FURNACE CO EMISSIONS UNDER NORMAL AND COMPROMISED VENT CONDITIONS

FURNACE #2 - MID-EFFICIENCY INDUCED DRAFT

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EXECUTIVE SUMMARY

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 report describes only the test results of a mid-efficiency induced draft furnace (Furnace #2) and does not address any associated health affects.

Tests were conducted in an environmentally controlled chamber with the furnace installed inside a closet located within the chamber. The chamber provided a well-mixed environment in which to measure the CO concentration and also allowed for the air exchange rate to be controlled. For each test, the CO concentration and air exchange rate in the chamber were measured. The CO emission rate from the furnace was then calculated using a simple mass balance model.

Three variables were investigated to determine how each affected the CO emissions from the furnace: the condition of the vent pipe, the input rate of the furnace, and the operating mode of the furnace. Tests were conducted with the vent pipe intact, partially or totally blocked, or totally disconnected. The input rate of the furnace was adjusted to its manufacturer's specified rate or to overfire conditions. The furnace was also operated continuously or cycled on and off.

The following is a summary of the test results:

- With a normal vent pipe (no blockage or disconnect), the average steady-state concentration of CO in the chamber was negligible (< 2 ppm).

- The furnace, as received, overfired by approximately 6 percent (106,000 Btu/hr versus 100,000 Btu/hr).

- During blocked vent tests,

  ➤ The average steady-state CO concentration in the chamber was a function of the degree of blockage, the furnace input rate, and the furnace cycle time.

  ➤ At the manufacturer's specified input rate, the concentration of CO in the chamber remained below 5 ppm for blockages up to 100 percent.

  ➤ Under severe operating conditions (18 percent overfire and continuous operation), the concentration of CO in the chamber reached a maximum of 880 ppm.

  ➤ When the furnace was overfired and the vent was partially blocked, the concentration of CO in the flue gas often exceeded the allowable ANSI Z21.47 limit of 400 ppm (air-free).

  ➤ Although ANSI Z21.47 does not have a shut off requirement for induced draft furnaces when the vent becomes blocked, this furnace was equipped with a pressure switch that shut off the furnace under certain blocked vent conditions. However, the location of the blockage affected whether or not the furnace would shut off.

- During disconnected vent tests,

  ➤ The average steady-state CO concentration in the chamber was a function of the disconnect location, the furnace input rate, and the furnace cycle time.

  ➤ At the manufacturer's specified input rate, the concentration of CO in the chamber remained below 6 ppm.

➤ Under severe operating conditions (18 percent overfire and continuous operation), the concentration of CO in the chamber reached 64 ppm.

➤ Higher concentrations of CO were generally obtained when the vent pipe was disconnected inside the furnace closet.

- For either blocked or disconnected vent tests, the concentration of CO in the chamber was generally 2 to 3 times higher when the furnace operated continuously compared to when the furnace cycled at a rate of 8 minutes on and 2 minutes off.

- When the supply voltage to the furnace was reduced to 85 percent of its normal value, the concentration of CO in the chamber generally increased relative to tests performed with the furnace operating at its normal supply voltage.

- As the gas input rate was varied from the manufacturer's specified rate to an overfire rate of 18 percent, the burner flames remained blue in color and did not impinge on the side of the heat exchanger. This may be of concern since the manufacturer's installation instructions state that for proper operation the flame should be stable and blue and should not touch the sides of the heat exchanger.

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 consists of testing several different furnaces under controlled conditions and measuring the amount of CO that accumulates in a room when the vent pipe is partially blocked, totally blocked, or disconnected. The test results will be used to model indoor air concentrations and assess health effects. These modeling results will then be used to support current and potential recommendations to the ANSI/CGA Z21.47 Gas Fired Central Furnace subcommittee. For mid-efficiency induced draft furnaces, section 2.22 of the ANSI Z21.47 standard (1998) requires that the CO present in an air-free sample of flue gas cannot exceed 400 ppm (0.04 percent) when the flue outlet is partially or totally blocked. The ANSI standard does not require the furnace to shut off under any blocked vent conditions and does not address the issue of disconnected vent pipes.

This report describes only the test results for a mid-efficiency induced draft furnace (Furnace #2) and does not address any associated health affects. Tests were conducted in an environmentally controlled chamber with the furnace installed inside a closet located within the chamber. The chamber provided a well-mixed environment in which to measure the CO concentration and also allowed for the air exchange rate to be controlled. The furnace was operated at conditions specified by the ANSI Z21.47 standard (1998) and those that could occur in actual use. For all tests, the CO concentration in the chamber and closet were measured as well as the air exchange rate in the chamber. The CO emission rate from the furnace was then calculated using the equilibrium CO concentration, the air exchange rate, and a simple mass balance model.

2. TEST EQUIPMENT AND SETUP

a. Furnace

Tests were conducted using an induced draft furnace (Furnace #2). Furnace #2 is a non-condensing, mid-efficiency gas furnace with an Annualized Fuel Utilization Efficiency of 80%. This furnace was shipped from the manufacturer preset for use with natural gas and with an energy input rate of 100,000 Btu/hr. It is AGA certified (ANSI Z21.47-CAN/CGA-2.3m 1993) as a Category I unit and for operation with a one-pipe vent (exhaust vent pipe) installation. The unit is configured for upflow operation (i.e., the circulation air blower is located at the bottom of the unit, blowing supply air upwards, across the heat exchanger). Appendix A provides additional details of the furnace setup and specifications of the furnace.

The unit was purchased from a local heating, ventilation, and air conditioning (HVAC) dealer and installed by CPSC staff. On March 24, 1999, CPSC staff met with furnace manufacturing representatives (including a manufacturing representative for Furnace #2) and a representative from the Gas Appliance Manufacturers Association (GAMA) to obtain their input on the test protocol and setup. On December 20, 1999, a representative of Furnace #2's manufacturer met with CPSC staff to witness the test setup and installation of the furnace and verified that the furnace was installed and operating properly.

Based on the design of the furnace, it is must comply with the draft test provisions in the ANSI Z21.47 standard (1998) for furnaces not equipped with draft hoods (Section 2.22). Section 2.22

requires that the CO present in an air-free flue gas sample cannot exceed 400 ppm (0.04 percent) when the flue outlet is either partially or completely blocked. There are no requirements in the ANSI standard for the furnace to shut off during any blocked vent conditions. Nevertheless, this unit is equipped with a pressure switch that monitors the static pressure at the inlet of the inducer fan and shuts off the furnace during certain blocked vent conditions. The furnace will remain off until the blockage is removed.

b.   Test Chamber and Furnace Closet

In order to accurately model room concentrations of CO, it was necessary to measure CO emissions from the furnace in a well-mixed room while controlling the number of air changes in that room. A modified environmental test chamber was therefore used for the tests. The internal volume of the chamber was 837 cubic feet (23.7 cubic meters). The chamber was designed to provide an environment in which the air was well mixed and the temperature, pressure, and air exchange rate could be controlled. In order to prevent back drafting, the differential pressure between the chamber and the laboratory was kept near zero using a pressure control system. Appendix B describes the chamber in greater detail.

A furnace closet was erected within the chamber. The internal volume of the closet was approximately 196 cubic feet (5.5 cubic meters). The closet complied with the National Fuel Gas Code (1996) and the manufacturer's requirements for a "Confined Space" furnace installation. A well-mixed environment within the closet could not be assumed since no fans were used to promote mixing. Fans were not used in the closet in order to prevent interference with the operation of the furnace. The furnace was positioned inside the closet so that the manufacturer's specification for minimum distances to combustible surfaces was met. Appendix B describes the furnace closet in further detail.

c.   Vent Blockage Device and Vent Disconnect

An optical iris was used to create various degrees of vent blockage. Figure 2.1 illustrates the iris (black in color) located in the vent system. Different blockages were obtained by adjusting the diameter of the iris. When the iris was totally closed, blockage was 99.6 percent since a small hole was still present. For testing purposes, it was assumed that a 99.6 percent blocked vent was equivalent to a totally blocked vent. The iris was located at a vertical height of 1.25 feet (0.38 meters) and a horizontal distance of 3.42 feet (1.04 meters) from the furnace. Figure C.1 in Appendix C illustrates the general location of the iris relative to the furnace.

To investigate the affect of the blockage location on the CO emission rate from the furnace, several tests were conducted with the outlet of the vent pipe totally blocked. Blockage was created using a vent tee cap. The vent outlet was located approximately at a vertical height of 5.60 feet (1.70 meters) and at a horizontal distance of 4.0 feet (1.21 meters) from the furnace.
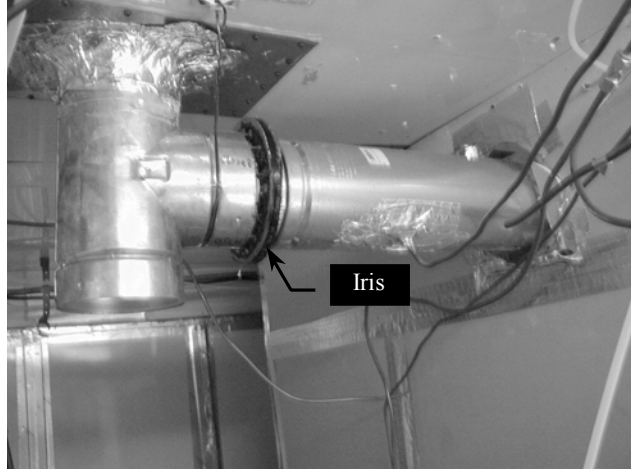
Figure 2.1. Iris Used to Create Vent Blockages

To simulate a disconnected vent pipe, the vent pipe was totally separated from a section of the vent system. The vent pipe was disconnected either inside or outside of the furnace closet. For disconnected vent tests where the vent disconnect was inside the closet, the vent pipe was separated from the furnace at the flue collar. For disconnected vent tests where the vent was disconnected outside of the closet, that is, in the chamber, the vent pipe was separated at the vent tee (Figure 2.2). The vent tee was located at a vertical height of 1.25 feet (0.38 meters) and a horizontal distance of 4.0 feet (1.22 meters) from the furnace. Figure C.1 in Appendix C illustrates the location of the flue collar and the vent tee relative to the furnace.
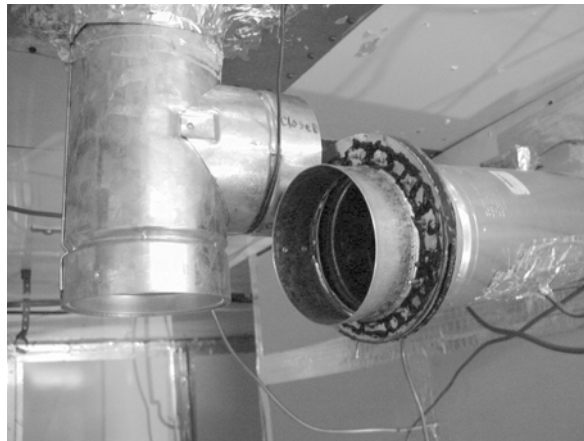
**Figure 2.2. Disconnected Vent Pipe Outside the Furnace
Closet Near the Vent Tee.**

d. Measuring Equipment

i) Furnace Operating Parameters

The operating parameters of the furnace were measured at different locations using a variety of equipment. Appendix C provides details of the equipment used and the general locations of the measurements. The natural gas flow rate to the furnace was determined using a digital mass flow meter. The gas manifold pressure was measured with a magnehelic pressure gauge. The static pressure in the vent pipe was determined using a piezo ring connected to a magnehelic pressure gauge. The piezo ring was constructed in accordance with Section 2.7 of the ANSI Z21.47 standard (1998). The static pressure between the return and supply ducts was measured with a magnehelic pressure gauge. The temperature rise across the heat exchanger was measured using two thermocouples, one in the return duct and one in the supply duct. The flue gas temperature was measured with a single thermocouple located in the center of the vent pipe. The air temperature near the combustion chamber was measured at two locations: (1) at the top opening of the combustion chamber, and (2) at the side opening of the combustion chamber.

ii) Gas Sampling Systems

Four sampling systems were used to measure the concentration of different chemical species at various locations. Appendix D provides details of the equipment used and a schematic illustrating the sampling systems. The first system was used to obtain CO, CO_2, and O_2 samples from the chamber. The concentrations of CO and CO_2 were measured using non-dispersive infrared (NDIR) gas analyzers and O_2 was measured using a paramagnetic analyzer. Samples were obtained from five locations inside the chamber. The sampling lines from these five locations fed into a common mixing manifold. The mixing manifold was then connected to the gas analyzers using a single sampling line.

A second sampling system was used to obtain samples from the closet or flue gas. A three-way valve was used to switch between the closet and flue gas sampling lines. Carbon monoxide, carbon dioxide, and hydrocarbons (HC) were measured using NDIR gas analyzers and oxygen was measured using a paramagnetic analyzer. Flue gas samples were taken from a single location downstream of the flue collar. Closet air samples were taken from five locations inside the closet. The sampling lines from these five locations fed into a common mixing manifold. The mixing manifold was then connected to the three-way valve using a single sampling line. To prevent water from condensing inside the gas analyzers during the sampling of the flue gas, the water was condensed out of the sample prior to entering the analyzers. A simple heat exchange system using recirculated chilled water was used to condense the water out of the gas sample.

A third sampling system was used to obtain the concentration of CO in the return and supply ducts. A three-way valve was used to switch between the return and supply duct sample lines. The concentration of CO was measured with a NDIR gas analyzer.

A fourth sampling system was used to obtain the background concentration of CO in the laboratory. A NDIR gas analyzer was used to measure the concentration of CO. The sampling line was positioned near the inlet pipe that brought fresh air into the chamber.

iii) <u>Air Exchange Rate</u>

To determine the air exchange rate in the chamber and closet, the tracer gas sulfur hexafluoride (SF_6) was injected into the chamber. The flow rate of SF_6 was measured using a rotameter and the concentrations of SF_6 in the chamber and closet were measured with an electron capture gas chromatograph analyzer. To ensure that the tracer gas was evenly distributed, the gas was injected above each set of fans used with the four fin-and-tube heat exchangers. Samples were obtained using the existing sampling lines for the chamber and closet (Appendix D). To verify the number of air changes per hour (ACH) obtained with the SF_6 tracer gas, CO was also injected into the chamber during several tests. A mass flow controller was used for the CO injection and the NDIR analyzers for the chamber and closet were used to measure the CO concentrations.

iv) <u>Room Temperature, Pressure, and Relative Humidity</u>

The temperature in the chamber was measured with four thermocouples. The thermocouples were located near each corner in the chamber. The temperature in the closet was measured with a single thermocouple located approximately midway between the floor and the ceiling. A thermocouple was also used to measure the ambient air temperature entering the chamber. The thermocouple was positioned near the inlet pipe for the fresh air supply to the chamber.

A photohelic pressure gauge was used to measure the differential pressure between the chamber and the laboratory. The pressure gauge was part of the pressure control system used to prevent the chamber from becoming over or under pressurized relative to the laboratory building in which the chamber was located.

The local pressure and temperature in the laboratory was obtained using a barometer with a built in thermometer. The relative humidity of the laboratory air was measured with a digital hygrometer.

v) <u>Natural Gas</u>

The furnace was fired with natural gas obtained from a city supply line. The daily average higher heating value of the natural gas was obtained from the local gas supplier (Washington Gas). In addition, the gas company supplied the daily average chemical composition of the natural gas.

vi) <u>Data Acquisition System</u>

A data acquisition system was used to record the majority of the data. The system consisted of a personal computer running LABTECH® NOTEBOOK data acquisition software that recorded the data every 20 seconds. The data acquisition program recorded the raw voltage output from the various measuring devices (gas analyzers, thermocouples, pressure gauges, and flow meter) into a data file. The program converts these voltage readings directly into the appropriate units for concentration (percent or parts per million), temperature (degrees Fahrenheit), pressure (inches of water column), and flow rate (cubic feet per minute). These converted values were recorded in the data file. The only items not recorded electronically were the SF_6 flow rate from the rotameter, the vent pressure, the differential pressure between the chamber and laboratory, and the barometric pressure, temperature and relative humidity of the laboratory. A second computer was used with the SF_6 analyzer to record the concentrations.

3. TEST METHODS AND PROCEDURES

a. Furnace Installation

The furnace was installed according to the manufacturer's installation instructions and the National Fuel Gas Code (1996). To confirm proper furnace operation, the temperature rise across the heat exchanger and the static pressure between the return and supply ducts were checked for compliance with the manufacturer's specifications.

b. Furnace Input Rate

The furnace input rate was set by adjusting the gas manifold pressure. This was accomplished by turning the adjustment screw of the pressure regulator clockwise to increase the pressure or counter clockwise to decrease the pressure. All input rates reported in this report are within ± 3 percent of the stated values. The input rates were calculated using an average higher heating value of 1040 Btu per cubic feet.

The input rate was initially determined before any adjustments were made to the gas manifold pressure. This input rate, termed "as received", is the rate that would occur if the furnace installer did not clock the gas flow or adjust the manifold pressure. The "as received" rate was approximately 106,000 Btu/hr, which was 6 percent over the manufacturer's specified rate of 100,000 Btu/hr. This rate is based on an average higher heating value of 1040 Btu per cubic feet. Since the installer may not clock the gas flow, a decision was made to test the furnace at its specified rate (100,000 Btu/hr) and at the "as received" rate (106,000 Btu/hr).

The original test plan included testing the furnace in accordance with the overfire provisions of ANSI Z21.47 (1998). These provisions require that the furnace input rate be adjusted to 12 percent above the manufacturer's specified rate. Since the "as received" firing rate of this furnace was 6 percent above the manufacturer's specified rate, and because staff felt it foreseeable that an installer might only adjust the manifold pressure, a decision was made to test the furnace at an input rate of 12 percent above the "as received" rate, as well as 12 percent above the manufacturer's specified rate. This resulted in firing rates of 118,000 Btu/hr and 112,000 Btu/hr, respectively. CPSC incident data demonstrates that some furnaces involved in CO exposure have, upon inspection, been found to be overfired.

c. Test Matrix

Table E.1 in Appendix E shows the Furnace Test Matrix. It should be noted that not all tests listed in Table E.1 were necessarily performed. The test plan design allowed for omission of some tests within the Baseline, Blocked Vent, and Disconnected Vent tests if certain criteria were satisfied. The criteria for omission were as follows: (1) if a shutoff device or other aspect of a furnace design caused it to shutdown during any of the incremental blockage or disconnected vent conditions; or (2) if the furnace continued to operate under partial blockage or disconnect conditions, but the resultant chamber CO concentrations were negligible; or (3) if the furnace input rate, as installed, was within ± 3 percent of the manufacturer's specified input rate. If either of the first two criteria were satisfied, then tests involving lesser degrees of vent blockage or disconnect were omitted.

Each test had three main variables: the condition of the vent pipe, the input rate to the furnace, and the operating mode of the furnace. The vent pipe was intact (baseline condition), blocked,

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or disconnected. For blockage tests, the vent was blocked from 50 to 100 percent. Tests with the vent totally blocked were similar to the blocked vent shut off test required by ANSI Z21.47 standard (Section 2.19, 1993). For disconnected vent tests, the vent was totally separated from the vent system in the closet or in the chamber. The furnace was tested at input rates of 100,000 Btu/hr, 106,000 Btu/hr, 112,000 Btu/hr, or 118,000 Btu/hr. The furnace was operated either continuously or it was cycled on for 8 minutes and off for 2 minutes. The cycling rate was based on information obtained from the AGA booklet, "Fundamentals of Gas Appliances" (1996). The booklet states that, as a rule-of-thumb, the optimal cycling rate of a furnace burner is approximately six times per hour. The booklet also states that this optimal cycling rate will be maintained if the furnace is operating 20 to 80 percent of the time. Therefore, a cycle time of 8 minutes on and 2 minutes off was used.

d. Test Procedures

At the start of each day, the gas analyzers were calibrated according to the instructions specified by the manufacturer of the analyzer. In general, the meters were zeroed with nitrogen gas and spanned using a gas of known concentration (EPA protocol). The analyzers were also checked at mid- and low-range concentrations to verify the performance of the analyzers. To begin an actual test, the data acquisition program was started. The furnace was then started by setting the cycle timer to operate continuously or to cycle on and off. The cycle timer was used to simulate a call for heat by a thermostat. The furnace was allowed to warm up for 15 minutes in order to reach equilibrium. This 15 minute warm up is similar to many test protocols in the ANSI Z21.47 standard (1998). During this warm up period the manifold pressure was adjusted as required to attain the desired input rate. At approximately 15 minutes, the flue gas sample was obtained and the gas flow rate was recorded. If the vent was to be blocked or disconnected, staff entered the chamber and closet (if necessary) and made the appropriate changes to the vent pipe. The closet and chamber doors were closed and the SF_6 tracer gas injection was started. The injection of the tracer gas continued until it had reached an equilibrium concentration in the chamber (approximately one hour). By this time, the concentrations of the other chemical species (CO, O_2, and CO_2) had also reached equilibrium. After reaching equilibrium, the injection of the tracer gas was stopped, and the tracer gas decay was monitored. The test was complete once the concentration of the SF_6 tracer gas was less than 10 percent of the SF_6 analyzer's full-scale value. The data acquisition program and cycle timer were then stopped, and the chamber and closet were allowed to air out before beginning the next test. As a back up to the electronic data, the concentration data were recorded manually at various times during the test. The times at which the three-way valves were switched to toggle between the return and supply duct samples and between the closet and flue samples were also recorded manually.

4. DATA REDUCTION

a. Equilibrium Determination

All data from the data acquisition program were imported into a Microsoft® Excel spreadsheet. The SF_6 concentration data were also imported into the same spreadsheet. The concentrations of CO and O_2 in the chamber and closet were then plotted versus time in order to determine the equilibrium period. Once the equilibrium period was established, the average values for all data were calculated during this time interval. For cycling tests, the gas flow rate and the manifold pressure were averaged only during the on time of the cycle. Once the average values were

obtained, the CO concentrations were corrected for any background CO present in the laboratory during the equilibrium period and also for any meter offset present at the start of the test. Unless otherwise noted, all reported concentrations are average steady-state values.

b. Air Exchange Rate

The number of air changes per hour (ACH) for the chamber was estimated from the SF_6 equilibrium concentration data in the chamber. The ACH was calculated based on the assumption that the chamber can be modeled as a one-zone system. In the one-zone model, the closet is treated as a non-participating volume. Thus, the actual chamber volume is the total internal volume of the chamber less the volume of the closet and any additional equipment (return duct, vent pipe, etc.) in the chamber. The net volume is 632 cubic feet (17.9 cubic meters). Appendix F provides a derivation of the following equation used to estimate the ACH in the chamber:

$$ACH = \left[\frac{S_{inj}}{C_{eq}V} \right]$$

[4.1]

where,

ACH = number of air changes per hour in the chamber, 1/hr

S_{inj} = injection rate of SF_6, cc/hr

C_{eq} = equilibrium concentration of SF_6 in chamber, 0.001 cc/m^3 or ppb

V = volume of chamber less volume of closet and any additional equipment, m^3

c. Emission Rate

The CO emission rate from the furnace was estimated using the CO equilibrium concentration data in the chamber. The emission rate was calculated based on the assumption that the chamber can be modeled as a one-zone system and that the emission source is the combined closet and furnace. The derivation of the emission rate is similar to the derivation of the ACH described in Appendix F. The CO emission rate is then calculated using the following equation:

$$E_{CO} = C_{CO_{eq}} ACH\ V$$

[4.2]

where,

E_{CO} = CO emission rate, cc/hr

C_{COeq} = equilibrium concentration of CO in the chamber, cc/m^3 or ppm

ACH = air exchange rate in the chamber, air changes per hour

V = volume of chamber less volume of closet and any additional equipment, m^3

d. CO Air-Free

The ANSI Z21.47 standard (1998) sets limits on the amount of CO that may be present in the flue gas. These CO concentrations are specified as "air free", which is a calculated value to remove excess air from the measured value. Air-free concentrations of CO in the flue gas were calculated using the following equation, which was obtained from the AGA booklet, "Fundamentals of Gas Combustion" (1996):

$$CO_{airfree} = CO\left[\frac{CO_{2,ultimate}}{CO_2}\right]$$

where,

COair free = air-free sample of CO, ppm

CO = measured CO in flue gas, ppm

$CO_{2, ultimate}$ = ultimate CO_2; the amount of CO_2 produced at stoichiometric conditions, %

CO_2, = measured CO_2 in flue gas, %

Based on the information provided by local gas supplier (Washington Gas), the average ultimate CO_2 was 11.9 percent.

5. RESULTS AND DISCUSSION

a. Baseline Tests (Normal Vent)

Tests were conducted with a normal vent pipe (no blockage or disconnect) to establish the baseline operating conditions of the furnace at different input rates and with the furnace cycling or operating continuously. For all test conditions, the average steady-state concentration of CO in the chamber was negligible (< 2 ppm) as illustrated in Table G.1 (Appendix G). The air exchange rate in the chamber varied from 10.1 to 11.2 air changes per hour.

b. Blocked Vent Tests

Four variables were considered during the blocked vent tests: (1) the location of vent blockage, (2) the degree of vent blockage, (3) the input rate of the furnace, and (4) the operational mode of furnace (continuous or cycling). For all blocked vent tests, the air exchange rate varied from 10.1 to 11.6 air changes per hour. Table G.2 (Appendix G) provides a list of the data. The following is a summary of the trends observed for each test variable.
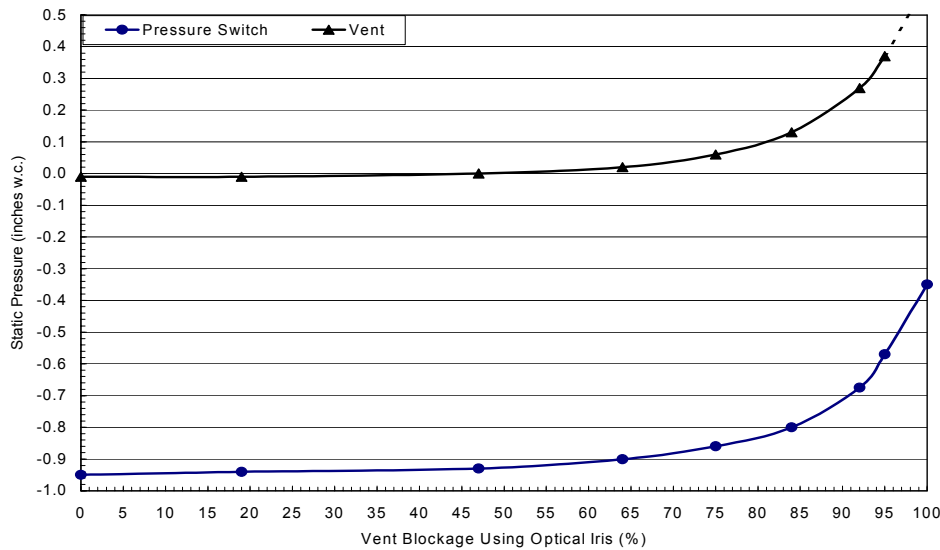
i) Location of Vent Blockage

To determine whether the blockage location affected the performance of the furnace, tests were conducted with the vent pipe completely blocked at the vent outlet in addition to the optical iris (approximately midway between the furnace and vent outlet). When the vent pipe was totally blocked at the iris, the furnace shut off immediately. However, when the vent pipe was totally blocked at the vent pipe outlet, the furnace continued to operate. At the manufacturer's specified input rate of 100,000 Btu/hr, the average steady-state CO concentration in the chamber was 4 ppm and the resulting CO emission factor was 774 cc/hr. Under severe operating conditions (18 percent overfire and continuous operation), the concentration of CO in the chamber reached a maximum of 880 ppm and the resulting CO emission was 183,290 cc/hr.

The reason why the furnace shut off when the vent pipe was completely blocked at one location and not another can be explained by considering the method used to shut off the furnace under certain blocked vent conditions. Furnace #2 is equipped with a pressure switch that monitors the static pressure at the inlet of the inducer fan and the furnace will shut off once the pressure limit of the switch is exceeded. The static pressure at the switch is

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a function of the pressure inside the vent pipe. The pressure inside the vent pipe is a function of the degree of vent blockage, the location of the blockage, and the degree of leakage from the vent pipe. The location of the blockage is important since the vent pipe is not airtight and flue gases may leak through the pipe joints, resulting in a lower vent pressure relative to an airtight vent. Therefore, blockage at one location may not produce the same vent pressure when the same blockage occurs at a different location.

Figure 5.1 illustrates how the static pressure at the switch and in the vent pipe varied when the vent pipe was blocked using the optical iris. The vent pressure was measured using a piezo ring that was located 2.17 feet (0.66 meters) in front of the iris. As illustrated in Figure 5.1, the static pressure at the switch and vent increased as the vent blockage increased. When the vent pipe was totally blocked at the optical iris, the pressures at the switch was approximately – 0.35 inches w.c. and the vent pressure exceeded 0.5 inches w.c., the maximum range of the pressure gauge. However, when the vent was totally blocked at the *vent outlet*, the pressure at the switch was approximately – 0.50 inches w.c. and the vent pressure was 0.5 inches w.c. Based on Figure 5.1, the *iris* would have to be blocked between 95 and 100 percent to generate the same vent and switch pressures as that obtained when the *vent outlet* was completely blocked. Depending on the degree of vent blockage and leakage, a pressure switch may not be effective in shutting off the furnace in response to vent blockage.

Figure 5.1. Static Pressure at Pressure Switch as a Function of Vent Blockage

ii) Degree of Blockage

Tests were conducted with the vent blocked at 85, 90, 95, and 100 percent at the optical iris. As discussed in the previous section, tests were also conducted with the vent pipe completely blocked at the vent outlet. Total blockage at the *vent outlet* was equivalent to a blockage between 95 and 100 percent using the *optical iris*. At the manufacturer's specified input rate of 100,000 Btu/hr, the degree of blockage had little affect on the magnitude of the CO concentration in the chamber. The average steady state CO concentration in the chamber reached a maximum of 6 ppm. At the "as received" rate of 106,000 Btu/hr, the CO

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concentration remained below 5 ppm until the vent outlet was completely blocked and the CO in the chamber increased to 40 ppm. Above an input rate of 106,000 Btu/hr, the degree of vent blockage had a greater affect on the magnitude of CO present in the chamber, reaching a maximum of 880 ppm when the furnace was overfired by 18 percent and the furnace operated continuously. Table G.2 in Appendix G lists the resulting CO emission rates, which ranged from 0 to 72,427 cc/hr.

Section 2.22 of the ANSI Z21.47 standard (1998) requires that the CO present in an air-free sample of flue gas cannot exceed 400 ppm (0.04 percent) when the flue outlet is either partially or totally blocked. As shown in Table G.2 (Appendix G), the furnace continued to operate when the CO in the flue gas exceeded 400 ppm. Concentrations of CO in the flue gas in excess of 400 ppm (air-free) were obtained when the furnace was overfired by as little of 6 percent. ANSI Z21.47 (1998) specifies that blockage tests are to be conducted in an atmosphere having a normal supply of oxygen (approximately 21 percent). However, as shown in Table G.2 (Appendix G), the average steady-state concentration of oxygen in the furnace closet ranged from 18.1 to 20.2 percent during the blocked vent tests. These test results represent a weakness in ANSI Z21.47 (1998) since the ANSI blockage test does not take into account the reduction in the ambient oxygen when a furnace is installed in a confined space, such as a closet, and the vent pipe is partially blocked.

iii) Input Rate

As mentioned in the "Test Methods and Procedures" section, tests were performed at input rates of 100,000 Btu/hr, 106,000 Btu/hr, 112,000 Btu/hr, and 118,000 Btu/hr. Figure 5.2 illustrates how the CO concentration in the chamber varied at different input rates for a given vent blockage and furnace operational mode. At the manufacturer's specified input rate of 100,000 Btu/hr, the maximum average steady-state concentration of CO in the chamber was less than 5 ppm, even when the vent was totally blocked. However, as illustrated in Figure 5.2, the chamber CO concentration increased as the furnace input increased above the manufacturer's specified rate. The rate of increase in CO was dependent on the degree of vent blockage, with the rate increasing as the vent blockage increased.


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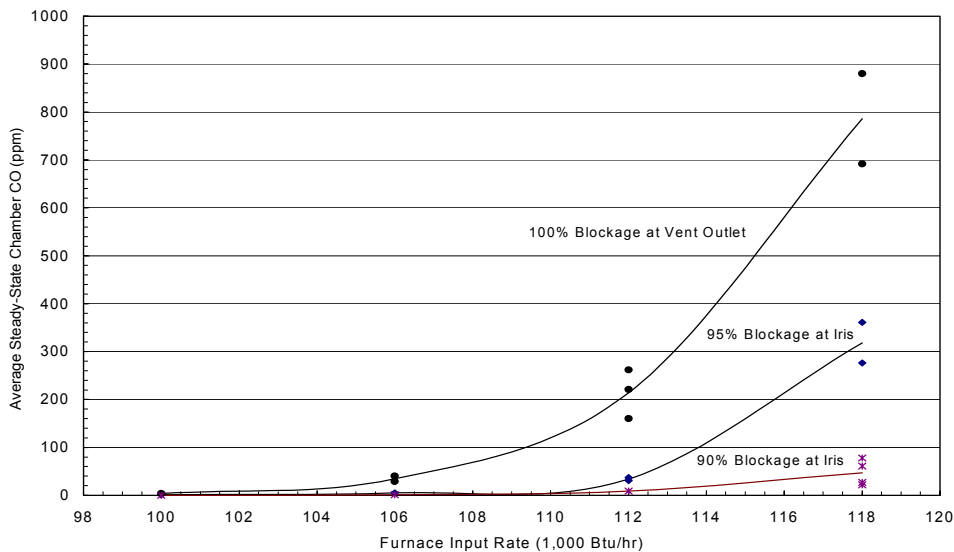
**Figure 5.2. Chamber CO Versus Input Rate At Various Vent Blockages
with the Furnace Operating Continuously**

iv) Cycling

Tests were performed with the furnace operating continuously or cycling at a rate of 8
minutes on and 2 minutes off. As Figure 5.3 illustrates, the furnace with a blocked vent
generated more CO when operated continuously compared to when it was cycled on and off.
Figure 5.3 plots the data for Furnace #2 operating at an input rate of 118,000 Btu/hr and with
the vent pipe blocked 95 percent. For all test conditions, the average steady-state
concentration of CO was approximately 2 to 3 times higher when the furnace operated
continuously than when the furnace was cycled at a rate of 8 minutes on and 2 minutes off.
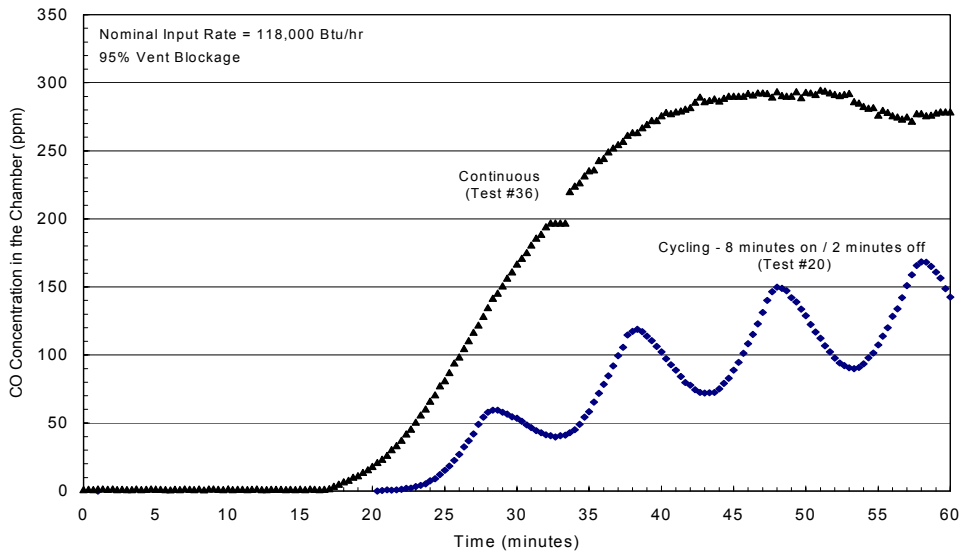
**Figure 5.3. Comparison of CO in the Chamber as Furnace #2 was Cycled
or Operated Continuously**

c. Disconnected Vent Tests

Four variables were considered during the disconnected vent tests: (1) the location at which the
vent pipe was disconnected, (2) the input rate of the furnace, (3) the operational mode of the
furnace (continuous or cycling), and (4) the degree of disconnect. The air exchange rate in the
chamber ranged from 10.5 to 13.1 air changes per hour. Table G.3 located in Appendix G
provides a complete list of the data. The following is a summary of the trends observed for each
test variable.

i) Location of Vent Disconnect

Tests were performed with the vent pipe totally disconnected inside or outside of the furnace
closet. As the data in Table G.3 illustrates, the average steady-state concentrations of CO
were generally higher when the disconnect occurred outside of the furnace closet as
compared to inside the closet

ii) Input Rate

As mentioned in the "Test Methods and Procedures" section, tests were performed at different input rates ranging from of 100,000 Btu/hr to 118,000 Btu/hr. Figure 5.4 illustrates how the average steady-state CO concentration in the chamber varied as the furnace input rate increased. Figure 5.4 plots the data for the furnace operating continuously and with the vent pipe totally disconnected inside the furnace closet. At the manufactures specified input rate of 100,000 Btu/hr, the maximum concentration of CO in the chamber was 6 ppm and the resulting CO emission rate was 1,212 cc/hr. At the maximum input rate tested (118,000 Btu/hr), the concentration of CO in the chamber was 64 ppm and the resulting CO emission rate was 12,942.
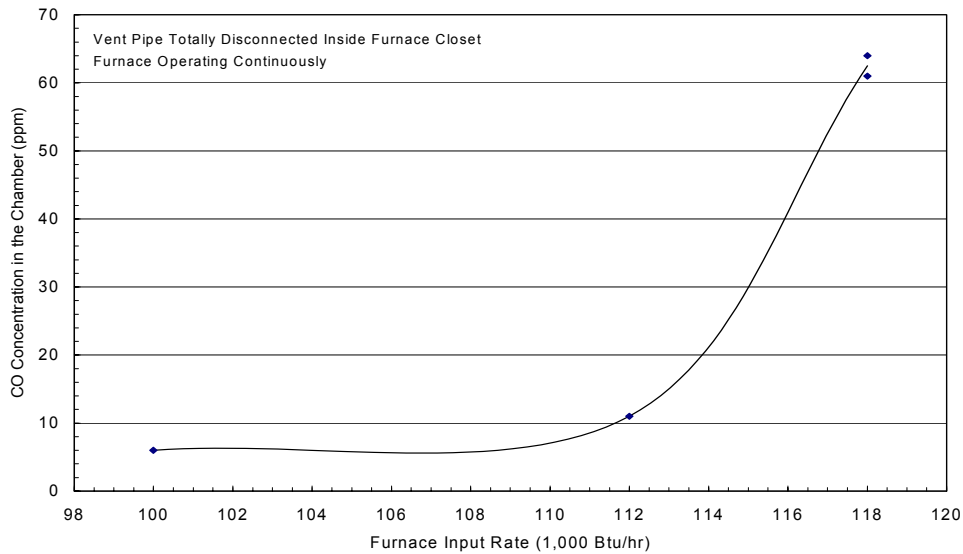
Figure 5.4. Concentration of CO in the Chamber as a Function of the Input Rate for Furnace #2

iii) Cycling

Tests were conducted with the furnace operating continuously or cycling at a rate of 8 minutes on and 2 minutes off. As Figure 5.5 illustrates, the furnace with a disconnected vent generated more CO when it operated continuously than when it was cycled on and off. Figure 5.5 plots the data for Furnace #2 operating at an input rate of 118,000 Btu/hr and with the vent pipe disconnected inside the closet. For a given input rate and vent disconnect location, the average steady-state concentration of CO was approximately 2 times greater when the furnace operated continuously than when the furnace was cycled on and off.
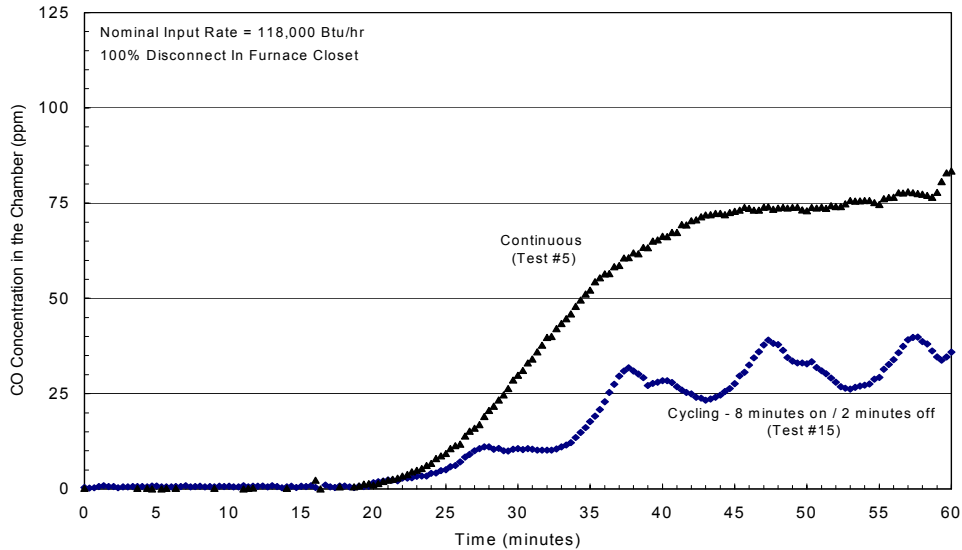
Figure 5.5. Comparison of CO in the Chamber for Furnace #2 as it is Cycled or Operated Continuously

iv) Size of Disconnect

To determine what affect the size of the gap created by the disconnected pipe had on the amount of CO present in the chamber, a test was conducted with one section of vent pipe separated approximately 1.25 inches from the other section. Although separated, the pipes were inline with each other. At 118,000 Btu/hr, the concentration of CO in the chamber was approximately 0 ppm. No additional tests were conducted since a negligible amount of CO was observed at the maximum input rate tested.

d. Observations

i) Reduced Supply Voltage

For induced draft furnaces, ANSI Z21.47 (1998) requires a 15 percent reduction in supply voltage to the furnace during certain tests. Therefore, several tests were conducted with the supply voltage reduced from its normal value of 120 volts to 102 volts, or 85 percent of its normal value. Since investigating the affects of a reduced supply voltage were not part of the original test plan, only four tests were conducted. Table G.4 in Appendix G provides a summary of the test results.

Table 5.1 compares the average steady-state CO concentrations obtained under normal and reduced supply voltages when Furnace #2 was operated continuously and with the vent disconnected inside the furnace closet. At the manufacturer's specified rate of 100,000 Btu/hr, relatively no difference existed in the CO present inside the chamber when the furnace supply voltage was reduced. However, the difference between the CO in the chamber increased as the input rate increased and the furnace operated continuously.

Table 5.1. Concentration of CO in the Chamber Under Normal and Reduced Supply Voltages with the Vent Pipe Disconnected in the Closet and the Furnace Operating Continuously

| Input Rate[1] | Average Steady-State Concentration of CO in the Chamber (ppm) | |
(Btu/hr)	Normal Supply Voltage	Reduced Supply Voltage
100,000	6	4
112,000	11	72
118,000	64	164

1. Actual input rate is within ± 3 percent of the listed values.

ii) Flame Appearance

No perceptible differences in the flame color, shape, or intensity were observed as the gas input rate varied from the manufacturer's specified rate of 100,000 Btu/hr to an overfire rate of 18 percent (118,000 Btu/hr). For all tests, the flame remained blue in color and did not impinge on the side of the heat exchanger. This may be of concern since the manufacturer's installation instructions state that the flame should be stable and blue and should not touch the sides of the heat exchanger for proper operation.

6. CONCLUSIONS

The following is a summary of the test results:

- With a normal vent pipe (no blockage or disconnect), the average steady-state concentration of CO in the chamber was negligible (< 2 ppm).

- The furnace, as received, overfired by approximately 6 percent (106,000 Btu/hr versus 100,000 Btu/hr).

- During blocked vent tests,

  ➤ The average steady-state CO concentration in the chamber was a function of the degree of blockage, the furnace input rate, and the furnace cycle time.

  ➤ At the manufacturer's specified input rate, the concentration of CO in the chamber remained below 5 ppm for blockages up to 100 percent.

  ➤ Under severe operating conditions (18 percent overfire and continuous operation), the concentration of CO in the chamber reached a maximum of 880 ppm.

  ➤ When the furnace was overfired and the vent was partially blocked, the concentration of CO in the flue gas often exceeded the allowable ANSI Z21.47 limit of 400 ppm (air-free).

  ➤ Although ANSI Z21.47 does not have a shut off requirement for induced draft furnaces when the vent becomes blocked, this furnace was equipped with a pressure switch that shut off the furnace under certain blocked vent conditions. However, the location of the blockage affected whether or not the furnace would shut off.

- During disconnected vent tests,

  ➤ The average steady-state CO concentration in the chamber was a function of the disconnect location, the furnace input rate, and the furnace cycle time.

➤ At the manufacturer's specified input rate, the concentration of CO in the chamber remained below 6 ppm.

➤ Under severe operating conditions (18 percent overfire and continuous operation), the concentration of CO in the chamber reached 64 ppm.

➤ Higher concentrations of CO were generally obtained when the vent pipe was disconnected inside the furnace closet.

- For either blocked or disconnected vent tests, the concentration of CO in the chamber was generally 2 to 3 times higher when the furnace operated continuously compared to when the furnace cycled at a rate of 8 minutes on and 2 minutes off.

- When the supply voltage to the furnace was reduced to 85 percent of its normal value, the concentration of CO in the chamber generally increased relative to tests performed with the furnace operating at its normal supply voltage.

- As the gas input rate was varied from the manufacturer's specified rate to an overfire rate of 18 percent, the burner flames remained blue in color and did not impinge on the side of the heat exchanger. This may be of concern since the manufacturer's installation instructions state that for proper operation the flame should be stable and blue and should not touch the sides of the heat exchanger.

REFERENCES

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APPENDIX A: FURNACE SPECIFICATIONS AND SETUP

Table A1 lists some general information about the test furnace.

TABLE A.1. Specifications of the Test Furnace (Furnace #2)

|	
Draft Type	Induced Draft
Input Rate	
Specified Rate	100,000 Btu/hr
Specified Manifold Pressure	3.5 inches w. c.
Burner Type	In Shot
Combustion Chamber	Closed
Vent Type	Type B
Block Vent Shutoff System	Pressure switch at inlet of inducer fan
Annual Fuel Utilization Efficiency (AFUE)	80 %
Return/Supply Air	
Temperature Rise	45 – 75 °F
Maximum Outlet Air Temperature	175 °F
Maximum Static Pressure	0.5 inches w.c.
Certifying Standard	ANSI Z21.47-CAN/CGA-2.3m 1993

The furnace was installed according to the manufacturer's installation instructions and the National Fuel Gas Code (1996). Three-quarter inch (1.91 centimeter) black galvanized pipe was used to connect the furnace to the main gas line. A pressure tap was added before the pressure regulated so that the supply pressure could be measured. The inlet pressure generally ranged from 6.5 to 7.0 inch w.c. The furnace was placed on a 13 inch (33.0 centimeter) high platform so that the return duct would not contact the chilled water lines that ran along the floor of the chamber. The cracks between the furnace bottom and platform were sealed with aluminum tape, per the manufacturer's instructions, to prevent a "possible negative pressure condition".

Flue gases from the furnace were vented using double-wall Type B vent material having an internal diameter of 5 inches (12.7 centimeters). The vent pipe had a total rise of 5.60 feet (1.70 meters) and a horizontal run of approximately 4.0 feet (1.21 meters). Figure A.1 illustrates the general vent system. Due to restrictions preventing modifications to the CPSC laboratory, the flue products had to be vented outdoors using an existing vent hood. The vent hood was located at a vertical distance of 5.0 feet (1.52 meters) from the furnace and a horizontal distance of 17.0 feet (5.18 meters). Due to the venting restrictions in the National Fuel Gas Code (1996) that states that the horizontal run of the vent pipe can not exceed 75 percent of the vertical height for draft hood equipped furnaces, the vent pipe could not be directly connected to the vent hood. Instead, the vent pipe terminated in a draft hood that was then connected to the vent hood (see Figure A.1). The draft hood was open in the back allowing air to be drawn in with the flue

products and a fan was used to transfer this mixture to the vent hood. When the fan for the draft hood was on and the furnace was off, the pressure in the vent pipe was 0.00 inches w.c. Therefore, the vent hood did not affect the operation of the furnace.

The return duct consisted of a duct that was 7.1 feet (2.16 meters) long, 16 inches (40.6 centimeters) high by 19 inches (48.3 centimeters) wide. The duct was attached to the furnace return air opening using flanges and screws. Aluminum tape was used to seal all seams along the duct and at the point of attachment between the duct and furnace. Air for the return duct was obtained from an adjoining room. A vent located at the end of the room prevented the pressure from going negative in this room when the furnace was operating. The supply duct consisted of several sections. The first section was a 16 inch (40.6 centimeters) long transition piece that reduced the 19 inch (48.3 centimeter) by 18 inch (45.7 centimeter) furnace supply air opening to an 8 inch (20.3 centimeter) by 20 inch (50.8 centimeter) opening. The second section consisted of a rectangular duct that was 4.25 feet (1.30 meters) long, 8 inches (20.3 centimeter) high by 20 inches (50.8 centimeter) wide. This section was connected to a 90-degree duct. The final section was an 8 inch (20.3 centimeter) by 20 inch (50.8 centimeter) duct that was 10.6 feet (3.23 meters) long. Screws connected the various sections of the duct together and all duct seams within the closet were sealed with aluminum tape. The heated air from the supply duct was released in the main section of the laboratory. This section of the building contained a vent hood that exhausted to the outdoors and thus prevented a positive pressure from occurring in the room.
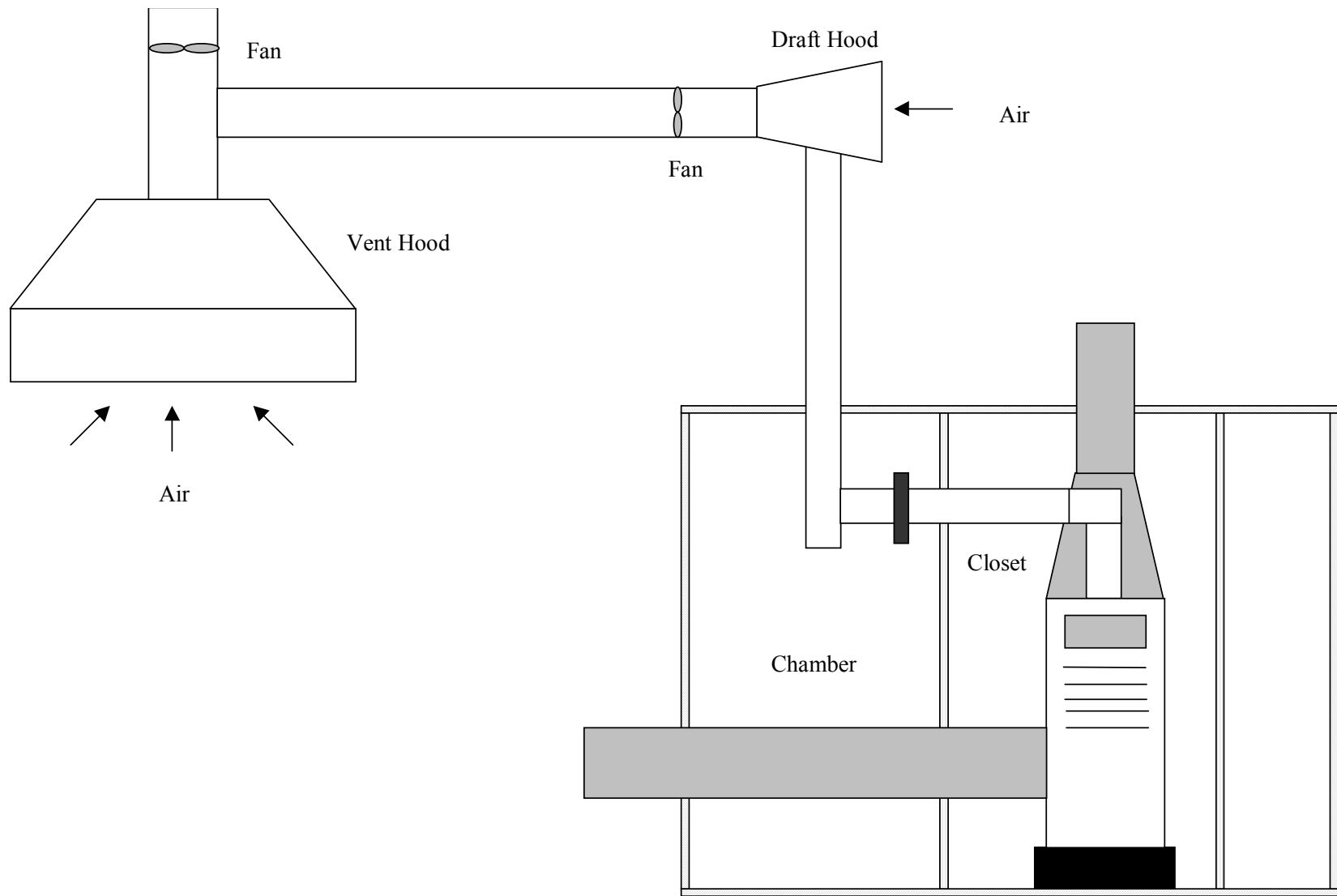
Figure A.1. Furnace Vent System Diagram

APPENDIX B: CHAMBER AND FURNACE CLOSET DESCRIPTION

CHAMBER

The test chamber was a modified environmental room manufactured by Hotpack. The internal dimensions of the chamber were 10 feet (3.05 meters) wide, by 12 feet (3.66 meters) long, by 7 feet (2.16 meters) high. The internal volume was 837 cubic feet (23.7 cubic meters). The inner walls of the chamber were constructed from enamel-coated aluminum. Holes were added through the chamber walls to allow for the return and supply ducts of the furnace and also for the vent pipe. Silicon glue was used to seal any gaps between the chamber walls and the ducts and vent pipe.

The temperature inside the chamber was controlled by removing heat from the chamber. This was accomplished by passing chilled water through four fin-and-tube heat exchangers located in the chamber (Figure B.1). Chilled water was provided by a recirculating chiller (Neslab, HX 750) located outside of the chamber. To assist in the cooling process, three small fans situated over each heat exchanger were used to draw air over the heat exchanger. These fans also ensured a well-mixed environment within the chamber.

The chamber was equipped with two fans to control air infiltration into the chamber. One fan brought fresh air from the laboratory into the chamber and the second fan exhausted air out of the chamber into an exhaust hood that vented outdoors.

The chamber also contained a pressure feedback system to maintain a near zero pressure differential between the chamber and the laboratory. This was done to prevent the furnace from back drafting. The feedback system consisted of the exhaust fan connected to a photohelic pressure gauge with transmitter (Dwyer, model 3000SGT). When the pressure differential exceeded the set pressure limit of ± 0.01 inches w.c., the exhaust fan would cycle off or on accordingly.

FURNACE CLOSET

A furnace closet was erected within the chamber. The closet was constructed using ½ inch dry wall and metal studs for the framing. The outside of the closet was 4.33 feet (1.32 meters) wide by 6.25 feet (1.91 meters) long by 7.08 feet (2.16 meters) high. The closet was positioned on a 0.75 inch (1.91 centimeter) thick piece of wood located on the chamber floor. The internal volume of the closet was 196 cubic feet (5.5 cubic meters). The closet contained a door, a hole for the vent pipe, and holes for the return and supply ducts. The hole for the vent pipe provided a 0.25 to 1.0 inch clearance around the vent pipe. In order to comply with the National Fuel Gas Code (1996) and the manufacturer's installation instructions for a "Confined Space" installation, the closet contained two vent openings. Both vents had a free area of 121 square inches, which met the requirement of a minimum of 1 square inch per 1,000 Btu/hr of the input rating (at 100,000 Btu/hr input, the minimum free area would be 100 square inches). One vent was located within 12 inches of the ceiling and the other was located within 12 inches of the floor, per the instructions. The furnace was positioned inside the closet so that the manufacturer's specification for minimum distances to combustible surfaces was met.
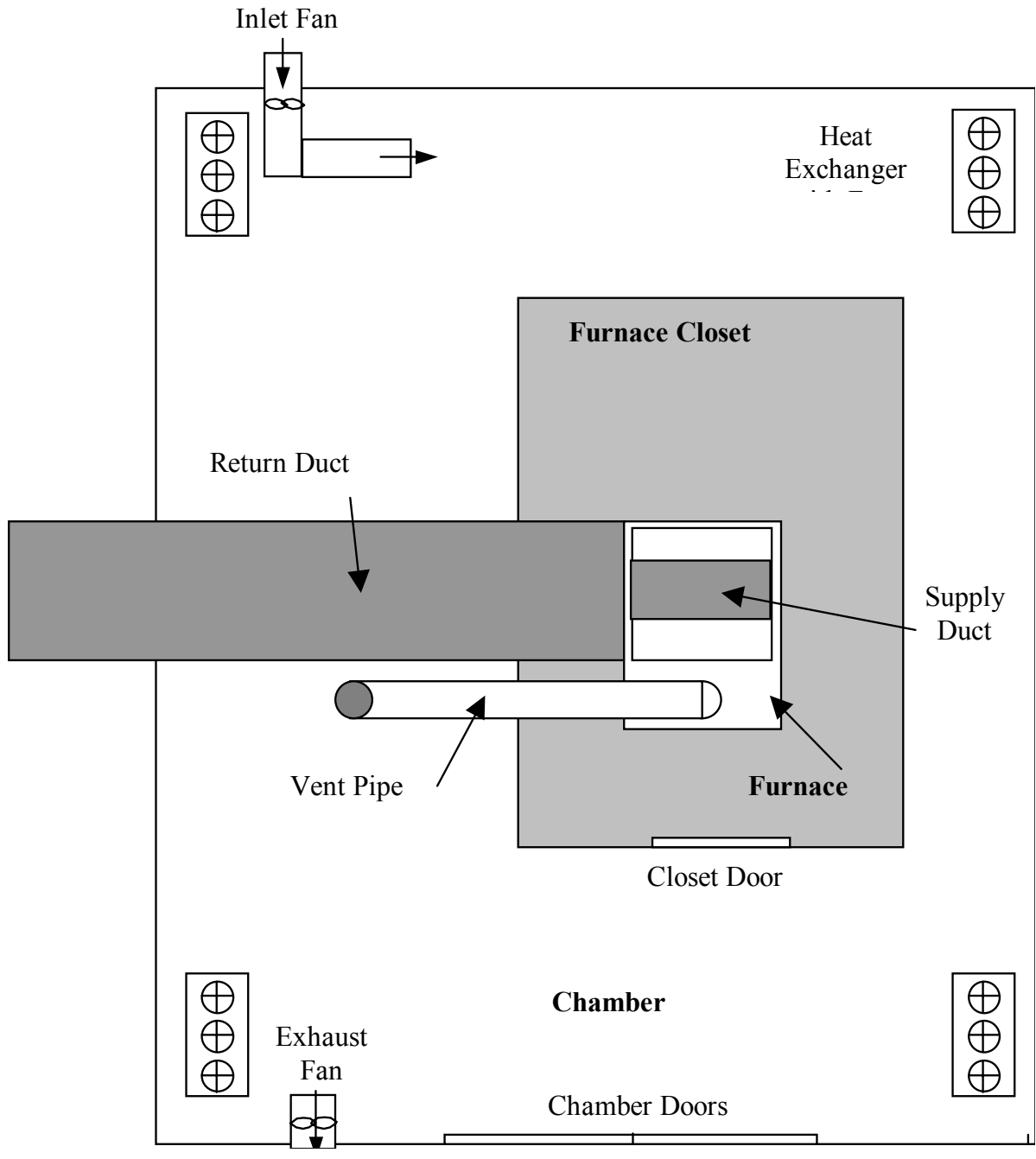
Figure B.1. Test Chamber Diagram (Top View)

APPENDIX C: MEASUREMENT OF FURNACE OPERATING PARAMETERS

Figure C.1 illustrates the general locations where the different operating parameters of the furnace were measured.
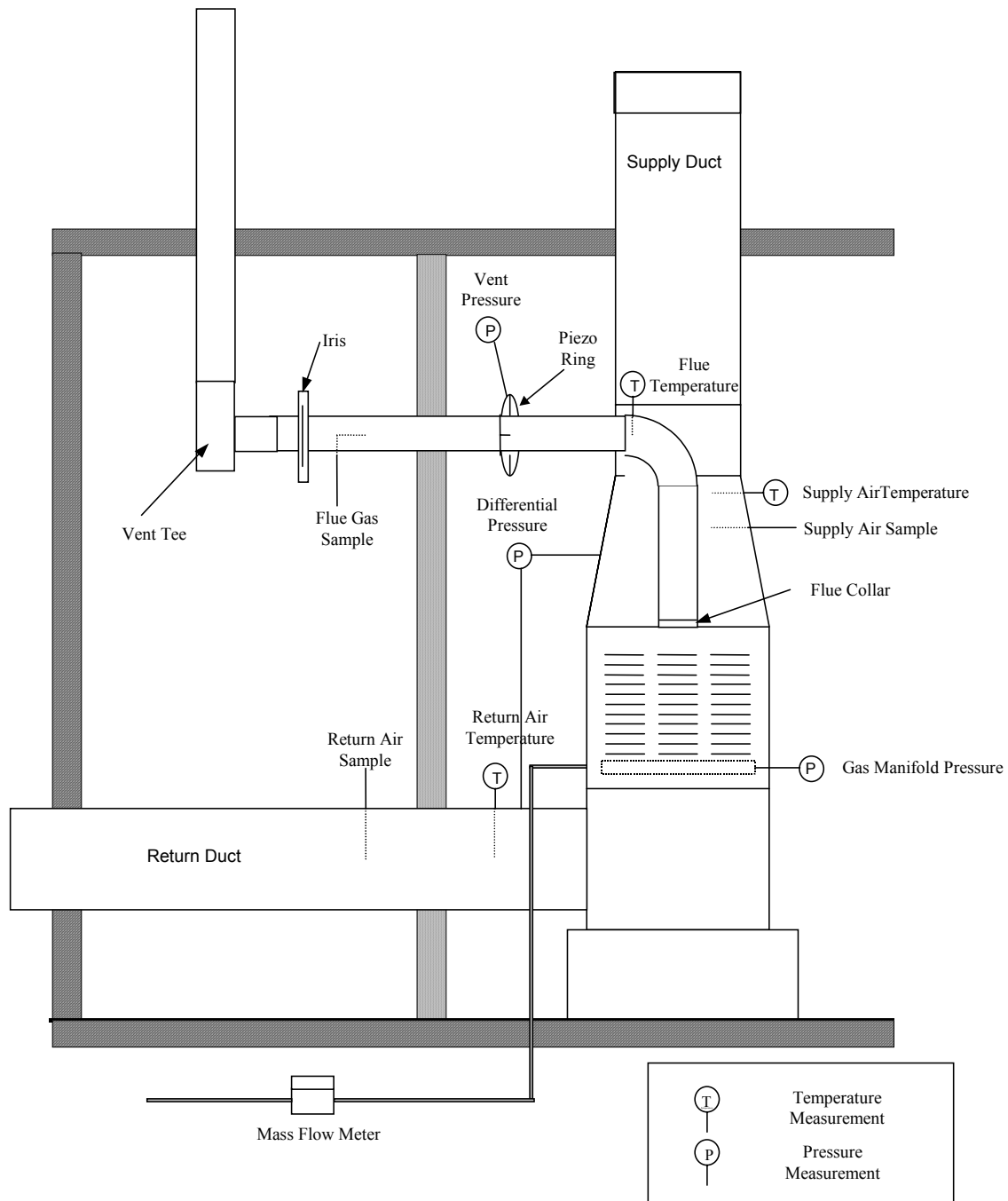
Figure C.1. Location of Measurements on Test Furnace

Table C.1. Equipment Used to Measure the Different Operating Parameters of the Furnace

Parameter Being Measured	Equipment Type	Manufacturer	Model	Range	Accuracy
Gas Manifold Pressure	Magnehelic Pressure Gage with Transmitter	Dwyer	605-10	0-10 inches w.c.	± 2% full scale
Differential Pressure Between the Return & Supply Air Ducts	Magnehelic Pressure Gage with Transmitter	Dwyer	605-1	0-1.0 inches w.c.	± 2% full scale
Vent Pressure	Magnehelic Pressure Gage	Dwyer	2301	0.5 – 0 – 0.5 inches w.c.	± 2% full scale
Gas Input Rate	Mass Flow Meter (methane)	Sierra	826-NX-OV1-PV1-V1	0-2 scfm	± 1.5% full scale
Flue Temperature, Return and Supply Air Temperature, Air Temperature Near Blocked Vent Shutoff System	Thermocouple	Omega	Type K, 28 AWG	-200 to 1250°C	2°C or 0.75% of Reading, which ever is greater

APPENDIX D: GAS SAMPLING SYSTEM
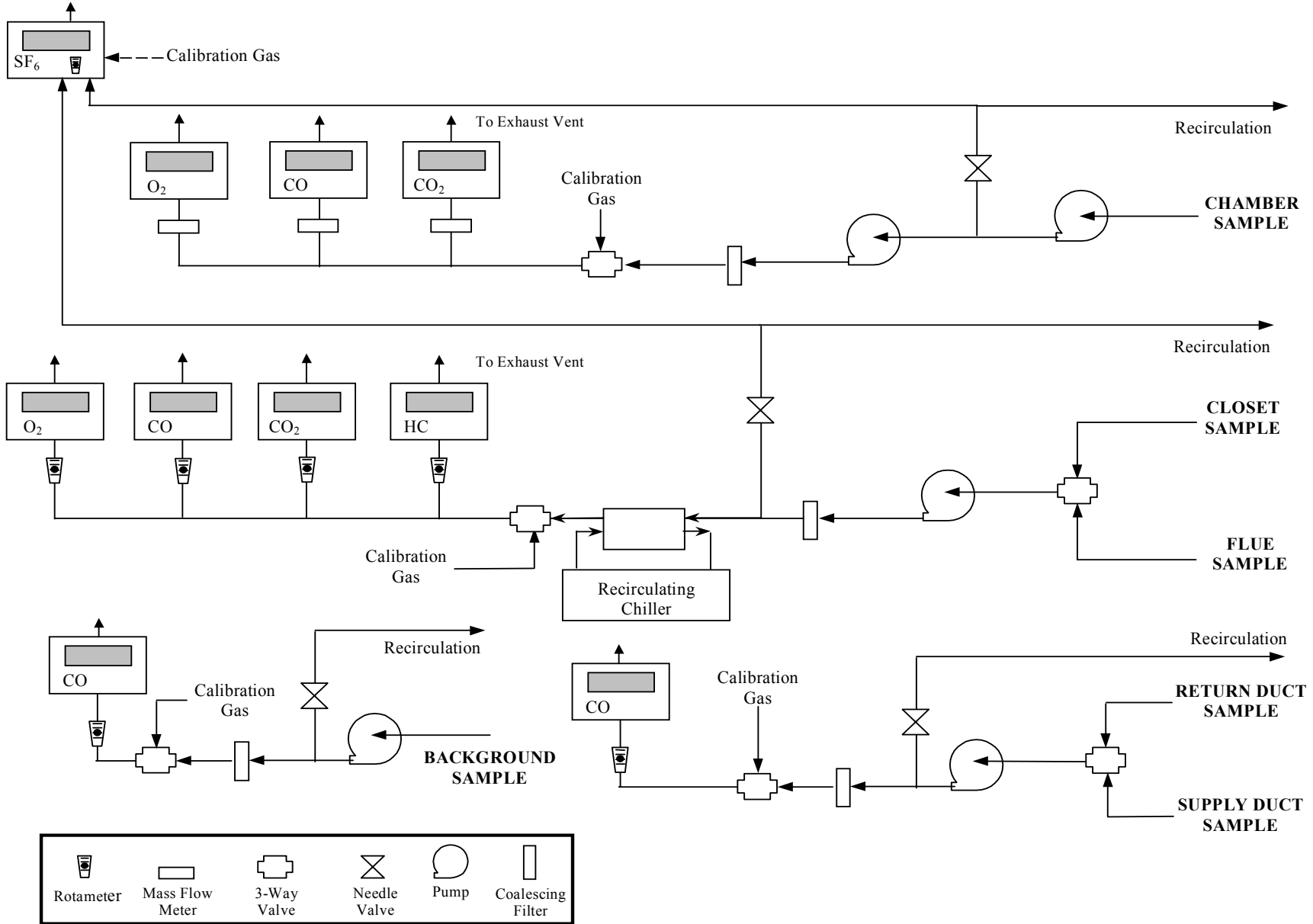
Figure D.1. Schematic of Gas Sampling Systems

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Table D.1. Equipment Used with the Gas Sampling Systems

Chemical Species	Location	Measuring Technique	Manufacturer	Model	Range	Accuracy
Carbon Monoxide (CO)	Closet/Flue	Non-Dispersive Infrared	Rosemount	880A	0-200 ppm, 0-1000 ppm	1% Full Scale
Carbon Dioxide (CO_2)	Closet/Flue	Non-Dispersive Infrared	Rosemount	880A	0-10%, 0-20%	1% Full Scale
Oxygen (O_2)	Closet/Flue	Paramagnetic	Rosemount	755R	0-25%	1% Full Scale or 0.01% O_2, which ever is greater
Hydrocarbon (HC)	Closet/Flue	Non-Dispersive Infrared	Rosemount	880A	0-100% LEL[1]	1% Full Scale
Carbon Monoxide (CO)	Return/Supply Air	Non-Dispersive Infrared	Rosemount	880A	0-100 ppm, 0-1000 ppm	1% Full Scale
Oxygen (O2)	Chamber	Paramagnetic	Rosemount	755R	0-25%	1% Full Scale or 0.01% O_2, which ever is greater
Carbon Monoxide (CO)	Chamber	Non-Dispersive Infrared	Rosemount	880A	0-200 ppm, 0-1000 ppm	1% Full Scale
Carbon Dioxide (CO_2)	Chamber	Non-Dispersive Infrared	MSA	Lira 3000	0-10%	1% Full Scale
Carbon Monoxide (CO)	Return/Supply Air	Non-Dispersive Infrared	Beckman	866	0-100 ppm	1% Full Scale
Sulfur Hexafluoride (SF_6)	Chamber and Closet	Electron Capture Gas Chromatograph	Largus Applied Technology	101	0-5 ppb	±3% of reading

1. Lower Explosion Limit of Methane (5% by volume)

APPENDIX E: FURNACE TEST MATRIX

Table E.1. Furnace Test Matrix Table

BASELINE TESTS
Normal
1. Baseline – Specified Rate (continuous)
2. Baseline – Specified Rate (w/cycling)
3. Baseline - "As Received" Rate (continuous)
4. Baseline - "As Received" Rate (w/cycling)
Overfire
5. 12% Over Specified Rate (continuous)
6. 12% Over Specified Rate (w/cycling)
7. 12% Over "As Received" Rate (continuous)
8. 12% Over "As Received" Rate (w/cycling)
BLOCKAGE TESTS
Normal
9. 100 % Vent Blockage @ Specified Rate (continuous)
10. 100 % Vent Blockage @ Specified Rate (w/cycling)
11. 100 % Vent Blockage @ "As Received" (continuous)
12. 100 % Vent Blockage @ "As Received" Rate (w/cycling)
13. Incremental Vent Blockage (80%-95%, 65%, 50%, 25%) (continuous)
14. Incremental Vent Blockage (80%-95%, 65%, 50%, 25%) (w/cycling)
15. Incremental Vent Blockage @ "As Received" Rate (80%-95%, 65%, 50%, 25%) (continuous)
16. Incremental Vent Blockage @ "As Received" Rate (80%-95%, 65%, 50%, 25%) (w/cycling)
Overfire
17. 100 % Vent Blockage - 12% Over Specified Rate (continuous)
18. 100 % Vent Blockage - 12% Over Specified Rate (w/cycling)
19. 100 % Vent Blockage - 12% Over "As Received" Rate (continuous)
20. 100 % Vent Blockage - 12% Over "As Received" Rate (w/cycling)
21. Incremental Vent Blockage (80%-95%, 65%, 50%, 25%) - 12% Over Specified Rate (continuous)
22. Incremental Vent Blockage (80%-95%, 65%, 50%, 25%) - 12% Over Specified Rate (w/cycling)
23. Incremental Vent Blockage (80%-95%, 65%, 50%, 25%) - 12% Over "As Received" Rate (continuous)
24. Incremental Vent Blockage (80%-95%, 65%, 50%, 25%) - 12% Over "As Received" Rate (w/cycling)

Table E.1. Furnace Test Matrix Table (continued)

DISCONNECTED VENT TESTS
Normal
25. ¼- Inch Gap @ Specified Rate (continuous)
26. 2-Inch Gap @ Specified Rate (continuous)
27. 100% Disconnected Vent in Closet @ Specified Rate (continuous)
28. 100% Disconnected Vent in Chamber @ Specified Rate (w/cycling)
29. 100% Disconnected Vent in Closet @ "As Received" Rate (continuous)
30. 100% Disconnected Vent in Chamber @ "As Received" Rate (w/cycling)
Overfire
31. ¼- Inch Gap – 12% Over Specified Rate (continuous)
32. 2-Inch Gap - 12% Over Specified Rate (continuous)
33. 100% Disconnected Vent in Closet - 12% Over Specified Rate (continuous)
34. 100% Disconnected Vent in Closet - 12% Over Specified Rate (w/cycling)
35. 100% Disconnected Vent in Chamber - 12% Over Specified Rate (continuous)
36. 100% Disconnected Vent in Chamber - 12% Over Specified Rate (w/cycling))
37. 100% Disconnected Vent in Closet - 12% Over "As Received" Rate (continuous)
38. 100% Disconnected Vent in Closet - 12% Over "As Received" Rate (w/cycling)
39. 100% Disconnected Vent in Chamber - 12% Over "As Received" Rate (continuous)
40. 100% Disconnected Vent in Chamber - 12% Over "As Received" Rate (w/cycling)

APPENDIX F: DERIVATION OF AIR EXCHANGE RATE AND EMISSION RATE

Air Exchange Rate

The air exchange rate in the chamber can be derived from a simple mass balance on the chamber. Figure F.1 illustrates the different flows into and out of the chamber. The chamber boundaries are displayed using a dashed line. A tracer gas is injected into the chamber (designated as S_{inj}) and the gas concentration (C) is measured inside the chamber over time. The number of air exchanges per hour inside the chamber is controlled by the amount of air brought into (Q_{in}) and out of (Q_{out}) the chamber. An allowance has been made for leakage (Q_{leak}) into the return duct. For this simple model, it is assumed that the furnace closet does not interact with the chamber, but behaves as a "black box". This assumption can be made if the concentration of the tracer gas in the closet is approximately the same as the concentration in the chamber.
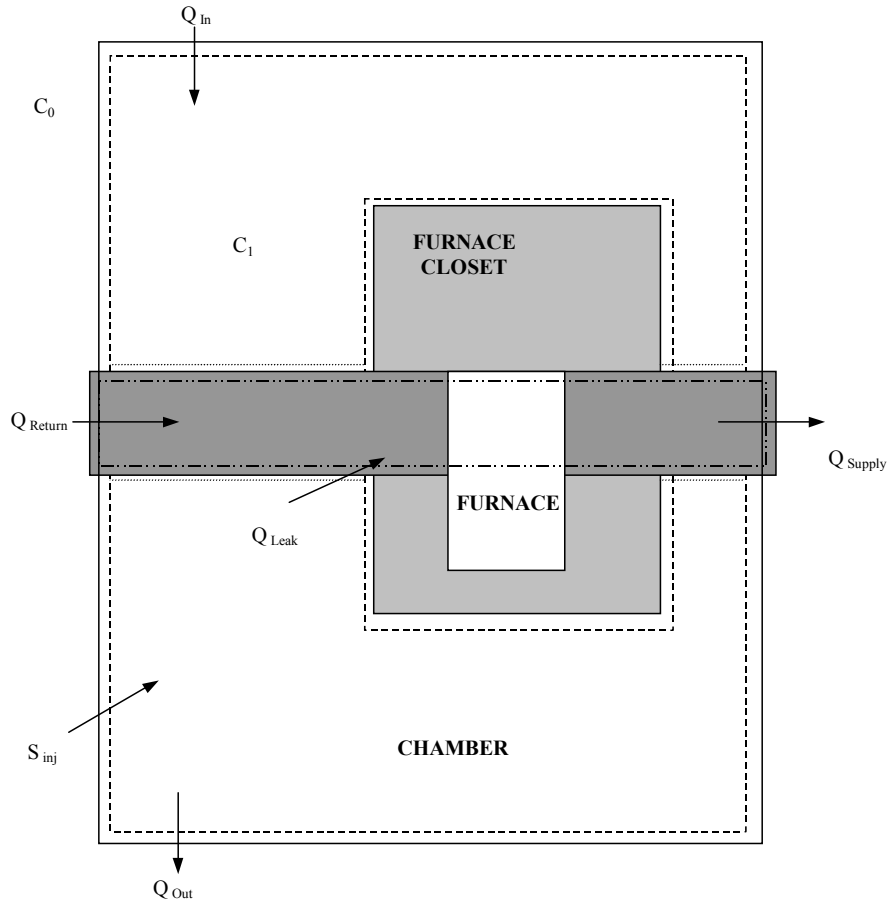
Figure F.1. Model of Test Chamber Used to Derive Air Exchange Rate Equation

Figure F.1 applies to the situation where the vent pipe is totally disconnected or fully blocked. When the vent pipe is intact or partially blocked, a portion of air from the chamber exits through the furnace's vent pipe. This is the air used in the combustion process (primary and secondary

air) and by the draft hood. Since a pressure control system is used to maintain a zero pressure differential between the chamber and the surrounding laboratory, less air exits the chamber through the chamber's exhaust fan when the furnace is operating. To simplify the model, any air that would be exhausted through the vent pipe to the outdoors will be combined with the term for the flow out of the chamber (Q_{out}).

Based on Figure F.1, a mass balance for chemical specie C inside the chamber yields the following equation:

$$V\frac{dC_1}{dt} = C_0 Q_{in} - C_1 Q_{out} - C_1 Q_{leake} + S_{inj} \qquad [F.1]$$

where,

V = volume inside the chamber less the closet and the return duct, m^3

C_1 = concentration of the tracer gas in the chamber, 0.001 cc/m^3 or ppb

C_0 = concentration of the tracer gas present in the background, 0.001 cc/m^3 or ppb

Q_{in} = flow rate of air into the chamber, m^3/hr

Q_{out} = flow rate of air out of the chamber, m^3/hr

Q_{leak} = leak rate of air into the return/supply duct, m^3/hr

S_{inj} = injection rate of tracer gas, cc/hr

In equation F.1, the following has been assumed: the air in the chamber is well mixed, the tracer gas does not get absorbed inside the chamber, any leakage from the supply duct to the chamber has been neglected, and the tracer gas does not get consumed in the burner flame.

Since a pressure control system is used to maintain a zero pressure differential between the chamber and the surrounding laboratory, the following equation can be written for the mass flow of air into and out of the chamber.

$$Q_{in} = Q_{out} + Q_{leak} \qquad [F.2]$$

Equation F.1 can be rewritten using the relationship in Equation F.2 as follows:

$$V\frac{dC_1}{dt} = C_0 Q_{in} - C_1 Q_{in} + S_{inj} \qquad [F.3]$$

or

$$\frac{dC_1}{dt} = \frac{C_0 Q_{in}}{V} - \frac{C_1 Q_{in}}{V} + \frac{S_{inj}}{V} \qquad [F.4]$$

At steady state, the rate of change of the chemical specie C inside the chamber is zero.

$$\frac{dC_1}{dt} = 0 \qquad [F.5]$$

The number of air changes per hour (ACH) in the chamber can be defined by the following equation:

$$ACH = \frac{Q_{in}}{V} \qquad \text{[F.6]}$$

Assuming that the background concentration of the tracer gas is zero, Equations F.5 and F.6 can be substituted into Equation F.4 to yield the following equation:

$$0 = 0 - C_1 ACH + \frac{S_{inj}}{V} \qquad \text{[F.7]}$$

Solving for ACH in Equation F.7 yields,

$$ACH = \frac{S_{inj}}{C_{1_{eq}} V} \qquad \text{[F.8]}$$

where $C_{1\ eq}$ is the equilibrium concentration of the tracer gas.

CO EMISSION RATE

The equation for the CO emission rate from the furnace can be derived using a method similar to that used to derive the air exchange rate equation (Equation F.8). Figure F.2 illustrates the different flows into and out of the chamber. The only difference between Figures F.1 and F.2 is that the term for the injection rate (S_{inj}) of the tracer gas is replaced with a term for the CO emission rate (E_{CO}) from the furnace. For this simple model, the furnace closet and furnace are combined to form a single "black box" emission source.
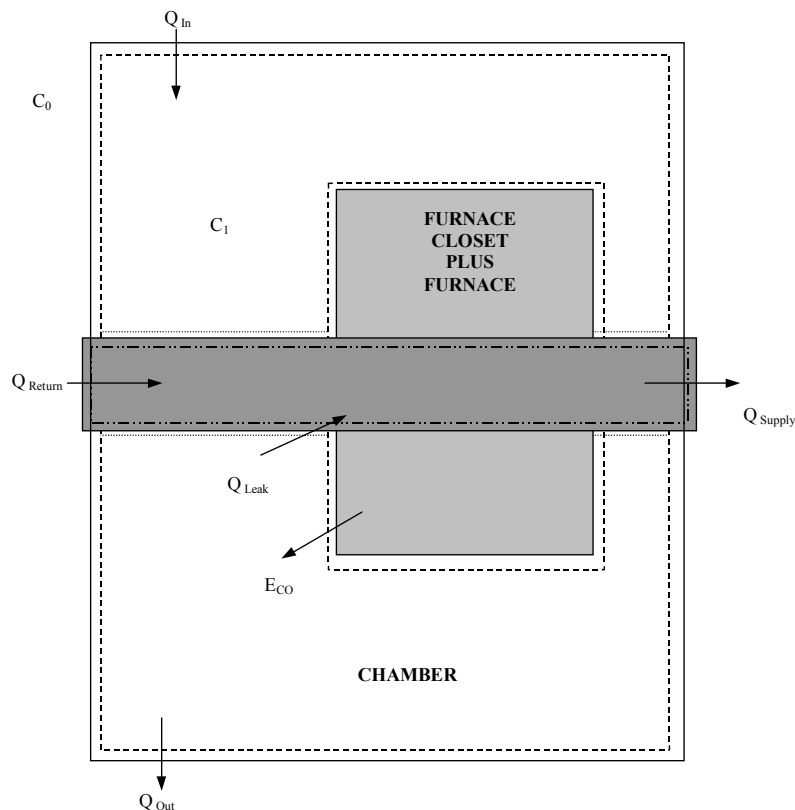
Figure F.2. Model of Test Chamber Used to Derive CO Emission Rate Equation

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Based on Figure F.2, a mass balance for chemical specie C inside the chamber yields the following equation:

$$V \frac{dC_1}{dt} = C_0 Q_{in} - C_1 Q_{out} - C_1 Q_{leake} + E_{CO}$$ [F.9]

where,

V = volume inside the chamber less the closet and the return and supply ducts, m^3

C_1 = concentration of carbon monoxide in the chamber, cc/m^3 or ppm

C_0 = concentration of carbon monoxide present in the background, cc/m^3 or ppm

Q_{in} = flow rate of air into the chamber, m^3/hr

Q_{out} = flow rate of air out of the chamber, m^3/hr

Q_{leak} = leak rate of air into the return/supply duct, m^3/hr

E_{CO} = emission rate of carbon monoxide from the furnace/furnace closet, cc/hr

Following a method similar to that used to derive the air exchange rate equation, Equation F.9 can be reduced and rearranged to yield the CO emission rate.

$$E_{CO} = C_{CO_{eq}} ACH \ V$$ [F.10]

where $C_{CO \ eq}$ is the equilibrium concentration of CO in the chamber.

APPENDIX G. TEST DATA RESULTS

Table G.1. Baseline Test Results

Test Number[1]	Input Rate[2] (Btu/hr)	Mode of Operation[3]	Average Stead-State CO Concentrations (ppm)				Air Exchange Rate	CO Emission Rate
			CO Chamber	CO Closet	CO Supply Air	CO Flue Gas[4]	(1/hr)	(cc/hr)
13	100,000	Continuous	0	0	0	18	10.5	0
1	106,000	Continuous	0	0	0	15	10.7	0
46	112,000	Continuous	0	0	0	17	10.1	0
3	118,000	Continuous	1	1	0	23	11.2	222
14	100,000	Cycling	0	0	0	15	10.5	0
2	106,000	Cycling	0	0	0	12	10.6	0
47	112,000	Cycling	0	0	0	19	10.2	0
4	118,000	Cycling	0	0	0	22	10.3	0

1. Test Numbers correspond to the order in which the test was performed and do not relate to the numbers in the Test Matrix (Appendix E).

2. Actual input rates are ± 3% of the listed values.

3. Cycling rate is 8 minutes on and 2 minutes off.

4. The CO present in the flue gas is specified on an air-free basis.

Table G.2. Blocked Vent Test Results

Test Number[1]	Degree of Vent Blockage	Location of Blockage	Input Rate[2] (Btu/hr)	Mode of Operation[3]	Did Furnace Shut Off?	Time of Shut Off (minutes)	Average Steady-State CO Concentrations (ppm)				Avg. Steady-State O_2 in Closet (%)	Air Exchange Rate (1/hr)	CO Emission Rate (cc/hr)
							Chamber	Closet	Supply Air	Flue Gas[4]			
35	85%	Iris	118,000	Continuous	No	N/A	11	18	0	253	19.1	10.2	2,007
33	90%	Iris	100,000	Continuous	No	N/A	0	2	0	17	19.5	10.7	0
32	90%	Iris	106,000	Continuous	No	N/A	1	1	0	30	19.5	10.4	186
17	90%	Iris	112,000	Continuous	No	N/A	9	13	0	NR	19.4	11.5	1,849
18	90%	Iris	118,000	Continuous	No	N/A	61	95	2	> 1,000	19.3	10.9	11,925
26	90%	Iris	118,000	Continuous	No	N/A	78	113	1	> 1,000	18.9	10.4	14,578
27	90%	Iris	118,000	Continuous	No	N/A	22	35	0	420	19.1	10.2	4,023
37	90%	Iris	118,000	Continuous	No	N/A	27	45	0	572	19.3	10.5	5,071
34	95%	Iris	100,000	Continuous	No	N/A	1	1	0	17	19.3	10.3	185
31	95%	Iris	106,000	Continuous	No	N/A	5	8	0	74	19.0	11.1	990
22	95%	Iris	112,000	Continuous	No	N/A	37	58	0	614	18.8	10.5	6,949
23	95%	Iris	112,000	Continuous	No	N/A	31	47	0	461	18.6	10.5	5,822
19	95%	Iris	118,000	Continuous	No	N/A	361	523	15	NR	18.4	11.2	72,427
36	95%	Iris	118,000	Continuous	No	N/A	276	435	11	> 1,000	18.7	10.8	53,411
17	100%	Iris	112,000	Continuous	Yes	Immediately	N/A	N/A	N/A	N/A	N/A	N/A	N/A
18	100%	Iris	118,000	Continuous	Yes	Immediately	N/A	N/A	N/A	N/A	N/A	N/A	N/A
43	100%	Vent Outlet	100,000	Continuous	No	N/A	4	5	0	49	18.3	10.8	774
42	100%	Vent Outlet	106,000	Continuous	No	N/A	40	59	0	414	18.2	11.1	7,942
44	100%	Vent Outlet	106,000	Continuous	No	N/A	29	44	0	313	18.3	11.0	5,728
40	100%	Vent Outlet	112,000	Continuous	No	N/A	262	394	10	> 1,000	18.1	11.3	52,982
45	100%	Vent Outlet	112,000	Continuous	No	N/A	221	336	11	> 1,000	18.2	11.0	43,652
48	100%	Vent Outlet	112,000	Continuous	No	N/A	160	251	7	> 1,000	18.3	11.1	31,685
38	100%	Vent Outlet	118,000	Continuous	No	N/A	880	> 1000	15	> 1,000	18.1	11.6	183,290
50	100%	Vent Outlet	118,000	Continuous	No	N/A	692	934	33	> 1,000	18.3	11.1	137,751

Table G.2. Blocked Vent Test Results (continued)

Test Number[1]	Degree of Vent Blockage	Location of Blockage	Input Rate[2] (Btu/hr)	Mode of Operation	Did Furnace Shut Off?	Time of Shut Off (minutes)	Average Steady-State CO Concentrations (ppm)				Avg. Steady-State O_2 in Closet (%)	Air Exchange Rate (1/hr)	CO Emission Rate (cc/hr)
							Chamber	Closet	Supply Air	Flue Gas[4]			
25	90%	Iris	118,000	Cycling	No	N/A	13	20	0	466	19.5	10.1	2,344
21	95%	Iris	112,000	Cycling	No	N/A	17	29	0	467	18.8	10.8	3,298
24	95%	Iris	112,000	Cycling	No	N/A	16	28	10	443	19.2	10.4	2,969
20	95%	Iris	118,000	Cycling	No	N/A	123	202	4	> 1,000	18.9	10.7	23,623
30	95%	Iris	118,000	Cycling	No	N/A	77	126	2	NR	18.7	10.4	14,321
41	100%	Vent Outlet	112,000	Cycling	No	N/A	63	105	2	> 1,000	18.6	11.0	12,348
49	100%	Vent Outlet	112,000	Cycling	No	N/A	115	193	4	> 1,000	18.7	11.0	22,598
51	100%	Vent Outlet	118,000	Cycling	No	N/A	463	683	18	> 1,000	18.6	11.0	91,216
39	100%	Vent Outlet	118,000	Cycling	No	N/A	480	722	18	> 1,000	18.6	11.0	94,080

1. Test Numbers correspond to the order in which the test was performed and do not relate to the numbers in the Test Matrix (Appendix E).

2. Actual input rates are ± 3% of the listed values.

3. Cycling rate is 8 minutes on and 2 minutes off.

4. The CO present in the flue gas is specified on an air-free basis.

Table G.3. Disconnected Vent Test Results

Test Number[1]	Size of Disconnect	Location of Vent Disconnection	Input Rate[2] (Btu/hr)	Mode of Operation[3]	Did Furnace Shut off?	Average Steady-State CO Concentrations (ppm)				Air Exchange Rate (1/hr)	CO Emission Rate (cc/hr)
						Chamber	Closet	Supply Air	Flue Gas[4]		
11	100%	Closet	100,000	Continuous	No	6	9	0	NR	11.1	1,212
10	100%	Closet	112,000	Continuous	No	11	17	1	NR	12.0	2,362
5	100%	Closet	118,000	Continuous	No	61	93	2	NR	12.2	13,336
29	100%	Closet	118,000	Continuous	No	64	96	0	NR	11.3	12,942
7	100%	Chamber	118,000	Continuous	No	39	37	0	NR	12.9	9,034
28	100%	Chamber	118,000	Continuous	No	38	37	0	317	11.9	8,091
12	100%	Closet	100,000	Cycling	No	3	5	0	NR	11.6	964
16	100%	Closet	112,000	Cycling	No	10	17	0	NR	11.9	2,159
6	100%	Closet	118,000	Cycling	No	38	59	1	NR	11.4	7,746
15	100%	Closet	118,000	Cycling	No	33	53	0	NR	11.9	7,125
29	1.25 inch gap	Chamber	118,000	Continuous	No	0	0	0	NR	10.5	0

1. Test Numbers correspond to the order in which the test was performed and do not relate to the numbers in the Test Matrix (Appendix E).

2. Actual input rates are ± 3% of the listed values.

3. Cycling rate is 8 minutes on and 2 minutes off.

4. The CO present in the flue gas is specified on an air-free basis.

Table G.4. Reduced Supply Voltage[1] Test Results

Test Number[2]	Vent Condition	Input Rate[2] (Btu/hr)	Mode of Operation[4]	Did Furnace Shut off?	Average Steady-State CO Concentrations (ppm)				Air Exchange Rate (1/hr)	CO Emission Rate (cc/hr)
					Chamber	Closet	Supply Air	Flue Gas[5]		
55	Vent Pipe Totally Disconnected Inside Closet	100,000	Continuous	No	4	4	0	NR	11.7	835
53	Vent Pipe Totally Disconnected Inside Closet	112,000	Continuous	No	12	20	0	152	11.4	2,453
54	Vent Pipe Totally Disconnected Inside Closet	112,000	Cycling	No	72	101	2	NR	11.6	14,956
52	Vent Pipe Totally Disconnected Inside Closet	118,000	Continuous	No	164	243	6	NR	11.7	34,252

1. Supply voltage was reduced to 85 percent of its normal value (120 volts).

2. Test Numbers correspond to the order in which the test was performed and do not relate to the numbers in the Test Matrix (Appendix E).

3. Actual input rates are ± 3% of the listed values.

4. Cycling rate is 8 minutes on and 2 minutes off.

5. The CO present in the flue gas is specified on an air-free basis.