2	3	2	1
100,000	closet	100	1,085	13	10	7	9	6	4	7	5	3
100,000	closet	80	1,550	15	11	8	10	7	5	8	6	4
100,000	closet	50	1,550	9	7	5	6	4	3	5	3	2
100,000	closet	33	1,550	6	4	3	4	3	2	3	2	2
112,000	chamber	100	892	11	8	6	7	5	4	6	4	3
112,000	chamber	80	1,229	12	9	6	8	6	4	6	4	3
112,000	chamber	50	1,229	7	5	4	5	3	2	4	3	2
112,000	chamber	33	1,229	5	4	3	3	2	2	3	2	1
112,000	closet	100	1,137	14	10	7	9	7	5	7	5	4
112000*	closet	80										
118,000	chamber	100	7,191	86	64	43	57	42	28	43	32	22
118,000	chamber	80	2,556	24	18	12	16	12	8	12	9	6
118,000	chamber	50	2,556	15	11	8	10	7	5	8	6	4
118,000	chamber	33	2,556	10	7	5	7	5	3	5	4	3
118,000	closet	100	21,736	258	191	129	170	126	85	129	95	65
118,000	closet	80	2,481	24	18	12	16	12	8	12	9	6
118,000	closet	50	2,481	15	11	8	10	7	5	8	6	4
118,000	closet	33	2,481	10	7	5	7	5	3	5	4	3
128,000	chamber	100	31,212	371	275	186	245	181	122	186	137	93
128,000	chamber	80	8,818	84	62	42	55	41	28	42	31	21
128,000	chamber	50	8,818	52	38	26	34	25	17	26	19	13
128,000	chamber	33	8,818	35	26	18	23	17	12	18	13	9
128,000	closet	100	41,423	493	365	247	325	241	163	247	182	123
128,000	closet	80	13,487	128	95	64	84	63	42	64	47	32
128,000	closet	50	13,487	80	59	40	53	39	26	40	30	20
128,000	closet	33	13,487	53	39	27	35	26	17	27	20	13

* The vent was disconnected in both the chamber and closet, therefore no modeling was performed