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Memorandum

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SUBJECT: Carbon monoxide (CO) emissions from a mid-efficiency, induced-draft furnace (Furnace #2): 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.

For mid-efficiency induced draft furnaces, the current ANSI standard for Gas Fired Central Furnaces, ANSI Z21.47, provides some degree of coverage for partial or total vent blockage scenarios in that it requires that 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 (Section 2.22, 1998). However, there are no specific requirements for a mechanism to shut off the furnace if the vent outlet is either partially or completely blocked. Also, the standard does not address the issue of disconnected vent pipes. The CPSC's Directorate for Laboratory Sciences (LS) recently issued a report concerning CO emissions from a natural gas-fueled, mid-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, mid-efficiency, induced draft furnace with a specified energy input rate of 100,000 Btu/hr, was tested by CPSC LS staff in a controlled environmental chamber. This furnace has only an exhaust vent pipe[1]. It is equipped

[1] this furnace does not have a "direct vent" to supply fresh combustion air from the outside.

with a pressure switch that monitors the static pressure at the inlet of the inducer motor and which will shut off the furnace if its preset pressure limit is exceeded. Increased pressure at this pressure switch can occur as a result of vent blockage (or from a blockage between the switch and the vent, within the furnace itself) (see pages 2 and 10, 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 (85-100% blockage) and the vent blockage location, and also by a totally disconnected vent and the vent disconnect location. Other important variables in the test matrix included the fuel input rate (100,000-118,000 Btu/hr, i.e., up to 18% 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 et al., 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. No modeling data are presented for baseline scenarios because relevant LS tests demonstrated little if any elevation in CO emission rates or steady concentrations. LS staff's projected residential CO levels for blocked vent and disconnected vent scenarios are presented in tabular form in the lab modeling 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[2]. 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. LS's projected 8h average CO exposures for blocked vent and vent disconnect scenarios 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.

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[2] 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.

Baseline Conditions

As mentioned above, the empiral test data did not demonstrate any elevated CO emission rates of concern during intact, unoccluded, baseline vent test scenarios, even when the furnace was fired continuously at 118,000 Btu/hr (18% overfire). Therefore, no adverse health effects of CO would be expected under these scenarios.

Blocked Vent Conditions

For blocked vent test scenarios, the modeling data indicates that at the manufacturer's specified fuel input rate of 100,000 Btu/hr with the burner firing continuously, minimal CO exposure would likely occur in the event of a vent blockage at either the vent outlet (100% block) or within the vent pipe itself (90-95% block). Therefore, no adverse health effects of CO would be expected for these scenarios. However, as the fuel input rate increased, the degree of blockage and the location of the vent blockage became important factors in the likelihood of exposure to hazardous CO levels.

Blockage by Iris Diaphragm:

At 100% vent blockage within the vent pipe (iris diaphragm), when the furnace burner operated continuously, the pressure switch immediately shut off the furnace at fuel input rates of 112,000 and 118,000 Btu/hr. This suggests that hazardous CO exposures would be unlikely under these operating scenarios. In contrast, the pressure switch did not activate at lesser degrees of blockage (80-95%) at this location. Consequently, the furnace continued to operate when the burners were fired continuously or cyclically. For these incomplete blockage scenarios, the projected 8 hour CO exposures at firing rates up to 106,000 Btu/hr were minimal (2 to 12 ppm in the worst case scenario of a small, weatherized home) with no adverse health consequences expected, even in compromised individuals with CAD. However, at 112,000 Btu/hr, the projected 8h CO exposures from a continuously operated furnace reached 76 ppm, equivalent to about 11% COHb. This CO exposure might begin to cause mild adverse effects in healthy individuals (fatigue and headaches) and could likely be of consequence to compromised individuals. At reduced burner firing times (33 to 80% duty cycle), the projected 8 hour CO exposures were reduced, rangingfrom 22 to 30 ppm CO for worst case scenarios (equivalent about 3 to 5% COHb), which could be of low to moderate concern for compromised individuals. A continuously fired furnace at a fuel input rate of 118,000 Btu/hr was projected to result in a peak 8 hour CO exposure of about 106 ppm at 90% vent occlusion. This is equivalent to about 15% COHb and would likely cause headaches and fatigue in healthy individuals, and could have serious consequences in susceptible populations. In furnaces operating in cycling mode (33, 50 and 80 % duty cycle), the equivalent projected CO exposures were lower (9, 14, and 22 ppm, respectively) and would be of little health concern to any individual.

As the degree of vent occlusion increased to 95%, the CO emissions increased dramatically. For continuous burner firing, the projected 8h CO exposures ranged from 187 ppm (~24% COHb) in a large leaky home (200 m^2 [480 m^3] with 0.7 ACH), to 748 ppm (~55% COHb) for the worst case scenario of a small weatherized home (100 m^2 [240 m^3] with 0.35 ACH). These are considered serious CO exposures with potential for lasting neurological impairment at the lower level and death at the higher level. At reduced burner firing times (33-80% duty cycle), the projected CO exposures are lower, but would still be of concern to healthy individuals under worst case scenarios (74-180 ppm, equivalent to 11-23% COHb).

Vent Outlet Blockage:

All vent outlet blockage tests were conducted at 100% blockage. In contrast to the iris diaphragm test results, the pressure switch failed to shut off the furnace when the vent furnace was overfired by 12 or 18%, even though the air free CO in flue gases exceeded 1,000 ppm. The corresponding 8 hour projected CO exposures for continuous burner operation were 509 ppm (~46% COHb) and 1909 ppm (~>75% COHb), respectively, both of which would likely be fatal for prolonged exposures. Even at reduced burner duty cycles, the projected 8 hour CO exposures at 118,000 Btu/hr ranged from 363 to 880 ppm (~38 to 60% COHb) which would likely result in lasting neurological impairment or fatal outcome.

Disconnected Vent Conditions

Table 2 shows data on projected 8h CO exposures that would occur when the furnace was operated with a disconnected vent in the furnace closet, at fuel input rates ranging from 100,000 to 118,000 Btu/rh. At 112,000 Btu/hr with continuous firing of the burner, the peak 8h exposure of 28 ppm (~4.5% COHb) would be of slight concern to compromised individuals such as CAD patients, but would be unlikely to cause perceptible effects in healthy individuals. At 118,000 Btu/hr with continuous firing, the highest projected 8h CO exposure of 156 ppm could result in about 21% COHb. Although this COHb level is unlikely to result in lethal effects in healthy individuals, it could cause mild to severe headaches and nausea, and lasting neurological impairment is considered possible if the exposure is sustained for long durations. Serious life-threatening compromise of susceptible individuals, such as CAD patients, is a possibility at this CO exposure level. However, HS staff notes that home size and ventilation rates significantly impact projected health effects; for the same CO emission rate modeled in larger, well ventilated homes, the projected indoor CO level drops to about 39 ppm, equivalent to about 6% COHb. This level would be unlikely to cause perceptible effects in healthy individuals, but would still be of mild concern to susceptible populations such as CAD patients. As is expected, the projected CO hazard associated with the vent disconnect in the closet decreases as the furnace firing time decreases to between 33 to 80% duty cycle.

The effect of the vent disconnect location was investigated only for the 18% overfire condition. Table 2 shows that relative CO hazard was reduced when the vent disconnect was located in the chamber, rather than in the furnace closet. Under these test circumstances, only the continuously fired furnace reached a projected 8h CO exposure level that might be expected to have mild impact in healthy individuals. This projected exposure level of 102 ppm could result in about 15% COHb, which could cause mild headaches and possibly nausea in healthy individuals, and would be of moderate to serious concern for compromised individuals.

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 at the manufacturer's specified fuel input rate, even when the furnace vents are fully blocked or disconnected. However, if overfired, the furnace can potentially cause catastrophic CO exposures, depending on the degree of vent blockage and the location of the blockage. The pressure switch failsafe activated appropriately to immediately shut off the furnace when overfired by 12 or 18% at a 100% vent blockage within the vent pipe (achieved with an iris diaphragm). However, it did not activate when the 100% blockage was located further away at the vent outlet, or at lesser blockages (85 to 95%) located within the vent pipe (via vent diaphragm). Consequently, if the furnace was overfired by at least 12%, catastrophic CO exposures could ensue under such blockage scenarios. The disconnected vent scenarios tested did not appear as dangerous as the blocked vent scenarios. However, the disconnected vent data indicate that if the furnace is overfired by 18% (118,000 Btu/hr), unhealthy though not life-threatening CO exposure of healthy individuals can occur, while compromised individuals could be more seriously impacted.

The likelihood and severity of adverse health effects of CO associated with vent blockages and disconnects decrease progressively as the furnace firing time decreases. 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, the projected indoor CO levels is greatly reduced. The staff's findings suggest that routine maintenance, if undertaken, can prevent hazardous CO exposures caused by overfired furnaces with compromised vent systems. However, targeted passive intervention strategies by means of performance standards requirements could be the most effective way to negate these particular CO hazard scenarios.

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 #2 – Mid Efficiency Induced Draft (September, 2000).

Porter WK Jr, CPSC LS memo. Indoor Air Modeling for Furnaces with Blocked or Disconnected Vents (Furnace # 2) (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 blocked vent scenarios, blockage locations, 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	Vent	Vent Blockage	cycle	CO source				Maximum 8h average CO ppm					
Btu/hr	% block	Location	% burner on	cc/hr									
100,000	100	Vent outlet	100	774	9	7	5	6	4	3	5	3	2
100,000	95	Diaphragm	100	185	2	1	1	1	1	1	1	1	1
100,000	90	Diaphragm	100	0	0	0	0	0	0	0	0	0	0
106,000	100	Vent outlet	100	6835	81	60	41	53	40	27	41	30	20
106,000	95	Diaphragm	100	990	12	9	6	8	6	4	6	4	3
106,000	90	Diaphragm	100	186	2	1	1	1	1	1	1	1	1
112,000	100	Diaphragm	100	shut off	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
112,000	95	Diaphragm	100	6386	76	56	38	50	37	25	38	28	19
112,000	95	Diaphragm	80	3133	30	22	15	20	15	10	15	11	8
112,000	95	Diaphragm	50	3133	19	14	10	13	9	6	10	7	5
112,000	95	Diaphragm	33	3133	12	9	6	8	6	4	6	4	3
112,000	90	Diaphragm	100	1849	22	16	11	15	11	7	11	8	6
112,000	100	Vent outlet	100	42773	509	377	255	336	249	168	255	188	127
112,000	100	Vent outlet	80	17473	166	123	83	110	81	55	83	61	42
112,000	100	Vent outlet	50	17473	104	77	52	69	51	34	52	38	26
112,000	100	Vent outlet	33	17473	69	51	35	46	34	23	35	26	17
118,000	100	Diaphragm	100	shut off	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A	N/A
118,000	95	Diaphragm	100	62919	748	554	374	494	365	247	374	277	187
118,000	95	Diaphragm	80	18972	180	133	90	119	88	59	90	67	45
118,000	95	Diaphragm	50	18972	113	84	57	75	55	37	57	42	28
118,000	95	Diaphragm	33	18972	74	55	37	49	36	24	37	27	19
118,000	90	Diaphragm	100	8899	106	78	53	70	52	35	53	39	27
118,000	90	Diaphragm	80	2344	22	16	11	15	11	7	11	8	6
118,000	90	Diaphragm	50	2344	14	10	7	9	7	5	7	5	4
118,000	90	Diaphragm	33	2344	9	7	5	6	4	3	5	3	2
118,000	85	Diaphragm	100	2007	24	18	12	16	12	8	12	9	6
118,000	100	Vent outlet	100	160520	1909	1413	955	1260	932	630	955	706	477
118,000	100	Vent outlet	80	92648	880	651	440	581	430	290	440	326	220
118,000	100	Vent outlet	50	92648	549	406	275	362	268	181	275	203	137
118,000	100	Vent outlet	33	92648	363	269	182	240	177	120	182	134	91

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 m² (240 m³)			150 m² (360 m³)			200 m² (480 m³)		
			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	closet	100	1,212	14	10	7	9	7	5	7	5	4
100,000	closet	80	694	7	5	4	5	3	2	4	3	2
100,000	closet	50	694	4	3	2	3	2	1	2	1	1
100,000	closet	33	694	3	2	2	2	1	1	2	1	1
112,000	closet	100	2,362	28	21	14	18	14	9	14	10	7
112,000	closet	80	2,159	21	16	11	14	10	7	11	8	5
112,000	closet	50	2,159	13	10	7	9	6	4	7	5	3
112,000	closet	33	2,159	8	6	4	5	4	3	4	3	2
118,000	closet	100	13,139	156	115	78	103	76	51	78	58	39
118,000	closet	80	7,435	71	53	36	47	35	23	36	26	18
118,000	closet	50	7,746	44	33	22	29	21	15	22	16	11
118,000	closet	33	7,746	29	21	15	19	14	10	15	11	7
118,000	chamber	100	8,562	102	75	51	67	50	34	51	38	26
118,000	chamber	80	2,822	27	20	14	18	13	9	14	10	7
118,000	chamber	50	2,822	17	13	9	11	8	6	9	6	4
118,000	chamber	33	2,822	11	8	6	7	5	4	6	4	3