



MEDIUM-SIZED COMBUSTION CHAMBER SYSTEM CHARACTERIZATION TESTS

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Note: This document has been reviewed by experts within the U.S. Government, outside of CPSC, and the experts' comments have been incorporated.

1. INTRODUCTION

The U.S. Consumer Product Safety Commission (CPSC) Laboratory in Gaithersburg, MD uses four different sized environment test chambers to evaluate consumer products with respect to the products of combustion. The Large Chamber (L-chamber) is 26.1 m³ (920 ft³) in volume and is used to test large gas-burning appliances, such as residential gas furnaces with thermal ratings up to 120,000 BTU/hr. The Medium Chamber (M-chamber) is 9.59 m³ (339 ft³) in volume and is used to test unvented combustion appliances, such as portable engine-driven electric generators or gas logsets with thermal ratings up to 60,000 BTU/hr. The M-Chamber was renovated in 2003. The Small Chamber (K-chamber) is 2.83 m³ (100 ft³) in volume and is used to test smaller unvented gas-burning appliances, such as propane-fired camping heaters with thermal ratings up to about 20,000 BTU/hr. Finally, the smallest chamber (D-chamber) is 1.02 m³ (36 ft³) in volume and is used to test carbon monoxide (CO) alarms, other gas sensing devices, and small heat generating devices up to about 5,000 BTU/hr.

This report provides detailed descriptions of the tests performed to characterize the M-chamber with respect to ventilation rates (i.e., air exchange rate) and chamber volume, and to determine how well mixed the gases were within the chamber. All of these factors are important when trying to measure the emission rate of a pollutant, such as carbon monoxide, from gas-fired equipment. Although the M-chamber can be used for testing different types of unvented combustion appliances, the chamber will be initially configured for testing engine-driven tools, such as gasoline-fueled portable electric generators. Therefore, the chamber characterization tests focused primarily on the test conditions expected during the testing of gasoline-fueled portable electric generators.

2. BACKGROUND OF TRACER GAS TESTS

The ventilation characteristics of the M-chamber and the volume of the chamber were obtained by conducting a series of tracer gas decay tests and constant injection tests. Both of these techniques are standard methods for characterizing the ventilation rates in a room and estimating the volume of the room. The following is a brief overview of each method. Appendix A provides detailed derivations of the equations listed below.

a. Air Exchange Rate by Tracer Gas Decay:

In this method, a tracer gas is injected into the room for a certain period of time and then stopped. The decay of the gas is then monitored. Using a simple mass balance of the tracer gas in the room, the decay of the tracer gas with time can be described by Equation 1. In deriving Equation 1, the following assumptions are made: (a) the tracer gas in the room is well mixed, (b) the tracer gas does not get absorbed inside the room, and (c) the background concentration of the tracer gas is zero.

$$C = C_0 e^{-kt} \quad [1]$$

In Equation 1, C is the concentration of the tracer gas at time t , C_0 is the initial concentration of the tracer gas at the start of the decay, k is the air exchange rate, and t is time. Equation 1 can be rearranged to solve for the quantity (kt) as follows:

$$\ln \frac{C}{C_0} = -kt \quad [2]$$

Equation 2 indicates that a plot of the quantity $\ln (C/C_0)$ versus time should be linear and that the air exchange rate (k) will be equal to the slope of this line.

b. Chamber Volume by Constant Injection:

In this method, a tracer gas is injected at a known rate into the room with a known ventilation rate. The gas concentration will eventually reach steady state. Using a simple mass balance of the tracer

gas in the room, the steady state equation reduces to Equation 3. In deriving Equation 3, the following assumptions are made: (a) the tracer gas in the room is well mixed, (b) the tracer gas does not get absorbed inside the room, and (c) the background concentration of the tracer gas is zero.

$$V = \frac{S_v}{C_{ss}k} \quad [3]$$

In Equation 3, V is the volume of the room, S_v is the injection rate of the tracer gas, C_{ss} is the steady state concentration of the tracer gas, and k is the air exchange rate. The volume is calculated directly from Equation 3, assuming that the injection rate, the steady state concentration, and the air exchange rate are all known.

3. TEST EQUIPMENT AND SETUP

This section describes the equipment used in the characterization tests and the general setup of the test equipment.

a. Test Chamber

The test chamber is a modified environmental room manufactured by Hotpack (Appendix B: Figure B1). The internal dimensions of the chamber are approximately 2.44 m (8 ft) wide by 1.83 m (6 ft) deep by 2.13 m (7 ft) high. Access to the inside of the chamber is gained through a magnetically-sealed door. The inner walls of the chamber are constructed from enamel-coated aluminum. Penetrations through the chamber walls were added to allow for the chamber's ventilation system, gas sample lines, tracer gas injection lines, electrical and data lines, and cooling water lines for the heat exchangers. Silicon adhesive, rubber gaskets, and aluminum plates are used to seal any gaps between the chamber walls and the protrusions.

The temperature inside the chamber is measured with five thermocouples located near the five gas sample locations. The temperature can be controlled through heat removal, which is accomplished by passing chilled water through two, 8.79 kW (30,000 Btu/hr) ceiling mounted fin-and-tube heat exchangers located in the chamber (Appendix B: Figure B2). A recirculating chiller located in the building provides chilled water at a constant temperature. The flow rate of chilled water to the heat exchangers is varied using a control valve that is adjusted automatically based on the average air temperature inside the chamber. Each heat exchanger contains two fans that draw air from the center of the chamber, across the heat exchangers, and out toward the walls. Condensate that forms on the heat exchanger fins collects in drip pans and gravity drains to a condensate pump that is located outside of the chamber. An isolation valve is located on the condensate line that prevents CO leakage into the laboratory spaces.

The chamber is equipped with two fans to control the ventilation rate of the chamber. One fan is located in a supply pipe and brings fresh air from the laboratory into the test chamber. The supply air pipe consists of one 10.2 cm (4 in) diameter pipe that, after entering the top of the chamber, tees to two openings, with each opening facing a heat exchanger (Appendix B: Figure B2). The second fan is located in the exhaust pipe and exhausts air out of the chamber into an exhaust hood that vents outdoors. The exhaust piping consists of two 10.2 cm (4 in) diameter pipes inside the chamber that merge to one pipe outside the chamber. One pipe is located at the front left of the chamber and the second pipe is located at the right rear of the chamber. Both pipes exit the top of the chamber and feed the one pipe that empties into a building exhaust hood. The inlets of the exhaust pipe are located 1.14 m (3.75 ft) below the ceiling of the chamber in opposite diagonal corners (left front and right rear). Manually varying the voltage supplied to each fan controls the flow rate of air through the supply pipe and exhaust pipe. The supply and exhaust pipes each contain a manually-operated iris, located outside the chamber that allows further control of the air exchange rate.

The differential pressure between the inside of the chamber and the laboratory is measured with a magnehelic pressure gauge and a digital pressure gauge. The local pressure and temperature in the laboratory is obtained using a barometer with a built in thermometer. The relative humidity of the laboratory air is measured with a digital hygrometer.

b. Tracer Gas Injection System

Carbon monoxide and sulfur hexafluoride (SF_6) are the gases used for the tracer gas injection tests. A known concentration of CO is injected into the chamber at a desired rate using rotometers or a digital mass flow controller. A known concentration of SF_6 is injected into the chamber at a desired flow rate using a digital mass flow controller. The injection lines were located either near the supply air port (high), or at a position (low) that was representative of the exhaust port of several gasoline-fueled portable electric generators. Specific injection locations are noted, as test conditions are discussed later in the report.

c. Gas Sample Analysis Systems

The concentrations of CO and SF_6 are measured using non-dispersive infrared (NDIR) gas analyzers. The analyzer that measures CO is part of a multi-gas analyzer, capable of measuring up to five gases: carbon monoxide, carbon dioxide, oxygen, hydrocarbons, and a second carbon monoxide. Depending on how the multi-gas analyzer is configured, the gases can be measured in series from the same location or in parallel from different locations. For the characterization tests, the multi-gas analyzer was used to measure CO only. Gas samples were obtained from several locations, including the chamber, the exhaust pipes, and the laboratory. Two separate sampling systems are used to obtain gas samples from different locations in the chamber. Appendix C provides details of the equipment used and a schematic illustrating the sampling systems.

One gas sampling system measures the concentration of CO and SF_6 inside the chamber. Gas samples are obtained from five different locations inside of the chamber and are blended using a gas-mixing manifold. The sample points are located at the following approximate coordinates: (0.74 m, 1.80 m, 0.41 m), (2.06 m, 0.61 m, 0.56 m), (1.83 m, 1.22 m, 1.30 m), (0.43 m, 0.53 m, 1.30 m), and (1.14 m, 0.91 m, 0.90 m) from the (0, 0, 0) coordinate ¹. The five lines inside the chamber are the same length from the gas-mixing manifold that is also located inside the chamber. A high flow rate pump draws the sample from the gas-mixing manifold into a recirculation line. The recirculation line leaves the chamber at the front of the chamber's ceiling, goes through a large pump, runs down the outer wall of the chamber and reenters the chamber near the floor. A single sample line branches from the recirculation line near the centerline of the chamber. The branching line conveys a small portion of the recirculation line sample to the gas analyzers, which are plumbed in series. Water vapor is condensed out of the sample prior to entering the analyzers using a cold trap. The cold trap consists of a simple chilled-water heat exchanger.

The second sampling system measures the background concentration of CO in the laboratory or the concentration of CO in either of the exhaust pipes. Several three-way valves are used to switch between drawing the sample from the laboratory or from the exhaust pipes. The CO analyzer for this second sampling system is part of the same multi-gas analyzer used in the first sampling system.

During several of the tests, a second multi-gas gas analyzer was available. With this unit in place, the CO concentration in the chamber and in each exhaust pipe could be measured simultaneously.

¹ Using a right handed coordinate system, the (0,0,0) coordinate is located at the rear (side opposite the entry door), leftmost (assuming the reader is inside the chamber with his back to the door), bottom inner corner of the M-Chamber)

All of the sample lines consist of 0.64 cm (1/4") stainless steel tubing and polyethylene tubing, except the recirculation line which is 0.95 cm (3/8") and made of copper tubing. Polyethylene tubing was selected, as it will not absorb CO or SF₆. The connecting fittings are made of brass and stainless steel.

d. Data Acquisition System

A data acquisition system (DAS) records the majority of test data. The system consists of a personal computer running TESTPOINT™ data acquisition software. The data is acquired at a rate between 10 seconds to 5 minutes, depending on the air exchange rate and the duration of the test. The data acquisition program records the raw voltage output from the various measuring devices (gas analyzers and thermocouples) into a data file. The data acquisition program then converts these voltage readings directly into the appropriate engineering units for concentration (percent or parts per million) and temperature (degrees Celsius). These converted values are recorded in the same data file as the raw voltages. In addition to obtaining the data electronically, these values are periodically recorded manually in a logbook during testing. The flow rates of the injection gases (CO and SF₆), the differential pressure between the chamber and laboratory, and the barometric pressure, temperature and relative humidity of the laboratory are recorded manually. Future upgrades to these sensors and the data acquisition system software will allow for these parameters to be automatically recorded.

4. TESTS PROCEDURES

This section describes the chamber operation test procedures in detail. Although the following discussion is divided into separate tests (e.g., air exchange rate, chamber mixing, etc.), several of the separate tests were often combined during an actual test. Therefore, a single test may be used for several different evaluations.

a. Common Test Procedures

Upon receipt of each gas analyzer, the linearization of the analyzer was checked at 10 points. If the error was greater than 1 percent full scale across the entire range, a new curve was made or the analyzer was returned to the manufacturer for maintenance. A factory-authorized technician performs on-site maintenance on the analyzers twice a year.

At the start of each day, each gas analyzer was calibrated according to the instructions specified by the manufacturer of the analyzer. In general, the gas analyzers were zeroed with nitrogen gas and spanned using a certified calibration gas of known concentration. The analyzers were also checked at mid- and low-range concentrations to verify the performance of the analyzers. The sample line conveys all sample and calibration gases to the analyzers at an approximate flow rate of 0.8 slpm (1.7 ft³/hr) and pressure of less than 6.90 kPa (1 psi).

Since the characterization tests were performed without any type of combustion appliance operating in the chamber, no heat removal was performed. However, the fans on the heat exchangers were still operated, since the fans provided mixing inside of the chamber. When the mixing fans were operated over a long period of time they tended to increase the temperature in the test chamber. Tests were conducted at ambient temperatures, which ranged from 20°C to 30°C (68°F to 86°F).

The ventilation rate of the chamber was set by first opening or closing the irises on the exhaust and the supply air pipes. Next, the exhaust fan's voltage was adjusted to the desired setting. Finally, the supply fan's voltage was adjusted until the desired differential pressure was achieved. The differential pressure of the chamber remained constant during each test.

Once the chamber ventilation was set, the data acquisition program was started and the tracer gas was injected into the chamber. Since the M-chamber was being configured to test portable gasoline-powered electric generators, carbon monoxide was injected at a rate that was expected to be representative of the CO emission rates from such equipment. Sulfur hexafluoride was injected at a

rate that would provide a desired steady state concentration at the anticipated air exchange rate. The tracer gases were injected until a steady state concentration was reached. Steady state was assumed once the variation between concentrations was less than 1 percent over a period that coincided with the inverse of the air exchange rate. Therefore, at lower air exchange rates, a longer time was required to establish equilibrium.

If the steady state concentration was high enough to provide adequate decay information for air exchange rate determination, the tracer gas injection was terminated and the decay was recorded. If not, the tracer gas injection rate was increased so as to achieve a higher concentration and thus an adequate decay time.

The test was complete once the concentration of the CO and/or SF₆ was less than 2 percent of the gas analyzer's full-scale value. The data acquisition program was then stopped, and the chamber was allowed to ventilate completely before beginning the next test. As a back up to the electronic data, the concentration data were recorded manually at various times during each test. When the three-way valves were switched to toggle between drawing the sample from the laboratory, front left exhaust pipe, or the rear right exhaust pipe, the time was also recorded manually.

b. Chamber Mixing Tests

A series of tests were conducted to determine how well mixed the gases were inside the chamber. Carbon monoxide was used as the tracer gas, since CO could be measured at up to four locations simultaneously with the two multi-gas analyzers. The tracer gas concentrations inside the exhaust pipes and inside the chamber were measured at steady state conditions. If the chamber is well mixed, the tracer gas concentration at all three locations should be equivalent at any time. The tests evaluated mixing as affected by the following three variables: (1) air exchange rate, (2) location of the tracer gas injection, and (3) the rate at which the tracer gas was injected. Tests were conducted at two conditions for each variable: low and high. Table 4.1 lists the low and high values for each of the three test variables. These values were considered representative of the extremes to be expected while testing gasoline-fueled portable electric generators. Tests were initially conducted at a slightly positive differential chamber pressure, but were then performed at a slightly negative differential pressure due to leakage of CO from the chamber. Mixing fans were on for all tests.

Table 4.1. Low and high values for the test variables of the mixing test

Test Variables	Low Value	High Value
Air Exchange Rate	1.5 to 5 ACH	24 to 30 ACH
Tracer Gas Injection Position	0.31 to 0.61 m above chamber floor	0.31 m below chamber ceiling
Tracer Gas Injection Rate	0.15 slpm CO	1 to 10 slpm CO depending on ACH

The test variables listed in Table 4.1 were combined to form a test matrix that is shown in Table 4.2.

Table 4.2 Test matrix for determining how well mixed the gases were inside the chamber

Test Variable		
Air Exchange Rate	Tracer Gas Injection Position	Tracer Gas Injection Rate
Low	Low	Low
Low	Low	High
High	Low	High
High	Low	Low
High	High	Low
High	High	High
Low	High	High
Low	High	Low

c. Air Exchange Rate Tests

Tracer gas decay data were used to determine the air exchange rates for different test conditions. The air exchange rate was evaluated using both CO and SF₆ as the tracer gases. Tests were conducted at differential pressure ranging from 0 to -6.27 mm w.c. (0 to -0.25 in w.c.), and at a number of fan voltage settings and iris settings. Table 4.3 provides a summary of the test matrix for the air exchange rate tests.

Table 4.3 Test matrix for the air exchange rate tests

Iris Settings		Exhaust Fan Setting (volts)	Differential Pressure ¹ (mm w.c.)
Supply	Exhaust		
Open	Open	15	-1.27
Open	Open	12	-1.27
Open	Open	10	-1.27
Open	Open	8	-1.27
Open	Open	6	-1.27
Closed	Closed	7.22	-1.27
Open	Open	15	-6.35
Open	Open	10	-6.35
Open	Open	7.49	-6.35
Closed	Open	4.86	-6.35
Closed	Closed	15	-3.81
Closed	Closed	0	0.00

1. The differential pressure between the chamber and the surrounding room was obtained by adjusting the irises and the voltage of the exhaust fan to the desired settings. The voltage of the supply fan was then adjusted to achieve the desired differential pressure.

d. Chamber Volume Determination

The chamber volume was estimated using two methods: (1) physical measurements, and (2) analysis of constant injection data of the tracer gases.

i) Physical Measurement

The physical measurement of the chamber consisted of measuring the width, height, and depth of the chamber five times on three different days with a tape measure. These measurements were then used to calculate the overall volume of the chamber. Since the heat exchangers and the exhaust pipes were located inside the chamber, these items decreased the overall volume of the chamber. Therefore, an attempt was made to account for these items. The exhaust pipes were measured twice, and the overall heat exchangers dimensions were measured three times. Since spaces exist between the fins of the heat exchangers, only fifty percent of the volume of the heat exchangers was subtracted from the overall chamber volume.

ii) Constant Injection

Steady state injections of SF₆ were used to estimate the volume of the chamber. The volume was established by running several tests at the same air exchange rate. Tests were conducted at an air exchange rate of 5 ACH, since it was thought that better mixing would occur inside the chamber at the lower air exchange rates. For comparison purposes, tests were conducted at air exchange rates greater than and less than 5 ACH. Tests were also performed with CO to determine how the air exchange rates estimated using the CO decay data compared to the air exchange rate calculated using the SF₆ decay data.

5. DATA REDUCTION

This section describes how the raw data collected during the tests was reduced into useful information.

a. Equilibrium

Data from the data acquisition program were imported into a Microsoft® Excel spreadsheet. The concentrations of CO and SF₆ in the chamber were then plotted versus time in order to determine when equilibrium was achieved. Steady state was assumed once the variation between concentrations was less than 1 percent over a period that coincided with the inverse of the air exchange rate.

Once equilibrium was established, the average values for all of the data were calculated. If necessary, the CO and SF₆ concentrations were corrected for any background concentrations present in the laboratory after equilibrium was achieved and 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 for the chamber was calculated from the decay of the tracer gases. As explained in Section 2 of this paper, the following equation is used to calculate the air exchange rate from the decay of the tracer gas data. A detailed derivation of Equation 2 is provided in Appendix A.

$$\ln \frac{C_t}{C_o} = -kt \quad [2]$$

In Equation 2, C_t is the concentration of the tracer gas at time t , C_o is the initial concentration of the tracer gas at the start of the decay, k is the air exchange rate, and t is time. Equation 2 indicates that a plot of the quantity $\ln (C_t/C_o)$ versus time (t) should be linear and that the air exchange rate (k) will be equal to the slope of this line. Since the line should be linear, linear regression can be used to fit a line to the data. An expression describing how well the line fits the data is the R^2 term, where R is the

correlation coefficient. An R^2 value of 1.0 indicates that the line obtained by linear regression fits the data perfectly. For most tests, a linear regression was performed on the tracer gas decay data and the air exchange rate was obtained from the slope of this line. Otherwise, the air exchange rates were obtained through a direct application of Equation 2 to the test data.

c. Volume

The volume of the chamber was calculated from the steady state concentration of the tracer gas. The following equation is used to calculate the volume. A detailed derivation of Equation 3 is provided in Appendix A.

$$V = \frac{S_v}{C_{ss} k} \quad [3]$$

In Equation 3, S_v is the rate of tracer gas injection, C_{ss} is the steady state concentration of the tracer gas, and k is the air exchange rate.

d. Steady State Concentration

Equation 3 can be rearranged to solve for the steady state concentration.

$$C_{ss} = \frac{S_v}{Vk} \quad [4]$$

The tracer gas injection rate (S_v), the room volume (V), and the air exchange rate (k) must all be known in order to calculate the steady state concentration of the injection gas.

6. RESULTS & DISCUSSION

Table D1 in Appendix D provides a summary of the test data. The table includes the following information: the chamber pressure; the voltage of the exhaust fan; the position of the iris in the supply pipe and in the exhaust pipe; the steady state injection rate of SF₆ and/or CO; the steady state concentration of SF₆ in the chamber; and the steady state concentration of CO in the chamber, the exhaust pipes, and in the laboratory. The only data not provided in Appendix D is the SF₆ and/or CO concentration decay data. If a decay test was performed, the calculated air exchange rates are provided in the table.

Example:

For Test Number 13, conducted at a chamber differential pressure relative to the lab of -1.27 mm w.c. with both the supply and exhaust vents completely open, the exhaust fan powered with 15 V, and respective injection rates of SF₆, and CO of 5460 cc/hr, and 600,000 cc/hr, the concentrations of SF₆ and CO in the chamber averaged 20.65 ppm and 2121 ppm, respectively at equilibrium.

a. Chamber Mixing

The M-chamber is being configured to test gasoline-fueled portable electric generators. It is anticipated that the chamber will operate at air exchange rates up to 30 ACH. At this high air exchange rate, it is not known whether the combustion products released from the generator will have sufficient time to mix within the chamber or whether the combustion gases will be exhausted prior to being properly mixed. If the gases are exhausted from the chamber prior to being properly mixed, then the gas concentration in the exhaust pipes may be greater than the gas concentration in the chamber. To determine if the chamber is well mixed, tests were conducted in which the concentration of the tracer gas was measured in the exhaust pipes and compared to the concentration of the tracer gas in the chamber. The sample from the chamber was a mixed-average of five samples, which was representative of the overall gas concentration within the chamber.

The first series of mixing tests were conducted with the supply fan and exhaust fan set at the same voltage. This resulted in the chamber being operated at a slightly positive differential pressure of 0.635 mm w.c. (0.025 in w.c.) relative to the laboratory. Two multi-gas analyzers were available for these tests, which allowed CO to be measured simultaneously in the chamber and in each exhaust pipe. All of the tests listed in Table 4.2 were performed at least once. A summary of the test results is provided in Table 6.1. When the CO concentration in each exhaust pipe was compared to the CO concentration in the chamber, the difference was less than 10 percent for each test. A greater error occurred at the lower CO concentrations and was most likely caused by the analyzer being less accurate at the lower end of its operating range. Since the CO concentrations in the exhaust pipes were similar to that in the chamber, the chamber appears to be well mixed at the conditions tested. The four fans that circulate air over the two heat exchanger coils most likely cause this well-mixed environment.

A second series of tests were conducted with the test chamber operating at a slightly negative pressure relative to the laboratory. Differential pressures ranged up to -6.35 mm w.c. (-0.25 in w.c.). The chamber pressure was maintained negative after some CO leakage was detected. The leakage occurred during tests where the chamber was operated at a positive pressure and a very high concentration of CO was present inside the chamber. Prior to these tests, one of the multi-gas analyzers had been removed from the test setup and replaced with an SF₆ analyzer. Therefore, simultaneous sampling of CO could only be accomplished from two locations instead of three locations. A valve was added between the exhaust pipe sample lines so that a gas sample could be obtained from either exhaust pipe. Due to time limitations, only a limited number of tests were conducted. Tests were primarily conducted with all three of the test variables at their maximum setting. A summary of the test results is provided in Table 6.2. When the CO concentration in each exhaust pipe was compared to the CO concentration in the chamber, the difference was less than 6 percent for each test. Therefore, the chamber still appeared to be well mixed at the test conditions tested.

Table 6.1 Summary of first series of mixing tests: Differential Pressure = +0.635 mm w.c.

Test #	Test Variable			CO Concentration (ppm)			Percent Difference (Exhaust relative to chamber)	
	ACH	Tracer Gas Injection		Chamber	Exhaust		Exhaust	
		Position	Rate		Left	Right	Left	Right
1	L	L	L	542	545	551	0.6	1.7
2	L	L	H	3804	3825	3842	0.6	1.0
3	H	L	H	287	259	284	-9.8	-1.0
4	H	L	L	57	53	58	-7.0	1.8
5	H	H	L	51	48	55	-5.9	7.8
6	H	H	H	264	243	289	-8.0	9.5
7	L	H	H	3352	3386	3439	1.0	2.6
8	L	H	L	536	533	544	-0.6	1.5
9	L	H	L	595	598	608	0.5	2.2
10	L	H	H	3725	3770	3805	1.2	2.1
11	H	L	H	2440	2458	2478	0.7	1.6
12	H	L	H	2604	2598	2550	-0.2	-2.1

Table 6.2 Summary of second series of mixing tests: Differential Pressure = -1.27 to -6.35 mm w.c.

Test #	Test Variable			CO Concentration (ppm)			Percent Difference (Exhaust relative to chamber)	
	ACH	Tracer Gas Injection		Chamber	Exhaust		Exhaust	
		Position	Rate		Left	Right	Left	Right
13	H	H	H	2121	2103	2218	-0.8	4.6
14	H	H	H	3027	*	3152	*	4.1
15	H	H	H	4676	4649	4810	-0.6	2.9
17	H	H	H	2560	2445	2668	-4.5	4.2
19	H	H	H	2203	2156	2336	-2.1	6.0
20	H	H	H	3409	3347	3505	-1.8	2.8
22	L	H	H	4080	*	4121	*	1.0

* Not measured

A third series of tests were conducted, similar to the second series of tests, but with the CO injected at a position relatively low and to the left of the center of the chamber. This injection position was selected since it is similar to the exhaust location on several of the gasoline-fueled portable electric generators that will be tested in the chamber. Due to time limitations, only a limited number of tests were conducted. A summary of the test results is provided in Table 6.3. The relative error between the CO concentration in the chamber and the CO concentration in each exhaust pipe was less than 9 percent for all tests. Therefore, the chamber still appeared to be well mixed at the test conditions tested.

Table 6.3 Summary of third series of mixing tests: Differential Pressure = -1.27 mm w.c.; Tracer Gas Injection Port Moved to more Closely Match Exhaust from Engine Generators

Test #	Test Variable			CO Concentration (ppm)			Percent Difference (Exhaust relative to chamber)	
	ACH	Tracer Gas Injection		Chamber	Exhaust		Exhaust	
		Position	Rate		Left	Right	Left	Right
34	L	L	H	5017	4973	4954	-0.9	-1.3
35	H	L	H	1623	1728	1739	6.5	7.1
36	L	L	H	4811	5202	5186	8.1	7.8

b. Air Exchange Rate

Decay tests were performed with both CO and SF₆ as the tracer gases to determine the range of air exchange rates for the test chamber. Based on Equation 2, the data was plotted and a linear line was fit to the data. The R² term, which is an indication of how well the line fit the data, was 0.999 or better for all tests. Table 6.4 provides a summary of the test results. The air exchange rates ranged from 0.12 ACH to 28.3 ACH, depending on the exhaust fan voltage setting and the settings of the irises. With the exception of one test, the air exchange rate calculated from the CO decay data agreed within 7 percent of the air exchange rate calculated from the SF₆ decay data.

Table 6.4 Summary of air exchange rate tests

Test #	Iris Settings		Exhaust Fan Setting (volts)	Differential Pressure ¹ (mm w.c.)	Air Exchange Rate (1/hr)		Percent Difference ¹
	Supply	Exhaust			SF ₆	CO	
13	Open	Open	15	-1.27	28.0	28.3	1.07
17	Open	Open	12	-1.27	23.9	24.4	2.09
14	Open	Open	10	-1.27	20.0	21.0	5.00
18	Open	Open	8	-1.27	16.8	17.1	1.79
15	Open	Open	6	-1.27	11.5	12.2	6.09
16	Closed	Open	2.3	-1.27	1.77	1.82	2.82
22	Closed	Closed	7.22	-1.27	1.65	1.61	-2.42
19	Open	Open	15	-6.35	26.5	28.0	5.66
20	Open	Open	10	-6.35	17.3	18.4	6.36
23	Open	Open	7.49	-6.35	10.7	12.0	12.15
24	Closed	Open	4.86	-6.35	3.84	3.81	-0.78
25	Closed	Closed	15	-3.81	2.66	2.77	4.14
21	Closed	Closed	0	0.00	0.12	0.12	0.00

¹ Air exchange rate by CO decay relative to air exchange rate by SF₆ decay.

c. Chamber Volume

The chamber volume was calculated by physical measurement and from the constant injection of the tracer gas.

i) Physical Measurement

The averaged values of tape measured height, depth, and width dimensions of the chamber interior were used to calculate the gross chamber volume as 9.71 m³ (343 ft³). The free space (net volume) of the chamber was determined by subtracting the calculated volumes of the internal heat exchangers and exhaust piping from the gross chamber internal volume. The net heat exchanger volume was estimated to be 50% of gross heat exchanger volume based on the amount of free air space within the heat exchanger. As a result, free space (net volume) in the chamber was determined to be 9.53 m³ (336 ft³).

ii) Constant Injection Tests

Constant injection tests were performed to determine the volume of the chamber. The first series of tests were conducted with SF₆ as the tracer gas and the air exchange rate was approximately 5 ACH. An air exchange rate of 5 ACH was selected since it was thought that better chamber mixing would occur at a lower air exchange rate. A lower air exchange rate was not used due to time limitations. Table 6.5 provides a summary of the test results. The volume was calculated using Equation 3 and the air exchange rate used in that equation was determined from the decay of the tracer gas for that test. The average volume of the four tests was 9.59 ± 0.10 m³ (339 ± 4 ft³). Therefore, the volume determined from steady state injection was 0.63 % greater than the volume estimated by physical measurement. A volume of 9.59 m³ (339 ft³) will be used as the net volume in the chamber for all future calculations. This is considered to be the most accurate measure of volume, based upon the measurement uncertainties associated with each method.

Table 6.5 Volume obtained steady state injection of SF₆ at an air exchange rate of 5 ACH.

Test #	Injection Rate (cc/hr)	Steady State Concentration (ppm)	Measured Air Exchange Rate (1/hr)	Calculated Volume (m ³)
26	3071	62.64	5.05	9.71
27	3079	64.17	5.06	9.48
31	3079	63.83	5.06	9.54
36	2978	64.13	4.83	9.61
Average ± Standard Deviation				9.59 ± 0.10

Table 6.6 provides a summary of the volumes calculated from steady state injection tests with SF₆ as the tracer gas, but at various air exchange rates ranging from 1.71 ACH to 30.2 ACH. The average volume for these tests was 9.46 ± 0.17 m³, which was within one standard deviation from the average volume calculated for the tests at a constant air exchange rate (Table 6.5).

Table 6.7 provides a summary of the volumes calculated from steady state injection tests with CO as the tracer gas and at various air exchange rates. The average volume for these tests was 9.61 ± 0.28 m³, which was within one standard deviation from the average volume calculated for the tests at a constant air exchange rate (Table 6.5).

Table 6.6 Volume obtained by steady state injection of SF₆ at various air exchange rates

Test #	Injection Rate (cc/hr)	Steady State Concentration (ppm)	Measured Air Exchange Rate (1/hr)	Calculated Volume (m ³)
32	911	54.27	1.71	9.82
36	2978	64.13	4.83	9.61
26	3071	62.64	5.05	9.71
27	3079	64.17	5.05	9.50
31	3079	63.83	5.06	9.53
33	911	18.22	5.42	9.23
28	3079	30.09	10.7	9.56
15	5460	50.47	11.53	9.38
17	5460	24.73	16.81	9.23
20	5460	33.62	17.28	9.40
29	3079	15.75	19.9	9.81
14	5460	28.80	19.98	9.49
19	5460	21.93	26.54	9.38
13	5460	20.65	28.03	9.43
30	3079	10.92	30.2	9.35
Average ± Standard Deviation				9.46 ± 0.17

Table 6.7 Volume obtained by steady state injection of pure CO at various air exchange rates

Test #	Injection Rate (cc/hr)	Steady State Concentration (ppm)	Measured Air Exchange Rate (1/hr)	Calculated Volume (m ³)
22	60,000	4080	1.61	9.13
36	234,000	4811	4.82	10.01
34	234,000	5017	4.91	9.50
15	540,000	4676	12.2	9.47
20	600,000	3409	18.39	9.57
14	600,000	3027	20.95	9.46
17	600,000	2560	24.44	9.59
19	600,000	2203	27.96	9.74
13	600,000	2121	28.27	10.0
Average ± Standard Deviation				9.61 ± 0.28

d. Steady State Concentration

The theoretical steady state concentration of the tracer gas can be calculated from Equation 4, if the following are known: the steady state injection rate of the tracer gas, the air exchange rate, and the volume of the room. Comparing the actual tracer gas concentration to the theoretical tracer gas concentration provides a means for determining the overall accuracy of the injection and measuring system. The tracer gas injection rate was obtained directly from the flow meter, the air exchange rate was calculated from the decay data, and the volume was calculated from the steady state concentration data (Table 6.5). For the following calculations, a volume of 9.59 m³ (339 ft³) was used.

Table 6.8 lists the theoretical and actual steady state concentrations of SF₆ for several tests that encompass a large range of measured air exchange rates. For these tests, the difference between the actual and theoretical concentrations was less than 4 percent.

Table 6.8 Comparison of the actual steady state concentration of SF₆ to the theoretical steady state concentration.

Test #	Injection Rate (cc/hr)	Air Exchange Rate (1/hr)	Steady State Concentration (ppm)		Percent Difference (%)
			Actual	Theoretical ¹	
36	2978	4.83	64.13	64.29	-0.3
15	5460	11.53	50.47	49.38	2.2
20	5460	17.28	33.62	32.95	2.0
14	5460	19.98	28.80	28.50	1.0
17	5460	23.92	24.73	23.80	3.8
19	5460	26.54	21.93	21.45	2.2
13	5460	28.03	20.65	20.31	1.7

1. Theoretical calculation based on a room volume of 9.59 m³.

Table 6.9 lists the theoretical and actual steady state concentrations of CO for the same tests as shown above (Table 6.8). For these tests, the maximum difference between the actual and theoretical concentrations was 5 percent.

Table 6.9 Comparison of the actual steady state concentration of CO to the theoretical steady state concentration.

Test #	Injection Rate (cc/hr)	Air Exchange Rate (1/hr)	Steady State Concentration (ppm)		Percent Difference (%)
			Actual	Theoretical ¹	
36	234,000	4.82	4811	5062	-5.2
15	540,000	12.2	4676	4615	1.3
20	600,000	18.39	3409	3402	0.2
14	600,000	20.95	3027	2986	1.4
17	600,000	24.44	2560	2560	0.0
19	600,000	27.96	2203	2238	-1.6
13	600,000	28.27	2121	2213	-4.3

1. Theoretical calculation based on a room volume of 9.59 m³.

The data in Tables 6.8 and 6.9 compare the steady state concentrations of SF₆ and CO to the theoretical steady state concentrations. Figures 6.1 and 6.2 compare the experimental transient concentrations of SF₆ and CO to the theoretical transient concentrations. As the figures illustrate, the experimental data tracks the theoretical data closely as the concentration increases to its steady state value.

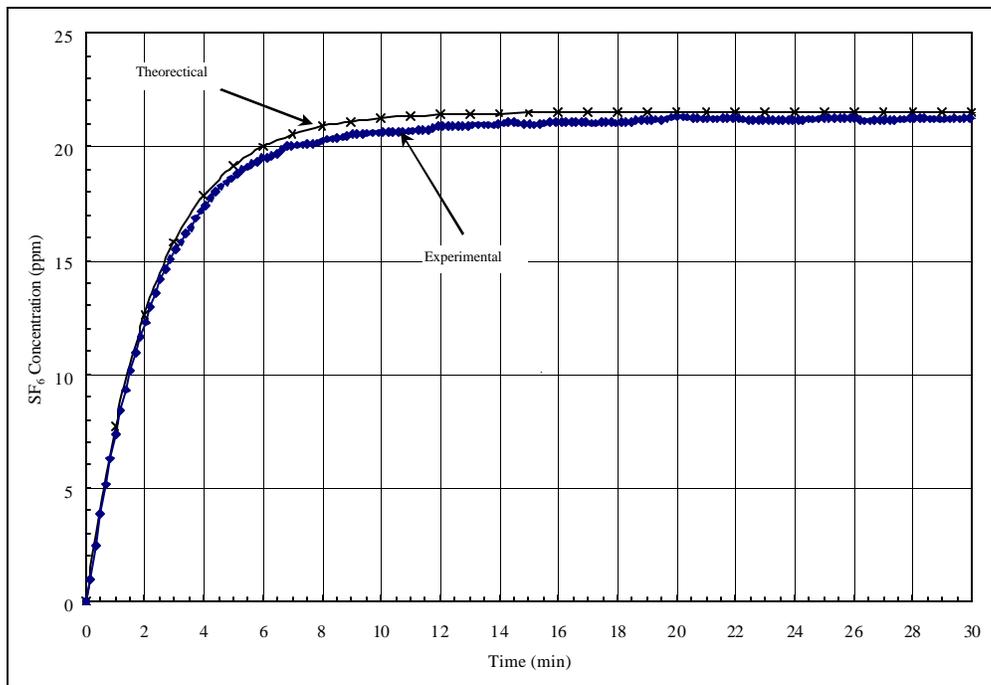


Figure 6.1 Theoretical and experimental SF₆ concentrations as a function of time. Data is from Test #19. Theoretical concentrations are based on a volume of 9.59 m³ and an injection rate of 5460 cc/hr.

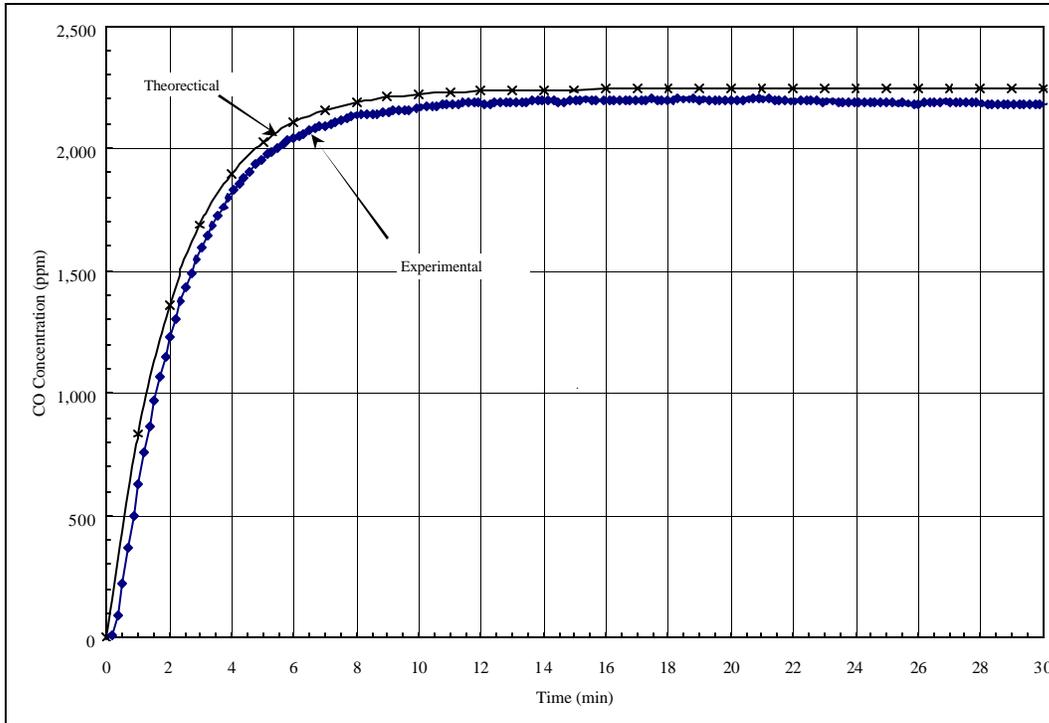


Figure 6.2 Theoretical and experimental CO concentrations as a function of time. Data is from Test #19. Theoretical concentrations are based on a volume of 9.59 m³ and an injection rate of 600,000 cc/hr.

Another approach to determining the overall accuracy of the injection and measuring system is to consider the ratio of the air exchange rates to the ratio of the concentrations. If two different constant injection tests are performed in the same room, then the following expression can be written by using Equation 3, since the volumes are the same.

$$\frac{S_1}{C_{1ss}k_1} = \frac{S_2}{C_{2ss}k_2} \quad [5]$$

If the injection rate is the same in each test ($S_1 = S_2$), Equation 5 can be reduced and rearranged as follows.

$$\frac{k_2}{k_1} = \frac{C_{1ss}}{C_{2ss}} \quad [6]$$

Therefore, an increase in the air exchange rate will result in a decrease in the steady state tracer gas concentration by an equal amount. For example, if the air exchange rate is increased by a factor of 10, then the tracer gas concentration will decrease by a factor of 10.

Four tests were conducted with SF₆ as the tracer gas at an injection rate of 3079 cc/hr. The air exchange rates for the tests were approximately 5, 10, 20, and 30 ACH. Table 6.10 provides a summary of the test results.

Table 6.10 Summary of tests comparing the increase in the air exchange rate to the decrease in the concentration. SF₆ tracer gas injected at 3079 cc/hr.

Test #	Air Exchange Rate (1/hr)	Steady State Concentration (ppm)	Factor of ACH Increase Relative to Test #27	Factor of Concentration Decrease Relative to Test #27	Percent Difference (%)
27	5.05	64.17	NA	NA	NA
28	10.7	30.09	2.12	2.13	0.47
29	19.9	15.75	3.94	4.07	3.19
30	30.1	10.92	5.97	5.88	-1.53

As illustrated in Table 6.10, the concentration decreased approximately the same amount that the air exchange increased relative to the test conducted at 5 ACH (Test 27). If there were problems with mixing in the chamber, then as the air exchange rate increased, the concentration would not decrease by an equivalent amount. For these tests, the maximum difference between ratios was less than 4 percent.

e. Chamber Leakage

Initially, the chamber was operated at a slightly positive pressure relative to the laboratory, since this allowed for the greatest range of air exchange rates. Normally during combustion tests (in the other chambers and with other appliances), background CO concentrations in the laboratory are less than 7 ppm. However, during some preliminary testing of gasoline-fueled portable electric generators, it was discovered that CO was leaking out of the chamber at an unacceptable rate resulting in elevated background CO concentrations (>35 ppm). This occurred when the CO concentration was greater than 3000 ppm inside of the chamber. Therefore, it was decided that the chamber would be operated at a negative pressure in all future tests. Tests were conducted at a differential chamber pressure of -1.27 mm w.c. (-0.05 in w.c.) and -6.35 mm w.c. (-0.25 in w.c.) with different concentrations of CO inside the chamber and the background CO concentration was measured. Table 6.11 provides a summary of the test results. As Table 6.11 illustrates, the leakage is similar at a differential pressure of -1.27 mm w.c. (-0.05 in w.c.) and -6.35 mm w.c. (-0.25 in w.c.). A wider range of air exchange rates is obtained at -1.27 mm w.c. (-0.05 in w.c.) than compared to -6.35 mm w.c. (-0.25 in w.c.). Background CO concentrations still remained above 7 ppm due to: 1) exhaust system leakage, and (2) infiltration of CO from outdoors. Future tests will be conducted at both differential pressures. Residential CO alarms are located throughout the lab to warn staff of excessive CO concentrations.

Table 6.11 Summary of chamber leakage tests

Test #	Differential Pressure (mm w.c.)	Chamber CO Concentration (ppm)	Background CO Concentration (ppm)
13	-1.27	2121	10.2
17	-1.27	2560	15.3
14	-1.27	3027	12.1
22	-1.27	4080	18.5
15	-1.27	4676	6.7
19	-6.35	2203	13.3
20	-6.35	3409	16.1

7. CONCLUSIONS

A series of tests were performed to characterize the M-chamber with respect to ventilation rates (i.e., air exchange rate) and chamber volume, and to determine how well mixed the gases were within the chamber. The air exchange rate was determined by the tracer gas decay method and the volume of the chamber was determined by the constant injection tracer gas technique. The chamber must be well mixed in order to use either of these techniques.

To determine if the chamber was well mixed, the tracer gas concentrations in the two exhaust pipes were compared to the average tracer gas concentration in the chamber. Three variables were considered during these mixing tests: the air exchange rate, the tracer gas injection position, and the tracer gas injection rate. High and low values were selected for each test variable, which were representative of the conditions to be expected while testing gasoline-fueled portable electric generators (the first product to be tested in the M-chamber). Carbon monoxide was used as the tracer gas, since CO could be measured simultaneously from several different locations. Based on the test results, the CO concentration in each exhaust pipe differed by less than 10 percent from the CO concentration in the chamber. Therefore, the chamber appeared to be well mixed. The four fans that circulate air over the two heat exchanger coils inside the chamber most likely caused this well-mixed environment.

Decay tests were performed with both CO and SF₆ as the tracer gases to determine the range of air exchange rates for the test chamber. Depending on the exhaust fan voltage setting, the settings of the irises, and the differential pressure between the chamber and the laboratory, the air exchange rates ranged from 0.12 ACH to 28.3 ACH. With the exception of one test, the air exchange rate calculated from the CO decay data agreed within 7 percent of the air exchange rate calculated from the SF₆ decay data. This indicates that accurate air exchange rates are consistently obtained from SF₆ and CO decay data.

The chamber volume was determined by physical measurement and by the constant injection tracer gas technique. The net volume of the chamber is the overall internal volume of the chamber less any other items inside of the chamber that occupy space, such as the heat exchangers and exhaust pipes. The net volume by physical measurement was 9.53 m³ (336 ft³) and the net volume by constant injection of SF₆ was 9.59 m³ (339 ft³). The constant injection tests were performed at an air exchange rate of 5 ACH. Constant injection tests were also performed with SF₆ at air exchange rates from 1.71 ACH to 30.2 ACH, which resulted in a net volume of 9.46 m³. Constant injection tests were also performed with CO at air exchange rates from 1.61 ACH to 28.3 ACH, which resulted in a net volume of 9.61 m³. Therefore, all of the volumes determined by the constant injection technique were within 3 percent of volume determined by physical measurement. The volume of 9.59 m³ (339 ft³) as determined by SF₆ injection will be used as the net volume in the chamber for all future calculations.

In order to determine how well the overall injection and measuring systems were performing, the actual steady state tracer gas concentration was compared to the theoretical steady state concentration. The difference between the actual and theoretical chamber concentrations was less than 5 percent at steady state conditions, for both the CO and SF₆ tracer gases. This indicates that the injection and measuring systems are acceptable.

Another approach to determining the overall accuracy of the injection and measuring systems is to consider the ratio of the air exchange rates to the ratio of the concentrations. An increase in the ratio of the air exchange rate will result in a decrease in the ratio of steady state tracer gas concentration by an equal amount. For these tests, the maximum difference between ratios was less than 4 percent. This indicates good mixing across a range of air exchange rates.

Tests were also performed at different chamber pressures to determine how the leakage of CO from the chamber was affected. The initial characterization tests were performed with the chamber at a slightly positive differential pressure. However, subsequent tests were performed with the chamber at a slightly negative pressure due to safety concerns. Tests at either a differential pressure of -1.27 mm w.c. (-0.05 in

w.c.) or -6.35 mm w.c. (-0.25 in w.c.) were adequate to prevent the room concentrations of CO from exceeding 35 ppm.

The maximum CO generation rate that the M-Chamber sample system can measure is approximately 2,200,000 cc/hr.² Under certain test conditions, some generators will produce CO in excess of this rate. The M-Chamber and the associated test systems are very well suited to measure the expected concentrations of most of the products that are expected to be tested in the chamber. They are not fully suited to measure the concentrations of some generators when tested under the full range of test conditions that could be applied. There were two noticeable issues: (1) temperatures below 13.6°C (57 °F) could not be attained with certain generator sizes, and (2) the ACH had to be high (29h⁻¹) for CO concentrations to not exceed analyzer range and lab safety guidelines. Both issues limited testing. For purposes of determining the maximum source strength for the generators under all test conditions, including low ACH or low temperature, the test systems are not as robust as desired. A larger chamber and/or an extended analyzer range would make the system more suitable for measuring the maximum CO concentrations, and generation rates from generator testing under all potential test conditions. However, some of the extreme test conditions may remain unfeasible due to laboratory safety concerns. In summary, for purposes of determining severe health risks associated with generators, the CPSC staff believes that the M-Chamber and associated test systems are quite sufficient and that this system is a good compromise of cost, suitability and flexibility.

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Programming: Dean LaRue

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² This maximum was determined using the maximum ACH that can be maintained by the system and the CO value that can be measured by the laboratory analyzers.

APPENDIX A: DERIVATION OF EQUATIONS

The following is the derivation of the equations (Equations 1, 2 and 3 in the report) used to calculate the air exchange rate from the tracer gas decay tests and the volume from the constant injection tests.

Chamber Model

The chamber can be modeled as a 1-zone system. Figure A.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_m) 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 mass flow of air into (m_{in}) and out of (m_{out}) the chamber.

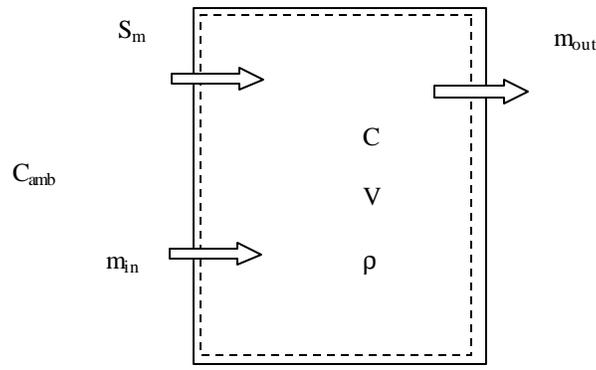


Figure A1. Chamber modeled as a 1-zone system.

In Figure A1, C_{amb} is the ambient concentration of tracer gas, C is the concentration of tracer gas in the chamber, m_{in} is the mass flow of air into the chamber, m_{out} is the mass flow of air out of the chamber, S_m is the source strength (i.e. injection rate), V is the volume of the chamber, and ρ is the density of air in the chamber.

Mass Balance of Tracer Gas in the Chamber

Based on Figure A1, a mass balance of the tracer gas inside of the chamber can be written as follows:

$$\frac{d(\rho VC)}{dt} = C_{amb} m_{in} - C m_{out} + S_m \quad [A1]$$

In deriving Equation 5, the following assumptions were made: the chamber is well mixed, the chamber is of uniform density, and no adsorption or absorption of the chemical occurs inside the chamber.

Mass Balance of Air Flowing Into and Out of the Chamber

Based on Figure A1, a mass balance of the air flowing into and out of the chamber can be written as follows:

$$\frac{d(\rho V)}{dt} = m_{in} - m_{out} \quad [A2]$$

Assuming that the temperature, pressure, and volume are constant inside the chamber, then Equation A2 reduced to the following

$$\frac{d(rV)}{dt} = 0, \therefore m_{in} = m_{out} = m \quad [A3]$$

Based on Equation A3, Equation A1 reduces to the following

$$rV \frac{dC}{dt} = C_{amb} m - C m + S_m \quad [A4]$$

Dividing through by ρV yields the following

$$\frac{dC}{dt} = C_{amb} \frac{m}{rV} - C \frac{m}{rV} + \frac{S_m}{rV} \quad [A5]$$

Equation A5 can further be reduced by assuming that the temperature and pressure of the air entering the chamber is the same as that inside the chamber and by making the following observations

$$\frac{m}{rV} = \text{air exchange rate} = k \quad [A6]$$

$$\frac{S_m}{rV} = \text{source strength (volume basis)} = S_v \quad [A7]$$

Therefore, Equation A5 reduces to the following

$$\frac{dC}{dt} = k (C_{amb} - C) + \frac{S_v}{V} \quad [A8]$$

Air Exchange Rate by Tracer Gas Decay

In the tracer gas decay tests, the tracer gas is injected into the chamber for a period of time and then stopped. The decay of the tracer gas is then monitored. Once the tracer gas injection has stopped, the source strength is zero ($S_v = 0$). Therefore, equation A8 reduces to the following

$$\frac{dC}{dt} = k (C_{amb} - C) + 0 \quad [A9]$$

Equation A9 can be rearranged as follows

$$\frac{dC}{(C_{amb} - C)} = k dt \quad [A10]$$

Solving Equation A10 results in the following

$$\ln (C_{amb} - C) + A = - k t \quad [A11]$$

The constant "A" in Equation A11 can be solved using the initial conditions that at $t = 0$, $C = C_0$. Therefore,

$$\ln (C_{amb} - C) - \ln (C_{amb} - C_0) = - k t \quad [A12]$$

Equation A12 can be rearranged as follows

$$\ln \frac{(C_{amb} - C)}{(C_{amb} - C_0)} = - k t \quad [A13]$$

If the background concentration of the tracer gas (C_{amb}) is negligible, then Equation A13 reduces to the following

$$\ln \frac{C}{C_0} = -k t \quad [A14]$$

Solving for the tracer gas concentration C , Equation A14 can be written as follows

$$C = C_0 e^{-kt} \quad [A15]$$

Equation A15 describes how the tracer gas decays over time.

The air exchange rate (k) can be calculated directly from Equation A14, since Equation A14 is in the form of a straight line.

$$y = m x + b \quad [A16]$$

In Equation A16, y is equal to the quantity ($\ln C/C_0$), m is the slope of line ($-k$), x is time (t), and b is the y-intercept, which is equal to zero. By fitting a straight line through the tracer gas decay data, the air exchange rate is equal to the slope of the line.

Volume by Constant Injection of the Tracer Gas

In the constant injection tests, the tracer gas is injected into the chamber at a constant rate. Over a period of time, the tracer gas concentration will eventually reach a steady state value (C_{ss}). At steady state, Equation A8 reduces to the following

$$\frac{dC}{dt} = 0 = k(C_{amb} - C) + \frac{S_v}{V} \quad [A17]$$

Equation A17 can be rearranged to solve for the volume (V) as follows

$$V = \frac{S_v}{k(C_{ss} - C_{amb})} \quad [A18]$$

If the background concentration of the tracer gas (C_{amb}) is negligible, then Equation A18 reduces to the following

$$V = \frac{S_v}{k C_{ss}} \quad [A19]$$

Therefore, the chamber volume can be calculated directly from Equation A19, if the constant injection rate (S_v) is known, if the air exchange rate (k) is known, and if the steady state concentration (C_{ss}) is known.

APPENDIX B: CHAMBER PHOTOS AND SCHEMATICS

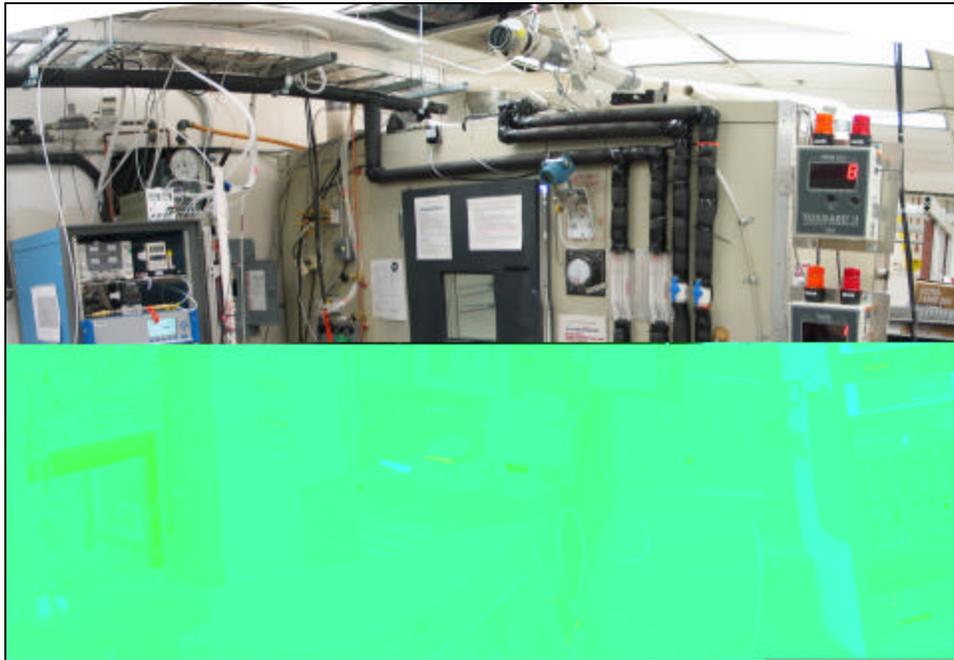
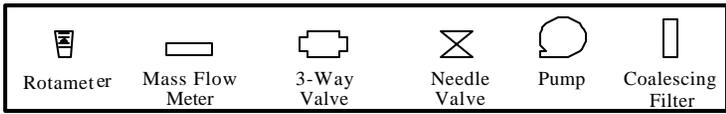
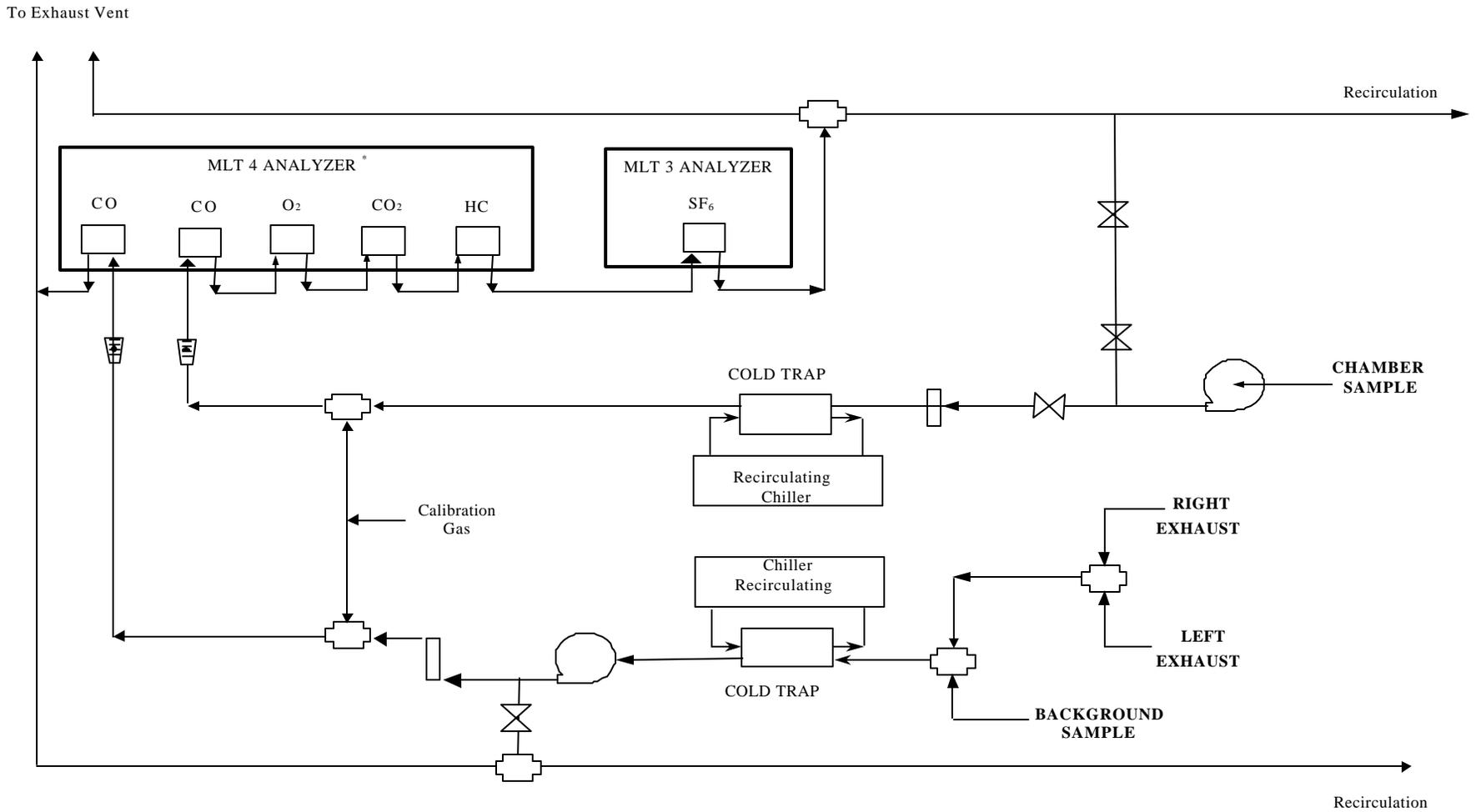


Figure B1. Outside view of the Medium Chamber

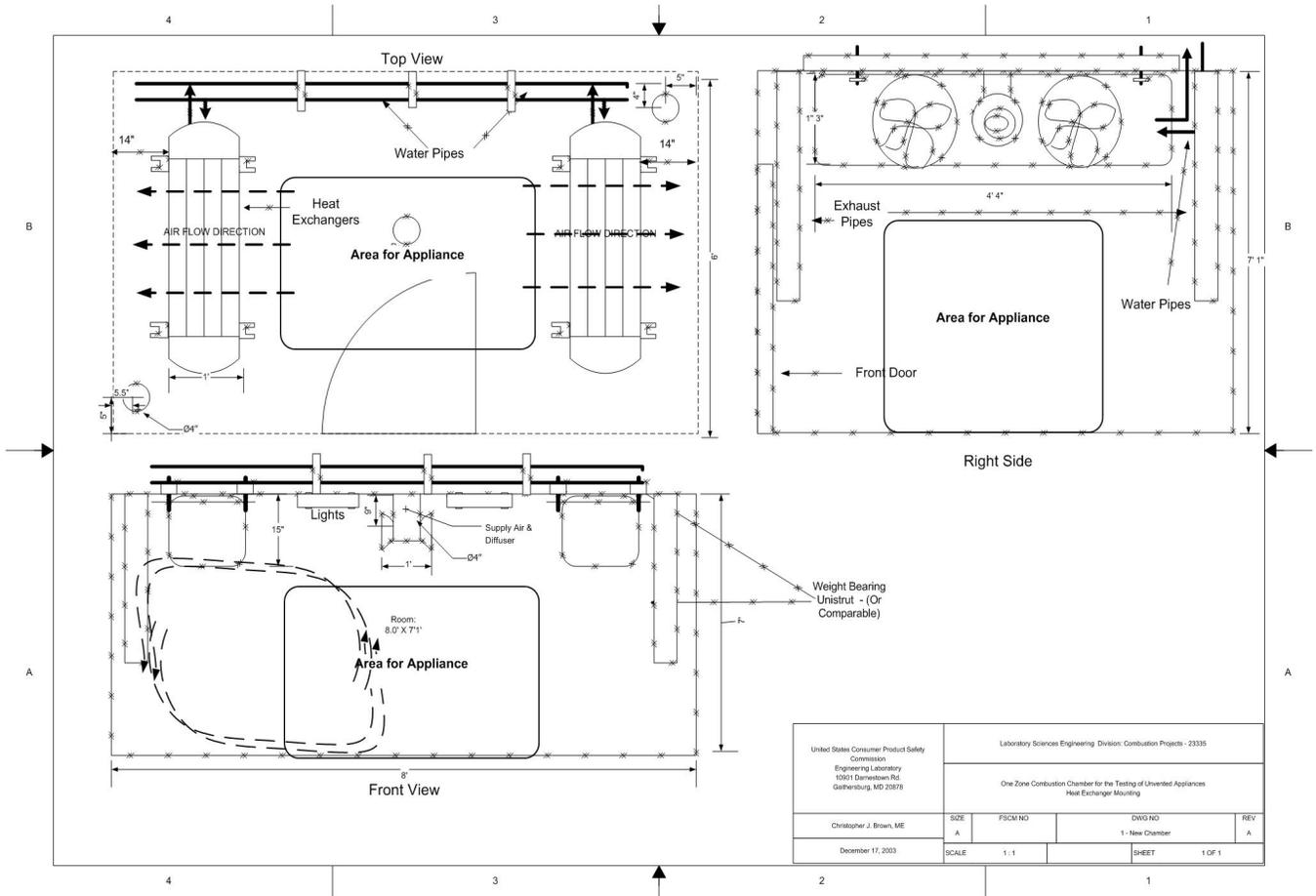


Figure B2. Inside view of the Medium Chamber. Air supply pipes are located at the top center of the chamber and are directed towards the heat exchangers.



* Although the MLT 4 was capable of measuring O₂, CO₂, and HC, these items were not measured during the characterization tests
 ** A second MLT 4 was available during the first series of tests and was used to measure the CO concentrations in the exhaust pipes. This unit is not shown on this figure.

Figure B3. Medium-Chamber gas sampling system



United States Consumer Product Safety Commission Engineering Laboratory 10901 Derbortree Rd. Gaithersburg, MD 20878	Laboratory Science Engineering Division: Combustion Projects - 23335			
	One Zone Combustion Chamber for the Testing of Unvented Appliances Heat Exchanger Mounting			
Christopher J. Brown, ME	SIZE A	FSCM NO	DWG NO 1 - New Chamber	REV A
December 17, 2003	SCALE 1:1		SHEET	1 OF 1

Figure B4. Medium Chamber – Schematic

APPENDIX C: CHAMBER TEST EQUIPMENT

Table C1. Equipment used to measure the different operating parameters of the chamber

Parameter Being Measured	Equipment Type	Manufacturer	Model	Range	Accuracy
Tracer Gas Injection Rate	Smart-Trak Mass Flow Controller- Digital	Sierra	Series 100	0-7.690 slpm CO 0-2.0 slpm SF ₆	± 1.0% full scale
Tracer Gas Injection Rate	Mass Flow Controller-Digital	Sierra	810c-DR-2-MP	0- 350 sccm CO 0- 91 sccm SF ₆	± 1.0% full scale
Tracer Gas Injection Rate	VF (Visi-Float®) Flowmeter	Dwyer	VFA-24-SSV VFA-22-SSV	1.0-10.0 slpm CO 0.15-1.0 slpm CO	± 5% full scale
Chamber/Room Differential Pressure	Magnehelic Pressure Gage with Transmitter	Dwyer	605-1	(-1)-1.0 inches w.c.	± 2% full scale
Chamber/Room Differential Pressure	Digital Differential Pressure Transmitter	Rosemount	3051C	(-3.0)-3.0 inches w.c.	± 0.075% full scale
Chamber Temperature	Thermocouple	Omega	Type K,	-200 to 1250 °C	2°C or 0.75% of Reading, which ever is greater

Table C2. Equipment Used with the Gas Sampling Systems

Chemical Species	Location	Measuring Technique	Manufacturer	Model	Range	Accuracy
Carbon Monoxide (CO)	Chamber (Manifold)	Non-Dispersive Infrared	Rosemount	NGA 2000 (MLT 4)	0-200 ppm, 0-1000 ppm, 0-7000 ppm	1% Full Scale
Carbon Monoxide (CO)	Exhaust Piping and Outside Chamber	Non-Dispersive Infrared	Rosemount	NGA 2000 (MLT 4)	0-200 ppm, 0-1000 ppm, 0-7000 ppm	1% Full Scale
Sulfur Hexafluoride (SF ₆)	Chamber (Manifold)	Non-Dispersive Infrared	Rosemount	NGA 2000 (MLT 3)	0-63 ppm	1% Full Scale
Gas Divider	Calibration Gases	Capillary Tube Type	Horiba	SGD-A10	10-point, 0-100%	0.5% Full Scale

APPENDIX D: TEST DATA

Table D1. Summary of data for tracer gas decay tests and constant injection tests

Test #	Differential Chamber Pressure (mm w.c.)	Exhaust Fan Voltage (V)	Iris Setting (O = Open) (X = Closed)		Injection Rate (cc/hr)		Steady State Concentration (ppm)					Chamber Air Exchange Rate (1/hr)	
							SF ₆		CO			SF ₆	CO
							Chamber	Chamber	Exhaust - Left	Exhaust - Right	Laboratory		
							Supply	Exhaust	SF ₆	CO	SF ₆	CO	Ex L
1	+0.635	1	O	O	N/A	9,000	N/A	542	545	551	N/A	N/A	N/A
2	+0.635	1	O	O	N/A	60,000	N/A	3804	3825	3842	N/A	N/A	N/A
3	+0.635	10	O	O	N/A	60,000	N/A	287	259	284	N/A	N/A	N/A
4	+0.635	10	O	O	N/A	9,000	N/A	57	53	58	N/A	N/A	N/A
5	+0.635	10	O	O	N/A	9,000	N/A	51	48	55	N/A	N/A	N/A
6	+0.635	10	O	O	N/A	60,000	N/A	264	243	289	N/A	N/A	N/A
7	+0.635	1.0	O	O	N/A	60,000	N/A	3352	3386	3439	N/A	N/A	N/A
8	+0.635	1	O	O	N/A	9,000	N/A	536	533	544	N/A	N/A	N/A
9	+0.635	1	O	O	N/A	9,000	N/A	595	598	608	N/A	N/A	N/A
10	+0.635	1	O	O	N/A	60,000	N/A	3725	3770	3805	N/A	N/A	N/A
11	+0.635	10	O	O	N/A	600,000	N/A	2440	2458	2478	N/A	N/A	N/A
12	+0.635	10	O	O	N/A	600,000	N/A	2604	2598	2550	N/A	N/A	N/A
13	-1.27	15	O	O	5460	600000	20.65	2121	2103	2218	10.2	28.03	28.27
14	-1.27	10	O	O	5460	600,000	28.8	3027		3152	12.1	19.98	20.95
15	-1.27	6	O	O	5460	540,000	50.47	4676	4649	4810	6.7	11.53	12.2
16	-1.27	2.3	X	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	1.77	1.82
17	-1.27	12	O	O	5460	600,000	24.73	2560	2445	2668	15.3	23.92	24.44
18	-1.27	8	O	O	5460	60,000	N/A	NA	N/A	NA	NA	16.81	17.09
19	-6.35	15	O	O	5460	600,000	21.93	2203	2156	2336	13.3	26.54	27.96
20	-6.35	10	O	O	5460	600,000	33.62	3409	3347	3505	16.1	17.28	18.39
21	0	0	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	0.12	0.12
22	-1.27	7.22	X	X	686.4	60,000	53.59	4080		4121	18.5	1.65	1.61
23	-6.35	7.49	O	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	10.74	11.95
24	-6.35	4.86	X	O	N/A	N/A	N/A	N/A	N/A	N/A	N/A	3.84	3.81
25	-3.81	15	X	X	N/A	N/A	N/A	N/A	N/A	N/A	N/A	2.66	N/A
26	-1.27	3.16	O	O	3071	N/A	62.64	N/A	N/A	N/A	N/A	5.05	N/A
27	-1.27	3.16	O	O	3079	N/A	64.17	N/A	N/A	N/A	N/A	5.05	N/A
28	-1.27	5.21	O	O	3079	N/A	30.09	N/A	N/A	N/A	N/A	10.7	N/A
29	-1.27	9.39	O	O	3079	N/A	15.75	N/A	N/A	N/A	N/A	19.93	N/A
30	-1.27	14.99	O	O	3079	N/A	10.92	N/A	N/A	N/A	N/A	30.15	N/A
31	-1.27	3	O	O	3079	N/A	63.84	N/A	N/A	N/A	N/A	5.06	N/A
32	-1.27	1.74	O	X	911	N/A	54.27	N/A	N/A	N/A	N/A	1.71	N/A
33	-1.27	3.31	O	O	911	N/A	18.22	N/A	N/A	N/A	N/A	5.42	N/A
34	-1.27	3.06	O	O	N/A	234,000	N/A	5017	4973	4954	N/A	N/A	4.91
35	-1.27	15	O	O	N/A	461,400	N/A	1623	1728	1739	N/A	N/A	29.94
36	-1.27	3.04	O	O	2978	234,000	64.13	4811	5202	5186	N/A	4.83	4.82