THE DESIGN AND DEVELOPMENT OF A CAPTURE EFFICIENCY TEST FACILITY BY USING TRACER GAS MONITORING FOR PERFORMANCE TESTING OF KITCHEN VENTILATION SYSTEMS

Thesis

by

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ABSTRACT

Effective kitchen ventilation systems are critical for removing hazardous pollutants generated during cooking to maintain acceptable levels of indoor air quality. Current indoor air quality standards specify air flow and sound ratings as the only metrics to analyze the performance of kitchen ventilation. Lawrence Berkeley National Laboratory has been working alongside ASTM to develop a test standard for analyzing the fraction of cooking pollutants removed by kitchen range hoods.

RELLIS Energy Efficiency Laboratory (REEL) was given the opportunity to design, develop, and construct a capture efficiency test facility using tracer gas monitoring to analyze the performance of kitchen ventilation systems. REEL established seven sub-components of the testing facility based on the requirements outlined in the test standard developed by LBNL. The 4.34 m x 3.93 m x 3.05 m testing chamber was sized to best represent a residential kitchen, which can accommodate range hood flow rates up to 200 L/s. All components and necessary equipment and instrumentation were designed and selected to conform to the dimensional, measurement, and accuracy requirements outlined in the test standard.

Testing procedures were developed and preliminary data for 5 kitchen range hoods were taken to qualify the room and to analyze the effects of range hood air flow, mounting height, and cooking surface temperature on capture efficiency. Air flow rates < 100 cfm yielded capture efficiencies between 55-82%, while air flow rates > 150 cfm yielded capture efficiencies between 86-92%. Average capture efficiencies were 67.7%

and 77.8% for mounting heights of 30” and 21” for flow rates < 150 cfm, respectively, while at air flow rates > 190 cfm, capture efficiencies were measured to be 88.2% (30”) and 90.3% (21”). At air flow rates < 130 cfm capture efficiencies were 66.4% and 55.6% for surface temperatures of 150 ^{0}C and 200 ^{0}C, respectively. At air flow rates > 160 cfm, capture efficiencies were measured to be 79.9% and 74.3%.

It was found that capture efficiency increased with increasing air flow rates, and decreasing mounting heights (closer to cooking surface) and surface temperatures. Large differences in measured capture efficiencies at flow rates < 150 cfm suggests that cooking and ventilation parameters are more impactful at lower operating speeds.

DEDICATION

This thesis is dedicated to my mom and dad for their continuous support and motivation throughout my entire collegiate career. I would not be where I am today without their love and parenting, and will always strive to make them proud.

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CONTRIBUTORS AND FUNDING SOURCES

Contributors

This work was supervised by a thesis committee consisting of Professor Michael Pate (advisor and committee chair), Professor Harry Hogan of the Department of Mechanical Engineering and Professor Maria King of the Department of Biological and Agricultural Engineering.

All work for this thesis was completed by the student, in collaboration with graduate students Sam Meleika, Jake Hodges, and Cesar Pelli, under the advisement of Professor Jim Sweeney of the Department of Mechanical Engineering. Jake Hodges assisted with the construction and development of the testing facility, Cesar Pelli assisted with the data gathering and processing of the testing procedure, and Sam Meleika assisted with the data analysis and preliminary results.

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NOMENCLATURE

ACH	Air Changes per Hour
ASHRAE	American Society of Heating, Refrigerating and Air-Conditioning Engineers
ASTM	American Society for Testing and Materials
CFM	Cubic Feet per Minute
DALY	Disability Adjusted Life Years
HVI	Home Ventilating Institute
IAP	Indoor Air Particles/Pollution
IAQ	Indoor Air Quality
ISO	International Organization for Standardization
LBNL	Lawrence Berkeley National Laboratory
PM	Particulate Matter
PPM	Parts Per Million
PSIG	Pounds per square inch (gauge)
REEL	RELLIS Energy Efficiency Laboratory
RMS	Root Mean Square
SEM	Standard Error of Mean
CE	Capture Efficiency [%]
$C_{ambient}$	Tracer gas concentration at inlet of chamber [ppm]

$C_{chamber}$	Tracer gas concentration in chamber [ppm]
$C_{exhaust}$	Tracer gas concentration in exhaust [ppm]
$\delta_p(C_{exhaust})$	Spatial (precision) error for exhaust concentration [%]
$\delta_p(C_{inlet})$	Spatial (precision) error for inlet concentration [%]
$\delta_p(C_{chamber})$	Spatial (precision) error for chamber concentration [%]
$\delta_{se}(C_{exhaust})$	Temporal error for exhaust concentration measurements [%]
$\delta_{se}(C_{inlet})$	Temporal error for inlet concentration measurements [%]
$\delta_{se}(C_{chamber})$	Temporal error for chamber concentration measurements [%]
$\delta(C_{exhaust})$	Total error for exhaust concentration measurements [%]
$\delta(C_{inlet})$	Total error for inlet concentration measurements [%]
$\delta(C_{chamber})$	Total error for chamber concentration measurements [%]
$\delta(CE)$	Total error of measured capture efficiency [%]
P	Power consumption of electric heaters [kW]
$T_{ambient}$	Ambient temperature of testing chamber [^{0}C]
T_{burner}	Surface temperature of burner plate [^{0}C]
t_{ss}	Steady-state time required for testing [min]
Q_{50}	Flow rate required to maintain 50 Pa of pressure [L/s]
Q_{Hood}	Flow rate of Range Hood [cfm]
V	Volume of Chamber [m^3]

TABLE OF CONTENTS

Page

ABSTRACT ii

DEDICATION iv

ACKNOWLEDGEMENTS v

CONTRIBUTORS AND FUNDING SOURCES vi

NOMENCLATURE vii

LIST OF FIGURES xii

LIST OF TABLES xiii

1. INTRODUCTION 1

1.1 Problem Overview 1
1.2 Problem Validation 2

2. BACKGROUND AND HISTORY 4

2.1 Air Pollutant Generation 4
2.2 Moisture Generation 5
2.3 Health Impacts of Air Pollutants 6
2.4 Kitchen Ventilation Use 8
2.5 Kitchen Ventilation System Efficiency 9
2.6 Range Hood Performance Standards 11

3. SYSTEM REQUIREMENTS 13

3.1 Overview 13
3.2 Testing Chamber 14
3.3 Range Hood and Cabinetry 14
3.4 Chamber Inlet 15

3.5 Chamber Exhaust ... 16
3.6 Cooking Surface ... 16
3.7 CO_2 Emitter System ... 16
3.8 CO_2 Detection System ... 18

4. EXPERIMENTAL APPARATUS AND VERIFICATION ... 19

4.1 Overview ... 19
4.2 Testing Chamber ... 19
4.3 Range Hood and Cabinetry ... 22
4.4 Chamber Inlet ... 27
4.5 Chamber Exhaust ... 29
4.6 Cooking Surface ... 31
4.7 CO_2 Emitter System ... 32
4.8 CO_2 Detection System ... 34
4.9 Instrumentation ... 36

5. DATA ANALYSIS METHODOLOGY ... 38

5.1 Overview ... 38
5.2 Uncertainty ... 38
5.3 Methodology ... 40

6. DATA ANALYSIS ... 44

6.1 Overview ... 44
6.2 Effects of Range Hood Flow Rate ... 44
6.3 Effects of Mounting Height ... 46
6.4 Effects of Cooking Surface Temperature ... 48
6.5 Repeatability ... 49

7. CONCLUSIONS ... 54

REFERENCES ... 59

APPENDIX A ... 62

APPENDIX B ... 65

APPENDIX C ... 68

APPENDIX D 72

APPENDIX E 74

APPENDIX F 76

APPENDIX G 87

APPENDIX H 102

APPENDIX I 105

APPENDIX J 109

APPENDIX K 114

LIST OF FIGURES

Page

Figure 1: Test chamber and sub-components for CO_2 capture efficiency testing 13
Figure 2: Plume diffusion/tracer gas emitter assembly.. 17
Figure 3: Schematic of testing chamber... 20
Figure 4: Material composite of Structurally Insulated Panels (SIP) 21
Figure 5: Adjustable railing system for range hood and cabinetry................................. 23
Figure 6: Schematic of height discrepancy of cabinetry requirements........................... 24
Figure 7: Designed cabinetry installed on adjustable railing system.............................. 25
Figure 8: Workbench and frame used to simulate countertop 26
Figure 9: Range hood, cabinetry, and cooking countertop assembly 27
Figure 10: Inlet filter and designed inlet diffuser plate.. 29
Figure 11: Venturi tube designed to satisfy uncertainty requirments............................. 30
Figure 12: Exhaust system designed to control the range hood flow rate 31
Figure 13: Electric burner and variac used to simulate cook-top 32
Figure 14: CO_2 emitter system used to simulate generated pollutants 34
Figure 15: CO_2 detection system used to measure location concentrations 35
Figure 16: Three CO_2 sampling locations to determine capture efficiency..................... 36
Figure 17: User interface for data acquisition software.. 41
Figure 18: Effects of air flow rate on capture efficiency 46
Figure 19: Effects of mounting height on capture efficiency 47
Figure 20: Effects of cooking surface temperature on capture efficiency 49
Figure 21: Effects of air flow rate on repeatability of system 50
Figure 22: Effects of mounting height on repeatability of system.................................. 51
Figure 23: Effects of cooking surface temperature on repeatability of system 52

LIST OF TABLES

Page

Table 1: Sensors and instrumentation selected for design 37

1. INTRODUCTION

1.1 Problem Overview

Indoor air quality is an important health metric for human exposure that often goes unrecognized. Air and biological pollutants contribute to the air quality within a residence and are threats to the health of both children and adults. Biological pollutants, such as mold, will thrive and grow at a rapid rate when exposed to a moist environment, becoming a threat to human health. There are a variety of different sources within a residence that contribute to excess moisture and pollutant concentrations.

One area of the home that largely contributes to poor indoor air quality is the kitchen. During the act of cooking, the amount of moisture generated depends on many different factors, including types of food and how the food is being prepared and cooked (covered or uncovered, time, temperature, etc.). Cooking activities not only generates a large amount of moisture, but also generates potentially harmful particles and gases, thus further contributing to poor indoor air quality within a residence.

In order to control the effects of excess moisture and air pollutants within a residence, proper ventilation practices must be taken. The main function of a kitchen ventilation system is to remove the pollutants, moisture, smoke and odors that are generated when cooking. Without the installation or proper use of kitchen ventilation systems, the generated moisture can lead to excessive levels of relative humidity and indoor air particles that threaten the health of individuals within the home.

1.2 Problem Validation

Appropriate kitchen ventilation is critical to alleviate hazardous pollutants generated during cooking activities. A major issue contributing to poor indoor air quality is the lack of requirements for mechanical ventilation systems in many older building codes. Although new standards are beginning to adopt requirements of proper kitchen ventilation, there is a large communication gap between the energy industry and homeowners that inhibits the use of these systems. Due to lack of knowledge about the importance of air quality and adequate ventilation within a dwelling, many homeowners do not properly use their kitchen ventilation systems.

The lack of building codes for kitchen ventilation has also created a large variety of system performance and efficiency. The wide range in system performance can be explained by the numerous variables that effect kitchen ventilation systems – among these are type of cooking, location of the range, location of the cook top, size and location of the hood, and type and size of the fan used in the system. The number of different variables affecting the performance and efficiency explains why ventilation systems need to be meticulously designed for proper control of ventilation and filtering allowing for acceptable limits of air pollutants within a residence.

Publishing a test standard for measuring the performance of a kitchen ventilation system will provide a greater opportunity for research labs to study the many different factors affecting the capture efficiency of range hoods and kitchen ventilation systems. Through collaboration and communication amongst research labs, researchers could study, document, and report the factors affecting capture efficiency, aiding manufacturers in the innovation of range hood technology while increasing the indoor air quality within a residence. As a result of this, it is the intent of this paper to outline the design and development of a testing facility and procedure used for assessing range hood and kitchen ventilation system performance.

2. BACKGROUND AND HISTORY

2.1 Air Pollutant Generation

The act of cooking within a residence produces a number of different air pollutants that contribute to the indoor air quality. A variety of factors contribute to the type and amount of emissions, including ingredients, cooking method, type of stove being used, and cooking temperature. Common air pollutants being generated from the cooking of food include fine particles ($PM_{2.5}$), ultrafine particles (UFPs), and volatile organic compounds (VOCs). Fine particles, or $PM_{2.5}$, are particles that are 2.5 microns or less in width, while ultrafine particles are particles less than 0.1 microns in width. Volatile organic compounds are organic chemical compounds that are emitted in to the air as gases from solids and liquids under normal indoor atmospheric conditions of temperature and pressure. Typical VOCs that are released when cooking food include formaldehyde, benzene, and toluene.

The combustion of fuel when using gas-fueled cooking appliance also contributes to a number of different air pollutants being generated. The main source of pollutants from gas appliances that directly impact health includes carbon monoxide, nitrogen dioxide, formaldehyde, and particulate matter concentration (Singer et. al., 2009). It was also found that both gas and electric cooking stoves are the most significant and impactful sources of UFP generation in residencies (Rim, Wallace, et. al., 2012).

The U.S. Environmental Protection Agency performed a study on the sources and strengths of fine and ultrafine particles generated when cooking with a gas stove. Over 600 hours of cooking morning and evening cooking activities over the course of the year were performed to compare the pollutant concentration during cooking and non-cooking periods within the home. It was found that cooking generated more than 10 times the amount of ultrafine particle concentration when compared to non-cooking periods, while $PM_{2.5}$ concentrations increased by a factor of 3 during cooking periods (Wallace et. al., 2004).

2.2 Moisture Generation

Cooking is also a major contributor to moisture generation within a residence. Moisture is typically generated from boiling or simmering foods on a cook top, as well as from microwaves and conventional ovens by removing moisture from food and venting it to the atmosphere. The amount of moisture being generated during cooking is dependent on many different factors, including type of cooking appliance, type of food, how the food is being cooked, cooking temperature, and duration of the cooking process. Additionally, using gas cook tops will result in a further increase in moisture generation due to water vapor being a byproduct of gas combustion. Parrott et al. (2003) summarized a study performed at the Cold Climate Housing Information Center, which estimated that nearly 0.35 pints, 0.52 pints, and 1.22 pints of moisture was generated when cooking a 4-person meal on an electric range for breakfast, lunch, and dinner, respectively (as cited in Angell and Olsen, 1988). When cooking this same meal using a gas range, it was found that the moisture generated was more than doubled that of an electric range. Another study performed by National Resource Council Canada estimated that cooking three meals a day generated roughly one liter (2.11 pints) of moisture, while using a gas stove contributed to an additional 1.5 liters (3.17 pints) of moisture generated (Rousseau, 1984).

2.3 Health Impacts of Air Pollutants

Long-term exposure to chronic levels of air pollutants can significantly impact the health of individuals living in homes, mainly harming the respiratory and cardiovascular systems. In a study performed at Brigham Young University, it was found that long-term exposures to $PM_{2.5}$ were associated with increases in ischemic heart disease, dysrhythmias, heart failure, and cardiac arrest (Pope et. al., 2002).

A study performed by See et al. (2006) analyzed the risk assessment of human exposure to indoor aerosols associated with cooking in Chinese homes. Health estimates based on maximum exposure and dose were determined to evaluate the potential health threats due to pollutant generation during cooking. Both non-carcinogenic and carcinogenic risks were estimated and compared to normal levels of air pollutants during non-cooking periods. It was found that non-carcinogenic risks, with no appreciable risks of long-term health effects, were approximately 50% higher than what is considered acceptable. For carcinogenic risks, however, the estimated risk was two orders of magnitude higher than the acceptable levels.

Jennifer Logue and other scientists at Lawrence Berkeley National Laboratory performed a study to quantify and compare the health impacts of several different indoor air pollutants. Logue and her team integrated available disease incidence and disease impact models with the data of measured concentrations to estimate the chronic health impact of several different indoor air pollutants (IAPs). The metric used to quantify the chronic health impacts due to inhalation of IAPs in residences is identified as disability-adjusted life years, or “DALYs”. This metric, commonly used by the World Health Organization, describes the amount of lost years of “healthy” life, measuring the current health status against an ideal health situation (World Health Organization, 2014).

During the study it was determined that the concentration of air pollutants in many residential homes exceeded the chronic and acute levels detailed in relevant health-based standards for indoor exposure. Of the 70 chemical pollutants studied, 33 were identified as chronic hazards, with nine of these pollutants being identified as priority hazards. Among the nine priority-hazard pollutants identified were acrolein and $PM_{2.5}$ – two pollutants accounting for the vast majority of DALY losses whose main source of generation stems from cooking activities (Logue, et al., 2012). The DALY losses due to exposure of indoor $PM_{2.5}$, acrolein, and formaldehyde combined was estimated to be 1,100 per 100,000 persons. This value was substantially greater than the estimated DALY losses of the remaining 67 air pollutants (40), and can even be compared to the 7,700 and 1,700 DALY losses within the United States each year caused by non-communicable diseases and both first- and secondhand smoking, respectively (McKenna et. al., 2005).

2.4 Kitchen Ventilation Use

The daily use of kitchen ventilation is an important measure to remove pollutants and moisture generated when cooking at home. A study performed by Kathleen Parrott and her research group at North Carolina State University outlined how frequent homeowners were effectively using their kitchen ventilation systems during cooking activities. Of the 78 participating households, 68% cooked complete meals five or more times a week and 97% prepared dinner on a regular basis (Parrott et. al., 2003). Although 92% of the households reported having mechanical kitchen ventilation systems, only 8% used their ventilation system during the process of cooking on the stove. Another 8% of participants reported they “almost never” used their ventilation system, while 15% used ventilation “very rarely”. When using the oven, 46% of participants reported never using ventilation, 28% used ventilation when cooking oily or greasy foods, and 17% when cooking food with strong odors.

Phillip Price and Lawrence Berkeley National Laboratory performed a similar study on new California homes. Of the 1,448 participants, 28% reported always using their ventilation system when using their cook top, while 32% only use it when odor or humidity seemed to be an issue (Price et. al., 2007). 26% of participants reported using their ventilation systems “sometimes”, while 11% and 2% reported “rarely” or “never” using it. When cooking with the oven, 15% reported always using their ventilation system, 12% only when odor or humidity was an issue, 15% using it “sometimes”, while 21% and 35% “rarely” or “never” used it.

2.5 Kitchen Ventilation System Efficiency

Kitchen ventilation can be accomplished by a variety of different exhaust system designs, although the most common system includes the use of a range hood mounted directly over the cooking area. A range hood is a device used for capturing cooking-generated contaminates over a stove, range, or cooktop, and exhausting them to the outside environment. Before the late 1900's, there was little information about the prevalence or fan usage patterns of kitchen fans in homes in the United States. Since then, techniques have been utilized to study the performance of kitchen range hood exhaust systems. In 1985, Nagda et al. (1989) performed complementary research to analyze the effects of a vented hood fan on combustion emission products from gas range operations. It was found that a vented fan hood could reduce the peak concentration of combustion products by roughly 50% when operating at the beginning of cooking activities.

A research laboratory at the University of Minnesota used flow visualization techniques to assess the performance of various kitchen exhaust ventilation systems. It was found that adding side baffles, reducing clearance height, and increasing flow performance increased the capture efficiency of wall-mounted range hood exhaust systems (Kuehn, et. al., 1992).

The Division of Building, Construction and Engineering in Australia performed a study for deriving the capture efficiency of kitchen range hoods in a confined space. It was stated that the definition of capture efficiency must follow the four principal issues (Li and Delsante, 1996):

- The ability to assess the performance of different hood designs in a defined environment
- The ability to guide hood designers in choosing an adequate exhaust flow rate
- The consistency of the concept
- The ease of numerical calculation, experimental and field measurements

A new derivation of kitchen range hood capture efficiency was studied by using a plume theory to analyze the air exchanges in a two-zone mixing model; namely the cooking zone and the room zone. The capture efficiency was found by calculating the ratio of captured flow rate to the total plume flow rate at the front canopy height.

Li and Ho (2001) further extended the definition of capture efficiency using a two-zone model by considering that there may not always be fully mixed conditions in the two zones due to strong buoyancy effects. When using a two-zone non-mixing model, at least four concentration measurements of a tracer gas or pollutant are necessary, including the average concentration at the hood boundary. In this study, it was found that at lower exhaust flow rates, an increase in heat power above 1,000 W significantly decreased the measured capture efficiencies due to the increase in thermal plume flow rates.

Hood performance studies conducted by LBNL analyzed the effects of environmental factors and range hood design on capture efficiency (Singer, et. al., 2010).

In one study, experiments were conducted on 15 exhaust hood devices varying in design and other characteristics. The capture efficiency was analyzed for various burner configurations and fan speed settings. It was found that higher flow rates yielded higher capture efficiencies, while using the back burners as opposed to the front burners yielded significantly higher capture efficiencies. Open hoods covering all cooktop burners while operating at higher air flow rates yielded the best and most consistent performance.

Further performance research at LBNL analyzed eight range hood models at 27 different mounting-height-flow-rate combinations (Walker et. al., 2016). The measured capture efficiency generally increased at higher flow rates and lower mounting heights, although different models had different capture efficiencies at the same flow rate. This explains that geometric and design factors of a range hood also contribute to its performance. Further observation showed that performance differences between different mounting heights were smaller for hoods with a deep sump or hoods with a depth large enough to cover the front burners.

2.6 Range Hood Performance Standards

There are published European standards that are used to analyze the performance of kitchen range hoods. One standard highlights fan performance, grease absorption and odor extraction to analyze hood performance, while another standard utilizes tracer gas to analyze the reduction in concentration of the room after operating the range hood for ten minutes (as cited in Walker et. al., 2016). However, these standards do not analyze the fraction of cooking pollutants directly exhausted by the range hood.

Current North American standards highlight only air flow, sound, and power consumption metrics to assess the performance of kitchen exhaust fans. ASHRAE 62.2 specifies exhaust fans used for kitchen ventilation must have a minimum air flow value of 100 cfm (50 L/s) and a sound rating of 3 sones or less (ASHRAE, 2013).

Due to the lack of test standards analyzing pollutant capture efficiency, Lawrence Berkeley National Laboratory, with the input from an ASTM working group, have developed a test method with the intent of it being published and used as an ASTM test standard. This thesis outlines the current test method and facility requirements in development for ASTM. RELLIS Energy Efficiency Laboratory at Texas A&M University was granted the opportunity by HVI to work alongside LBNL to design, develop, and construct a new testing facility for range hood capture efficiency, and further establish a structured testing procedure.

3. SYSTEM REQUIREMENTS

3.1 Overview

The testing facility and its components will be built to best represent a cooking environment within a residential kitchen as shown in Figure 1. Our lab categorized seven key components of the testing facility according to the requirements established in the ASTM CO_2 Capture Efficiency Test Method developed by LBNL. The seven components of the test facility are the test chamber, chamber inlet, chamber exhaust, range hood and cabinetry, cooking surface, CO_2 emitter system, and CO_2 detection system. Not pictured in Figure 1, is the associated instrumentation and data acquisition system of the testing facility.

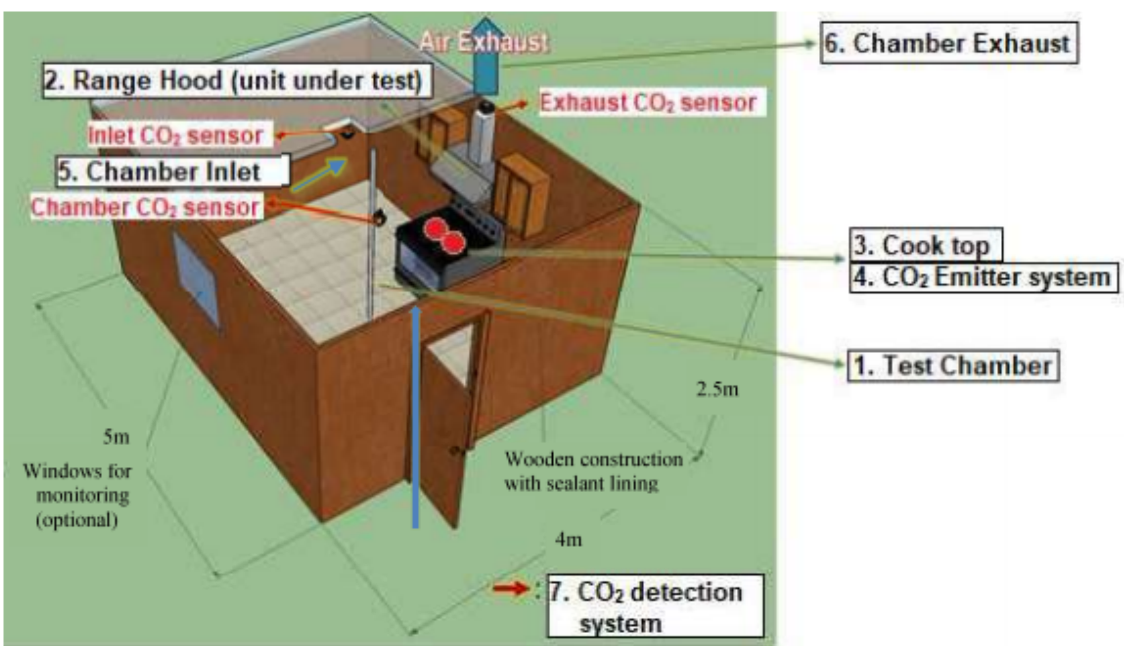

Figure 1: Test chamber and sub-components for CO_2 capture efficiency testing

3.2 Testing Chamber

The capture efficiency testing must be preformed inside a test chamber with minimum wall lengths of 2.5 m and 3.5 m, and a wall heights between 2.4 m to 2.5 m. The testing chamber must have an air tightness of no greater than 2.5 air changes per hour, and shall be tested in accordance with ASTM-E3087.17. The air tightness is tested by imposing a gauge pressure of 50 Pa and measuring the air flow required to maintain this pressure. The chamber of the volume, V, shall have less than 2.5 air changes per hour, and is calculating using the formula:

$$Air\ Changes\ per\ Hour = \frac{3.6\ Q_{50}}{V}$$

- Q_{50}: flow rate required to maintain 50 Pa (L/s)
- V: Volume of the chamber (m^3)
- 3.6: Conversion ratio (m^3 → L and sec. → hr.)

3.3 Range Hood and Cabinetry

The chamber and its components must also be designed to accommodate range hoods as large as 0.9 m (36 in.) wide with air flows up to 200 L/s (424 cfm). The range hood being tested shall be installed on the longest wall of the test chamber, with cabinetry installed on both sides of the range hood. The testing facility must be designed to ensure that the range hood can be mounted at various heights, and positioned flush with the back wall and adjacent to the cabinetry while under test. The range hoods shall be operated at specified operating points. Prior to capture efficiency testing, range hoods will undergo air flow testing in accordance to ANSI/AMCA 210-07 to determine air flow performance at a specified rated static pressure.

The cabinetry must be installed to contact the ceiling while extending down 1 m to 1.1 m. The cabinets must also be at least 0.5 m wide with a depth of 0.3 m to 0.4 m. To greater represent a cooking environment in a residential kitchen setting, a countertop below the range hood and cabinets is required. The countertop's surface should be 0.9 m from the ground, with a width and depth of 1.93 m and 0.65 m, respectively, and must make contact with the back wall.

3.4 Chamber Inlet

The chamber inlet must be designed so that incoming air is directed away from the wall where the range hood and tracer gas emitters are located. The inlet must also be effectively located to ensure there is at least 1 m (3 ft.) of separation between the inlet and range hood being tested. This design eliminates the possibility of incoming air disrupting the thermal plume created when resembling cooking activities. The inlet must be sized to ensure an average inlet air velocity of no more than 0.5 m/s, and a diffuser should be used to establish uniform air flow entering the chamber. A sufficient inlet size or number of inlets must be used to ensure the chamber is not depressurized by more than 5 Pa while operating a range hood at maximum air flow (200 L/s).

3.5 Chamber Exhaust

An auxiliary fan and damper should be connected in line with the range hood exhaust, which allows for the user to obtain desired range hood air flow rates. A flow meter having an accuracy of +/- 5% of the measured flow must also be connected in line with the range hood to measure the air flow rate of the range hood under test. The airtightness of the exhaust system must be measured, and have a maximum air leakage no greater than 2.5 L/s at a test pressure of 25 Pa.

3.6 Cooking Surface

Non-inducting heating elements supplying heat to the tracer gas emitters must be used. The heating elements shall be 200 mm +/- 10 mm in diameter, and each element being used must supply an average power input of 1.0 kW +/- 0.1 kW throughout the testing period. The number of heating elements used is dependent on the size of the range hood being tested. For 0.61 m (24 in.) and 0.75 m (30 in.) wide range hoods two heating elements will be used, while for 0.90 m (36 in.) wide range hoods three heating elements will be used.

3.7 CO_2 Emitter System

A plume diffusion/tracer gas emitter assembly must be fabricated and used for each operating heating element. The design and dimensions of the emitter assembly was established by LBNL, and consists of two circular metal plates along with an injector array. Each plate has a diameter of 250 +/- 5 mm, with a thickness of 13 +/- 1 mm. The emitter plate must emit tracer gas over the both the upper and lower surface of the top plate through holes 3.5 mm in diameter. A minimum of 30 holes is required for the upper surface while 15 holes are required for the lower surface. Figure 2 shows the provided schematic with given dimensions for the emitter assembly plates designed by LBNL. A temperature sensor must be mounted on the top plate near the center of the assembly, and must have an accuracy of +/- 5 ^{0}C.

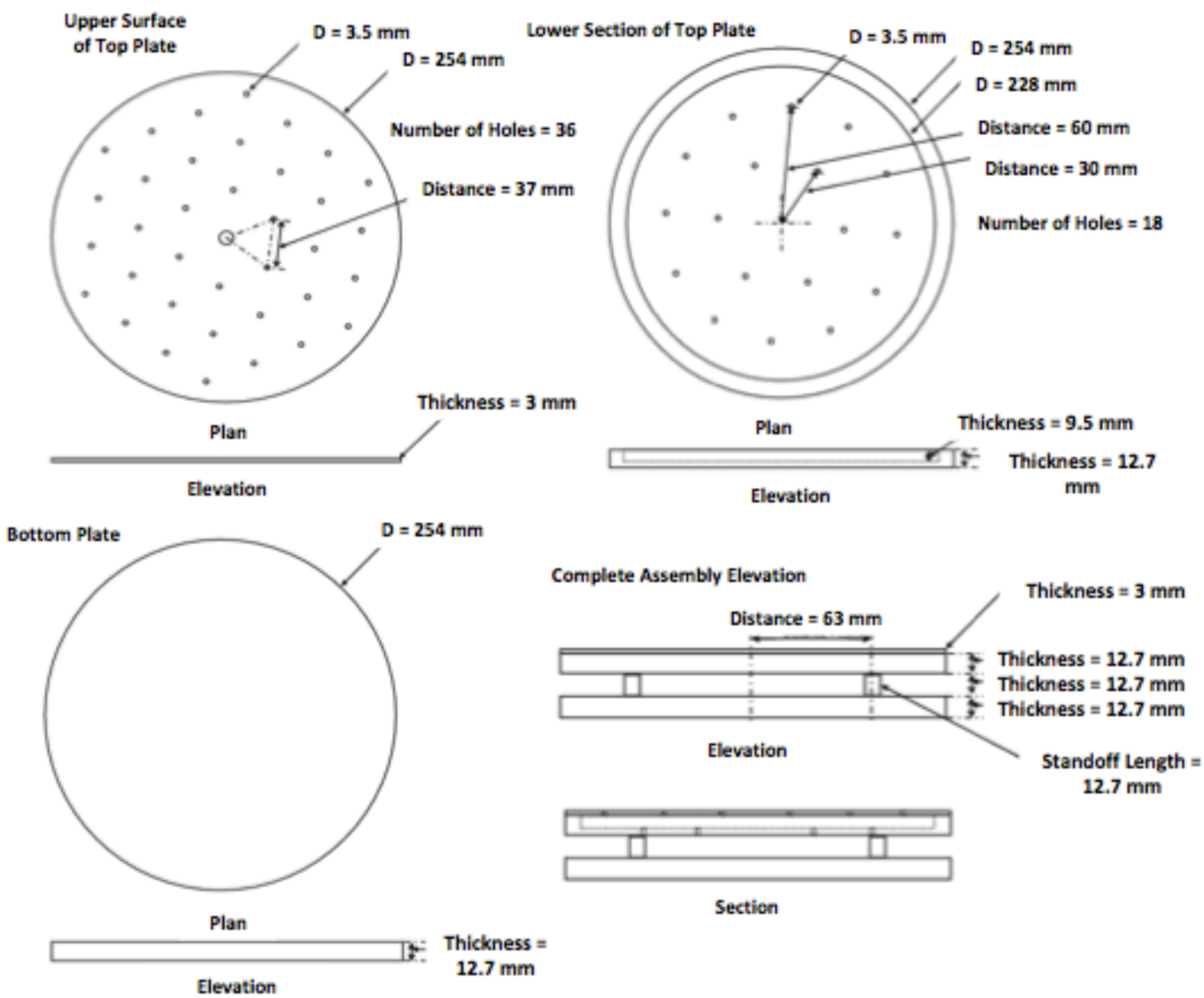

Figure 2: Plume diffusion/tracer gas emitter assembly

3.8 CO_2 Detection System

A non-toxic, non-flammable tracer gas stable up to 400 ^{0}C must be used, although CO_2 is the preferred choice. The tracer gas must be injected through the center of the emitter assembly, and the injection rate must be controlled to within +/- 1% using a mass control system. The flow rate of the tracer gas shall be less than 0.5% of the air flow rate through the range hood. The concentration of tracer gas must be measured at three different locations. The ambient tracer gas concentration, $C_{ambient}$, will be measured at the air inlet to the chamber. The chamber tracer gas concentration, $C_{chamber}$, will be measured on the centerline of the range hood, 0.5 m away from the countertop and at a height half way between the top of the countertop and the bottom of the range hood. Lastly, the exhaust tracer gas concentration, $C_{exhaust}$, will be measured within the range hood exhaust ducting at least 10 duct diameters downstream of the connection to the range hood. There must also be five sample points across the cross-section of the exhaust duct. These three tracer gas concentrations will be used to calculate a capture efficiency of the range hood.

4. EXPERIMENTAL APPARATUS AND VERIFICATION

4.1 Overview

A series of verification and validation checks were performed on each sub-component of the test facility before installation in order to meet the specifications and requirements of the current ASTM CO_2 Capture Efficiency Method drafted standard. The following describes the methods used to verify and validate each of the system's sub-components. Additionally, all instrumentation used in the data acquisition process was calibrated with certificates of compliance, provided in Appendix G.

4.2 Testing Chamber

When designing the testing chamber, the selected dimensions were 15'-9" by 13'-1 3/16" (4.34 m by 3.93 m), with wall heights of 10'-0" (3.05 m). The dimensioned of the testing chamber were designed for the future accommodation of testing island-mounted range hoods, which require larger ventilation rates than wall-mounted range hoods. (Home Ventilating Institute). Two circular cutouts were made through the roof of the testing facility to accommodate for inlet air and the exhaust system. A 3'- 2 1/2" by 6'- 10 1/2" cutout and centered along the front wall of the testing facility was made to accommodate for the installation of an interior door. A schematic of the testing chamber with necessary dimensions and cutouts is outlined in Figure 3.

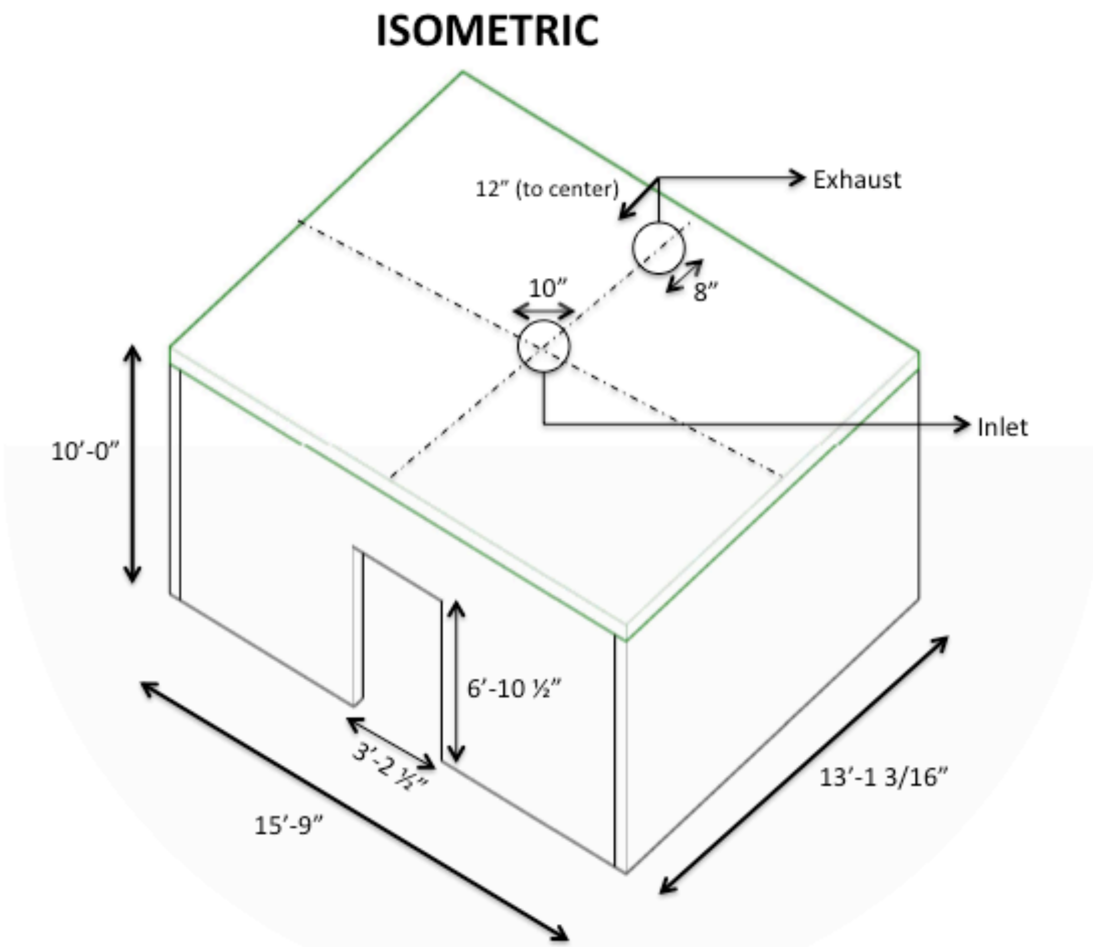

Figure 3: Schematic of testing chamber

Structural insulated panels, or SIPS, were chosen for the walls and structure of our testing chamber due to their high strength, energy efficient and cost effective advantages. The panels, shown in Figure 4, consist of an insulating foam core sandwiched between two oriented strand boards (OSB). These insulated panels were the material of choice for our construction because SIPs costs roughly the same as building with a wood frame when factoring in the labor savings resulting from shorter construction time and less hardware. SIPs also provide the advantage of meeting air infiltration requirements without any additional air sealing measures that would otherwise be needed on wood frame structures.

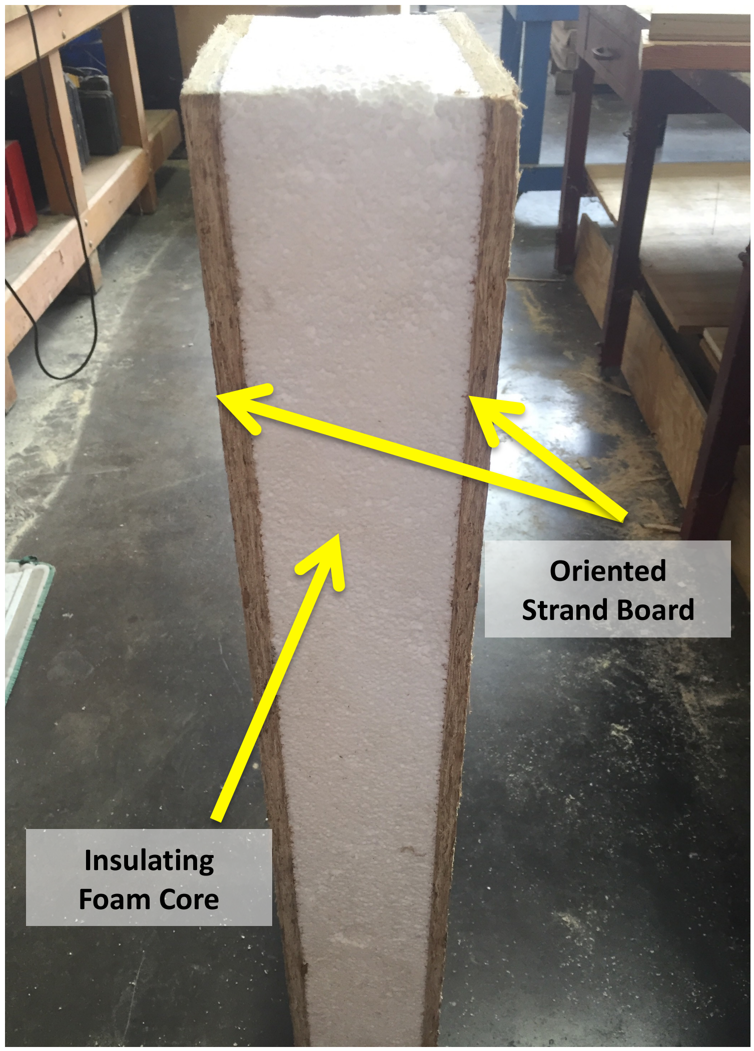

Figure 4: Material composite of Structurally Insulated Panels (SIP)

The air infiltration testing of the chamber was performed by DPIS Engineering Incorporated. At a pressure of 50 Pa, the leakage was measured to be 57 cfm (27 L/s). Given that the volume of the chamber is ~52 m^3, the corresponding air changes per hour was calculated to be 1.86 ACH. Given that the maximum air infiltration rate of the chamber is 2.5 ACH, the constructed chamber was determined to be acceptably airtight. A full report of the air infiltration test results can be found in Appendix H.

4.3 Range Hood and Cabinetry

Range hoods are often designed and manufactured for a variety of different shapes and sized. Because range hoods are not all the same dimensions, the cabinets were designed to mount onto horizontally adjustable rails, so that they would make contact with any sized range hood. Different range hood manufacturers recommend different installation heights for the user depending on the size and geometric design of the unit. For this reason, vertically adjustable rails were incorporated in the design so that the affect of range hood mounting height on capture efficiency can easily be analyzed.

Additionally, a custom wood frame was designed and built to accompany different sized range hoods. The framework was strategically designed so that any sized range hood can be quickly mounted onto the adjustable rails. Metal shims can also be used when mounting the range hood to ensure that the unit under test is level in both the x- and z- directions. The track systems for both the cabinets and range hood can be shown in Figure 5.

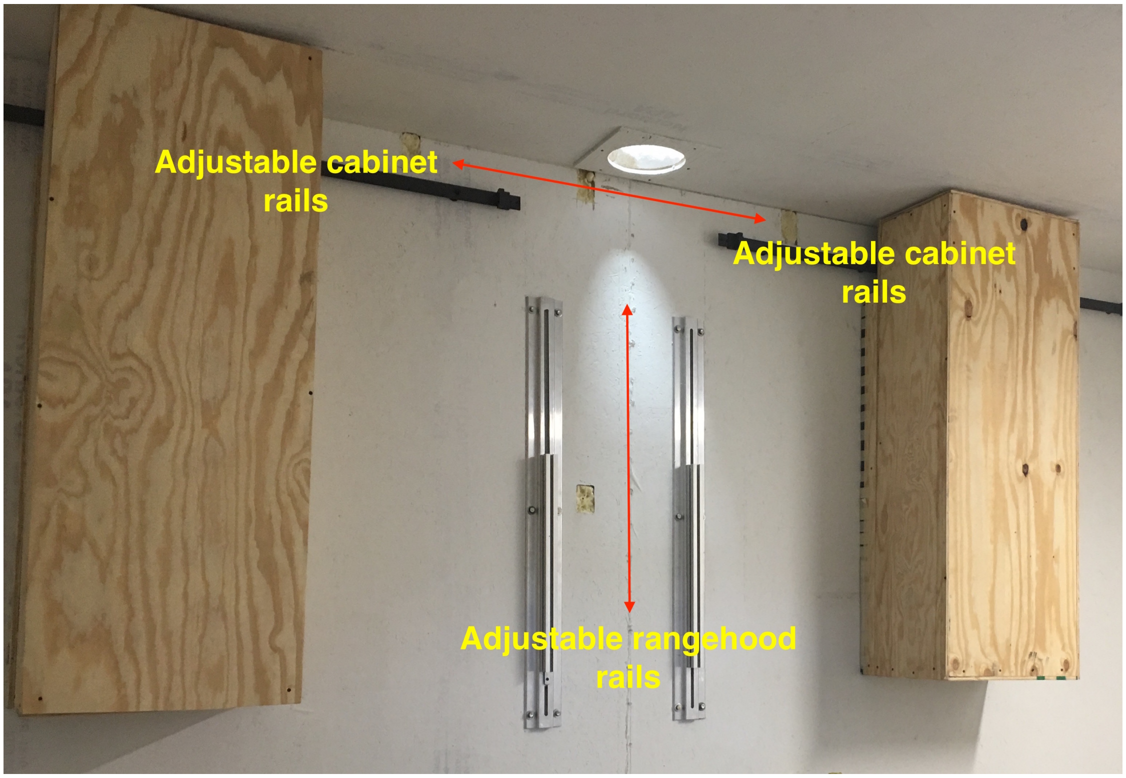

Figure 5: Adjustable railing system for range hood and cabinetry

The cabinetry was built in-house using plywood and angle brackets, and was designed to be 61” (1.54 m) long, 22” (0.56 m) wide, and 18” (0.46 m) in depth. The length and width of the cabinets meet the requirements outlined in the ASTM standard, however the length exceeds requirements to accommodate the added height of the test chamber walls. Our test chamber was designed to be 120” in height, which is over 20” taller than the dimensional requirements outlined in the standard. Also, many installation requirements of range hoods recommend a mounting height of 36” above the cooking surface. When factoring in the test chamber height, countertop height, and mounting height recommendations, designing cabinets to satisfy the length requirements would cause the mounted range hood to extend past the bottom of the cabinets. In a typical residential kitchen, range hoods are positioned above the bottom surface of the adjacent cabinets. For this reason, we designed our cabinets to be 61” long to best replicate a residential kitchen setting. Detailed schematics outlining the height discrepancy between the ASTM requirements and our design are shown in Figure 6. The designed cabinetry installed on to the adjustable railing system is shown in Figure 7.

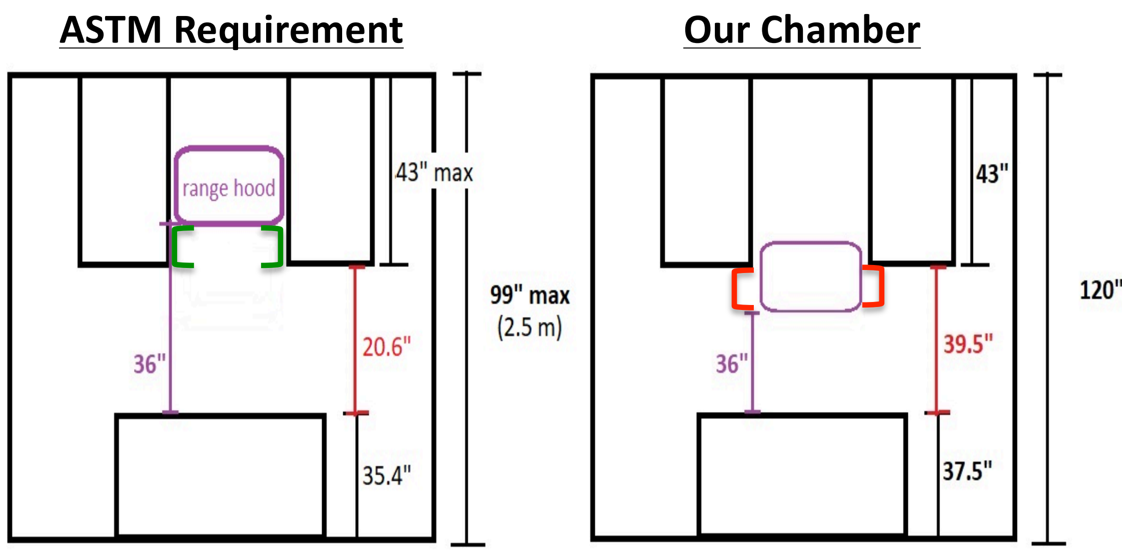

Figure 6: Schematic of height discrepancy of cabinetry requirements

Figure 7: Designed cabinetry installed on adjustable railing system

A workbench was used to simulate the counter top within a residential kitchen. The workbench was selected for its mobility and storage capabilities, and with a slight modification, meets the size requirements outlined in the ASTM standard. The dimensions of the workbench are 76” x 36” x 20”. To accommodate for a shortened depth, a wooden frame was built and installed behind the workbench, thus extending the depth 6” as shown in Figure 8. The range hood, cabinetry, and counter top assembly used for testing is shown in Figure 9.

Figure 8: Workbench and frame used to simulate countertop

Figure 9: Range hood, cabinetry, and cooking countertop assembly

4.4 Chamber Inlet

The inlet of the system was cut on the centerlines of the chamber ceiling, which is 6 feet from the back wall to ensure that the minimum distance between the range hood and inlet is maintained. A simplified version of the Bernoulli's equation was used to determine the necessary size of the air inlet. The formula to determine the inlet area is outlined below:

$$\Delta P = \frac{1}{2}\rho({V_2}^2 - {V_1}^2)$$

Equation 1: Simplified Bernoulli's equation used to determine inlet area

Where ΔP is the differential pressure between the chamber's inlet and exhaust, ρ is the density of air at atmospheric conditions, and V_1 and V_2 are the air flow velocities at the inlet and exhaust, respectively. The differential pressure was assumed to be 5 Pa, which is the maximum chamber depressurization requirement from the ASTM standard. Using an exhaust outlet area of 8 inches, and assuming the maximum range hood flow rate of 200 L/s (~424 cfm) outlined in the standard, the maximum air flow velocity at the exit was calculated to be 6.2 m/s. Based on the values established from valid assumptions, the inlet area was calculated to be 10 inches in order to maintain a chamber depressurization less than 5 Pa at maximum range hood flow rates.

A MERV-11 air filter was positioned on top of the chamber to ensure adequate filtration of incoming air. A diffuser plate, similar to that used by LBNL, was designed and installed to ensure that the inlet air does not disturb the flow pattern of the range hood being tested. MERV-11 filters were used on three sides of diffuser plate for further filtration, and were positioned so that inlet air is delivered in all directions except towards the range hood and emitter assemblies. The filtration system and installed diffuser plate for the chamber inlet is represented in Figure 10.

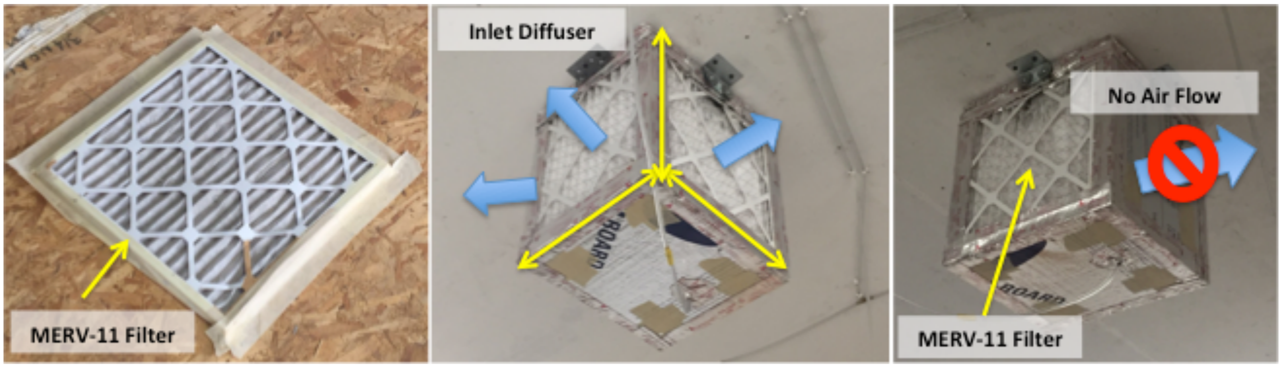

Figure 10: Inlet filter and designed inlet diffuser plate

4.5 Chamber Exhaust

The outlet diameter of the exhaust was dictated by the geometric design of the flow measurement device included in the exhaust duct. The flow measurement device selected was a venturi tube due to its cost effectiveness, low uncertainties, and ease of fabrication. The venturi tube was designed to be in accordance with ISO 5167-4 for measurement of fluid flow by means of a pressure differential advice. After fabrication, the device was inspected by both Brazos Custom Fabrication and lab personnel to ensure conformance to the ISO standard. A detailed schematic used for fabrication and inspection can be found in Appendix K.

To maintain an uncertainty of less than 5% in the flow measurement, certain geometric characteristics of the venturi tube were satisfied. The geometric requirements are represented below (ISO 5167-4, 2003):

- Diameter ratio (β) between 0.4 and 0.7 (*no additional uncertainty)*
- Diameters between 200 mm (7.87”) and 1200 mm (47.24”) (*no additional uncertainty)*

- Fabricated using welded sheet iron (*1.5% baseline uncertainty)*
- 3 duct diameter entry/exit length (*additional 0.5% uncertainty)*
- Diameter deviation of no more than 10% from mean diameter (*additional 0.5% uncertainty)*
- Uncertainty in discharge coefficient (*additional 1% uncertainty)*

The venturi tube, shown in Figure 11, was designed to have a total uncertainty of 3.5%, which meets the requirements outlined in the ASTM standard for capture efficiency.

Figure 11: Venturi tube designed to satisfy uncertainty requirments

An inline fan rated from 0-540 cfm and adjustable damper were installed in the exhaust system to allow for the control of range hood flow rates and to ensure the unit is being tested at a specified rating point (e.g. external static pressure). The exhaust system, detailed in Figure 11, runs from the range hood outlet, through the test chamber, and ends with a duct termination exhausting air to the outdoors.

An air infiltration test was performed by DPIS Engineering on the exhaust system after installation. The air infiltration rate yielded a result of 2.7 cfm (1.3 L/s) at

25 Pa, which is less than the 2.5 L/s rate specified by ASTM. A full report of the air infiltration test performed on the exhaust system is provided in Appendix I.

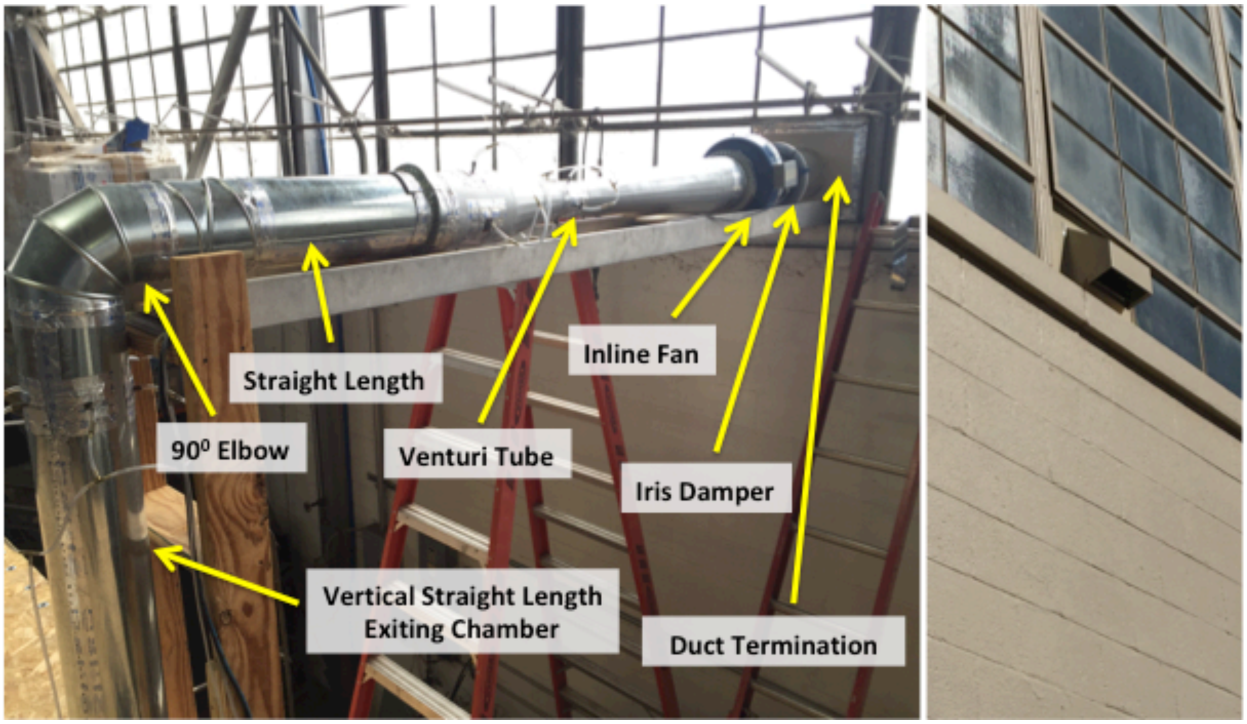

Figure 12: Exhaust system designed to control the range hood flow rate

4.6 Cooking Surface

Because ASTM-E3087.17 requires varying the locations of the heating elements depending on the size of the range hood, the cooking surface will be comprised of three portable electrical heaters. Our lab selected Cadco CSR-3T portable electric burners with a diameter of 7.5", thus meeting the dimensional requirements specified in the ASTM standard. These burners were rated at 120 V and 1.5 kW. In order to meet the power consumption requirements (1 kW), a variable power transformer was connected in line with the burners. From preliminary examination, it was determined that the electric burners normally consume 1.4 kW of power, thus the power transformer was set to a 71% capacity in order to ensure the electric heaters are consuming 1 kW of power during testing. The electric burners connected in line with the variable power transformers are displayed in Figure 13.

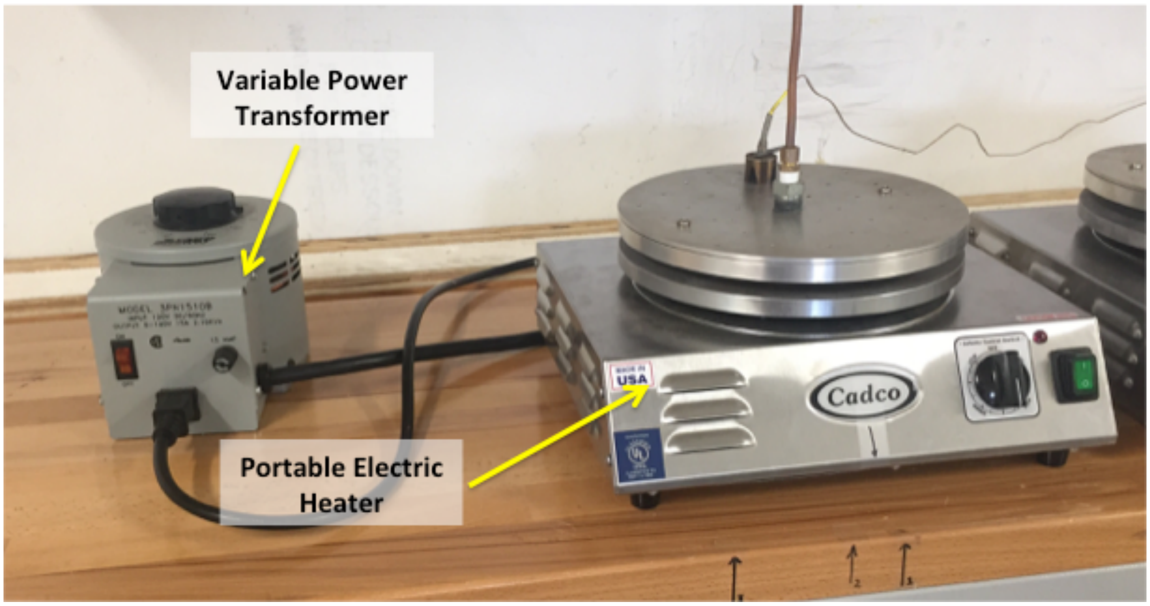

Figure 13: Electric burner and variac used to simulate cook-top

4.7 CO_2 Emitter System

Our lab designed three tracer-gas emitter assemblies that were fabricated by BVD Machining in Bryan, TX. The emitter assembly was designed by the REEL team to meet the specifications recommended by LBNL, and was then verified by lab personnel. The dimensional drawings for the emitter plates can be found in Appendix J. The assembly design allows for copper tubing to be connected at the center of the plates for CO_2 injection.

The ASTM standard specifies that the CO_2 injection rate shall be no greater than 0.5% of the air flow rate through the range hood being tested. Given that the test chamber is designed for air flow rates up to 200 L/s (423 cfm), the maximum CO_2 injection rate was calculated to be 1 L/s (60 lpm). A Cole-Parmer mass flow controller capable of measuring CO_2 mass/volumetric flow rates within the range of 0-100 lpm was selected for our design. The mass flow controller has a maximum operating line pressure of 145 psig and an accuracy of +/- 0.8%.

Our research lab rents a storage container housing six, 50-pound CO_2 cylindrical tanks from Praxair Solutions due to their location and delivery services. It was estimated that six tanks allow for roughly 15-20 full tests to be performed before running empty. For the safety of lab personnel and instrumentation, a gas regulator connected inline with the CO_2 cylinders is required. A single-stage inert gas regulator with an operating pressure range of 0-100 psi was selected, as it conforms to the line pressure requirements of the mass flow controller. When emitting tracer gas, it is recommended to adjust the regulator to 35 psi for optimal results, as the mass flow controller being used was calibrated at this operating pressure. An inline CO_2 heater is connected in between the regulator and CO_2 cylinder to prevent CO_2 regulator freeze-up and further damage. An image of the CO_2 emitter system, outlined in Figure 14, shows the process of tracer gas flowing from the cylinders to the emitter assemblies on the cooking surface.

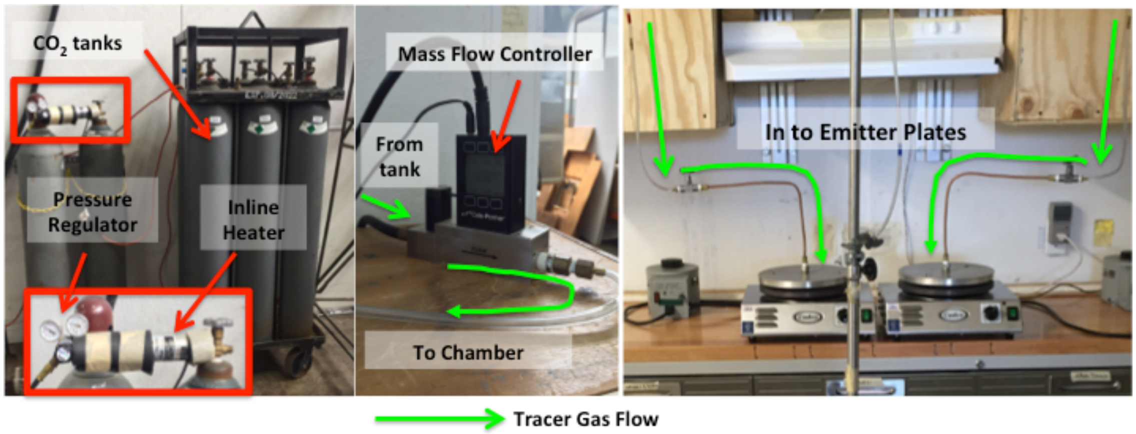

Figure 14: CO_2 emitter system used to simulate generated pollutants

4.8 CO_2 Detection System

The designed CO_2 detection system, shown in Figure 15, consists of a CO_2 gas analyzer along with a directional control valve to allow for analyzing multiple different sample locations using the same instrument. Previous studies showed that the maximum CO_2 reading in the exhaust, at the injection rate specified, typically does not exceed 3,000 ppm (Yang-Seon, et. al, 2018). Using a conservative estimate, our research lab purchased a gas analyzer ranging from 0-5,000 ppm, with an accuracy of 0.3%. The SBA-5 CO_2 gas analyzer, supplied by PP Systems, performs an 'auto-zero' function at regular intervals to ensure accuracy and frequent analyzer calibration. The gas analyzer is connected to an 'auto-zero' column that brings air into the unit filtered free of CO_2 in order to set a reference point for the infrared technology used to determine CO_2 concentration. Ambient air passes through the Sofnolime beads within the column, which removes the CO_2 from the air before passing into the gas analyzer.

The directional control (solenoid) valve, purchased from Valco Industries, has the capability for cycling between eight different sampling points. There are only three CO_2 sample locations needed to determine the capture efficiency, so the remaining five ports of the valve remain sealed. The valve is controlled manually using the provided hardware, so that the researcher can cycle between the sampling locations.

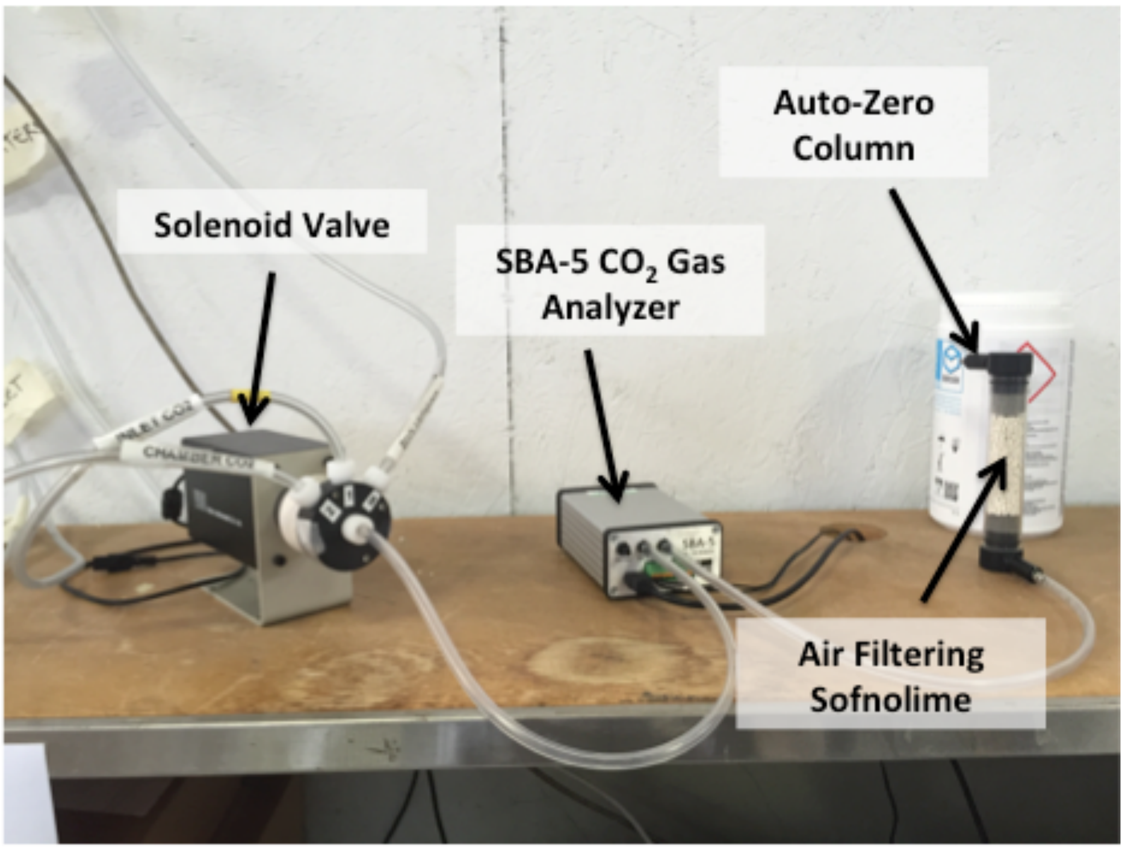

Figure 15: CO_2 detection system used to measure location concentrations

Three different sampling tubes, detailed in Figure 16, were installed within the system. To conform to the requirements outlined in the ASTM standard, certain measures were taken to ensure proper placement of the sampling tubes. The sampling tube for the chamber's CO_2 concentration was fixed to a mobile and vertically adjustable frame so that the tube can be positioned halfway between the cooking surface and range hood at various mounting heights. The sampling tube for the exhaust's CO_2 concentration was positioned 10 duct diameters downstream of the range hood, and consists of five sample points across the cross-section of the duct. Lastly, the sampling tube of the ambient CO_2 concentration was strategically positioned and fixed to the diffuser plate, facing the inlet of the chamber.

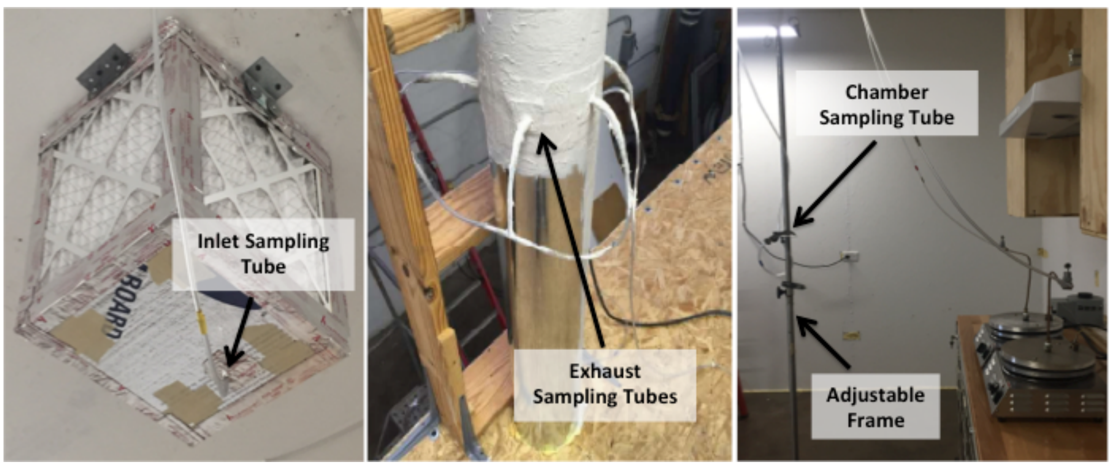

Figure 16: Three CO_2 sampling locations to determine capture efficiency

4.9 Instrumentation

The instrumentation selected for capture efficiency testing using tracer gas monitoring is shown in Table 1. In addition to the instrument/sensor name, also tabulated are the manufacturer, model number, measurement quantity/purpose, sensor range and measurement uncertainty.

Table 1: Sensors and instrumentation selected for design

Device	MFG/Model No	Measuring Quantity/Purpose	Range/Uncertainty
Temperature Sensor	McMaster/6445 T68	Emitter plate surface temperature	32 - 1000°F / ±0.75%
Temperature Sensor	AcuRite/00829	Chamber temperature measurement	32 - 122ºF / ±1°F
CO_2 Mass Controller	Cole-Parmer / 32907-75	CO_2 mass and volume flow rate and control	0.05-100 L/min / ±0.8%
CO_2 Cylinder	N/A	Tracer Gas Source	N/A
CO_2 Regulator Valve	ProStar/PRS235 01	Regulates pressure to mass flow controller	0-100 psi
Precision Energy Meter	Watts-On Mark II/	Monitor Power Consumption of Electrical Heaters	0-10 Amps / 0.1% (A), 0.1% (W)
In-line heater	ProFax/CO2-heater	Prevents frost build-up in CO_2 line	N/A
CO_2 sensor	PP Systems / SBA-5	CO_2 concentration measurement	0-5000 ppm / ±0.3%
CO_2 Solenoid Valve	Valco/C45R-8148EMT	Multiple Sampling points using same CO_2 sensor	8 position selection
Pressure transducer	Setra/264	Measures pressure drop across venturi tube	0-3 in. H_2O / ±0.4%
Pressure transducer	Setra/264	Measures chamber depressurization	0-1 in. H_2O / ±0.4%
NI-DAQ TC	National Instruments/9213	Temperature DAQ	-200-1300 ±0.02ºC
NI-DAQ Analog In	National Instruments/9207	Analog Input DAQ	0-10V_{DC} / ±0.52%
NI-DAQ Analog Out	National Instruments/9263	Analog Output DAQ	-10 – 10V / ±0.35%
Tachometer	Monarch/ACT-3X	Measuring range hood RPM	0-99999 rpm / ±0.04%
Inline fan	Vents/VKM-200	Make-up air for range hood rating points	0-541 cfm
Iris Damper	Fantech/IR-8	Increasing chamber static pressure	K=220-1600

5. DATA ANALYSIS METHODOLOGY

5.1 Overview

The capture efficiency of the unit is calculated by using the measured tracer gas concentrations at three different locations: the chamber inlet (C_{inlet}), inside the exhaust ducting ($C_{exhaust}$), and inside the test chamber at a specified location from the cooking surface and range hood ($C_{chamber}$). The formula detailing the capture efficiency (CE) is:

$$\boldsymbol{CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}}}$$

Equation 2: Capture Efficiency Equation Using Ratios of Differences

The strategy for using ratios of differences to calculate the capture efficiency is to eliminate the bias error when taking measurements. The equation for capture efficiency yields a fraction, but capture efficiency will be expressed as a percentage, with 100% meaning the range hood has captured all of the emitted tracer gas.

5.2 Uncertainty

Precision and temporal based errors both contribute to the uncertainty of the capture efficiency measurements.

Precision Error

The precision error is a combination of the accuracy of the tracer gas analyzer and the spatial variations in concentration, and arises because the tracer gas is not spatially uniform. The precision error for the exhaust concentration can be effectively assumed to be zero because the multiple sample locations and distance from the unit conform to the requirement outlined in ASTM E2029. The precision error for the inlet concentration can also be assumed to be zero because the inlet stream is a combination of well-mixed ambient sources. The precision error for the chamber concentration can be calculated by taking the root mean square of the difference between each tracer gas concentration measured and the overall average concentration recorded.

Temporal Error

The temporal error of the tracer gas measurements is derived from the standard error of mean concentration values for each 10-point sample. SEM is calculated by dividing the standard deviation for each data set by the square root of the sample size.

Total Error

The total error of the concentrations combines both the precision and temporal error, and can be calculated with the formulas:

$$\delta(C_{location}) = \sqrt{\left(\delta_p(C_{location})\right)^2 + \left(\delta_{se}(C_{location})\right)^2}$$

Equation 3: Combining precision and temporal errors to calculate a total error for tracer gas concentration measurements

This general equation can be used to find the total error for tracer gas measurements at all three locations. The total error for tracer gas measurements at all three locations is combined to calculate the total error in capture efficiency using the formula:

$$\boldsymbol{\delta(CE) = CE\left[\sqrt{\frac{\left(\delta(C_{exhaust})\right)^2 + \left(\delta(C_{chamber})\right)^2}{(C_{exhaust} - C_{chamber})^2} + \frac{\left(\delta(C_{exhaust})\right)^2 + \left(\delta(C_{inlet})\right)^2}{(C_{exhaust} - C_{inlet})^2}}\right]}$$

Equation 4: Combining total error and concentration of tracer gas to derive the total error in capture efficiency for the unit under test

5.3 Methodology

A software code using the LabVIEW program was written to perform the necessary data acquisition needed during the testing process. The software was designed to measure the range hood exhaust flow rate through the venturi tube, the chamber depressurization, and the surface temperature of the hot plates. In addition, the software is also used to record the CO_2 concentration of the different sampling locations, determine the steady state time required before beginning concentration measurements, and adjust the mass flow rate of CO_2 injected into the emitter plates. A screen shot of the LabVIEW user interface for the data acquisition process is shown in Figure 17.

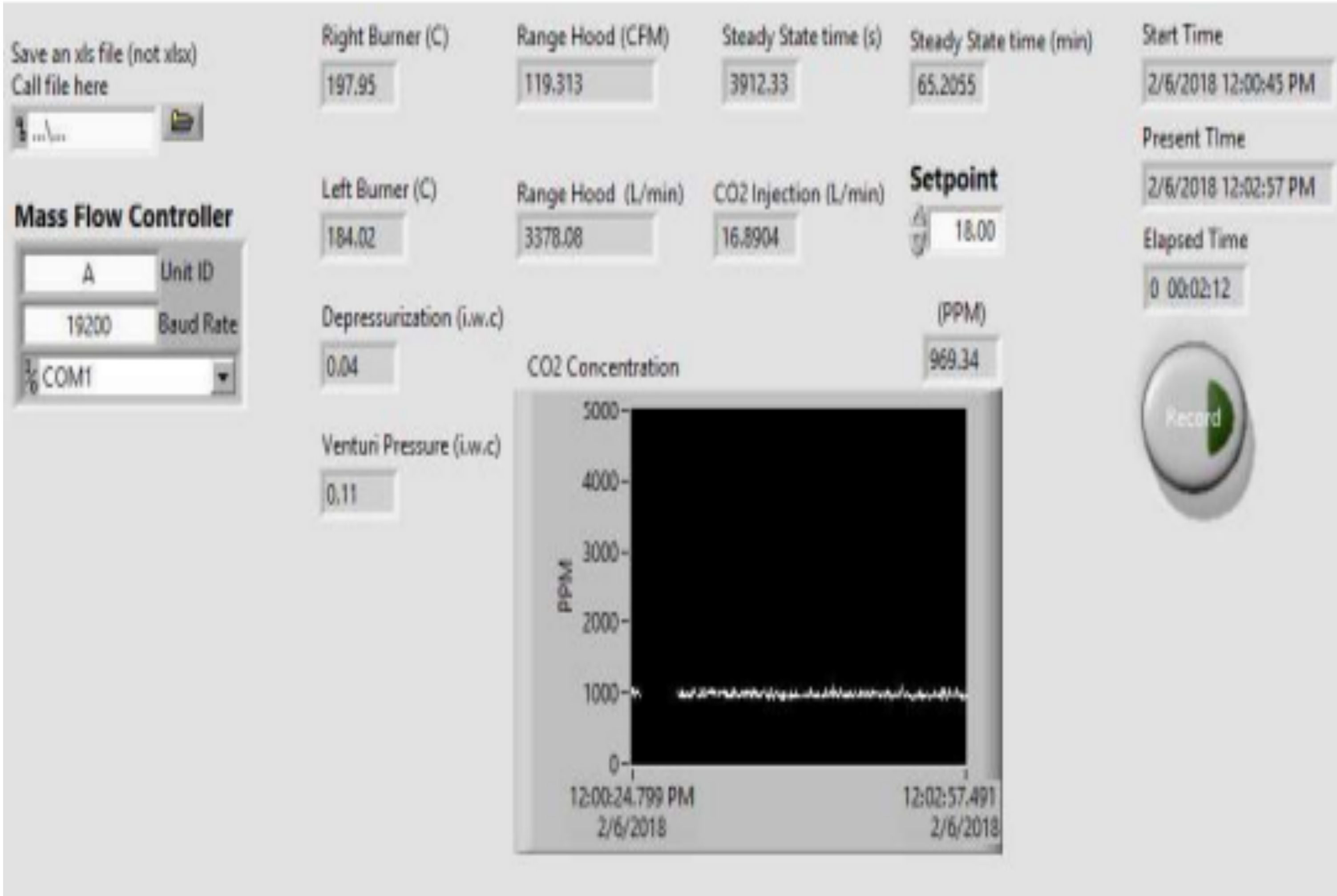

Figure 17: User interface for data acquisition software

To begin, the range hood will be installed conforming to the manufacturers instruction provided by the installation and operating manual. The installation height, or distance between the bottom edge of the range hood and the countertop, must be recorded along with the chamber's ambient temperature before testing. The range hood will then be turned on and adjusted to the desired operating speed (low speed, high speed, etc.), and the auxiliary fan may also be used to obtain the target air flow rate through the range hood. After obtaining the target air flow rate of the range hood the heating elements shall be turned on and adjusted using a variable transformer to maintain a surface temperature of 200 ^{0}C +/- 10 ^{0}C while maintaining the power consumption of the electric heaters at 1.0 +/- 0.1 kW. The tracer gas will be injected into the system, and the injection rate must be adjusted so that the measurement device's accuracy is less than 1% of the difference in concentrations between $C_{exhaust}$ and $C_{ambient}$. The tracer gas injection rate must also be less than 0.5% of the air flow rate of the range hood.

The steady state time of the system can begin once the air flow rate, heating elements, and CO_2 are all operating or entering the chamber. Steady state will be reached after four air changes of the test chamber have been completed. After reaching steady state, the tracer gas concentrations at the three different locations will be averaged over a 10-minute (minimum) period with a minimum of 10 tracer gas concentration measurements at each location. The flow rate through the range hood, power input to the heating elements, surface temperature of the emitter assembly, and chamber temperature must also be averaged over the same time period of the tracer gas measurements. After the testing is complete, the capture efficiency and standard error will be calculated and reported, along with the range hood flow rate, power consumption, surface temperatures, and chamber temperature.

Based on the amount of time required to achieve steady state, it is estimated that each test will take approximately 1.5-2.5 hours. This time is comprised of an approximate 30-minute set-up, 1-1.5 hour runtime, and 30 minutes estimated to uninstall the unit and generate the capture efficiency test reports.

A detailed version of the test procedure, including individual steps and illustrations, was created so that future students can be easily trained and prepared for capture efficiency testing. This test procedure, outlined in Appendix C, references the current ASTM standard draft and LBNL reports for capture efficiency testing of domestic range hoods. It should be noted that a formal and official procedure will be developed in cooperation with HVI after the completion of this project. Therefore, the procedure described is currently based on preliminary research.

6. DATA ANALYSIS

6.1 Overview

A total of five different kitchen exhaust fan units were installed and tested between two capture efficiency technicians. In order to protect the privacy of our customers, the exhaust fans were labeled Fan A – Fan E[1]. Of the five different units tested, four were kitchen range hoods while one, Fan D, was a microwave oven with an exhaust fan. Fan A had depth and width dimensions of 18.625" x 30". Fans B and E had depth and width dimensions of 35.375" x 19.125" and 20.87" x 30", respectively. Fan D, the microwave, had width, depth and height dimensions of 29.88" x 15.4" x 16.45".

Between the five units, a total of 36 capture efficiency tests were conducted at different mounting heights, exhaust flow rates, and cooking surface temperatures. The results of the tests that were analyzed, along with other procedural requirements, are provided in Appendix A. The repeatability of these results, along with the impact of air flow rate, mounting height, and surface temperature on the capture efficiency of the ventilation system is highlighted throughout the remainder of this section.

6.2 Effects of Range Hood Flow Rate

Fans A, B, C were each installed at a mounting height of 27 inches above the cooking surface. While conducting the tests, the CO_2 injection rate was 0.5% of the range hood flow rate. The surface temperatures of the emitter plates were closely held

[1] It was asked by the manufacturers of Fan C to keep all aspects of their design in privacy as the product has yet to enter final production.

between 150 ^{0}C +/- 10 ^{0}C while recording the CO_2 concentrations at each location. Each fan was designed to incorporate three speed settings using an adjustable knob, namely “Low”, “Medium” and “High”. Fan C had four speed settings – “Low”, “Medium-Low”, “Medium-High”, and “High”. Fan A was tested at Low speed, Fan B was tested at Low and High speeds, and Fan C was tested at Low, Medium-Low, and Medium-High speeds.

Figure 18 outlines the effects of air flow rate on range hood capture efficiency. Each range hood tested along with the speed setting used has a unique symbol and color. From observation, there is a positive correlation between the range hood air flow rate and the measured capture efficiency, meaning as air flow rate increased the capture efficiency of the tested unit also increased. The variability of capture efficiency is much more significant at low air flow rates compared to high air flow rates. At air flow rates less than 100 cfm (~47 L/s), capture efficiencies varied from 55% to 82%, while air flow rates above 150 cfm (~70 L/s) yielded more consistent capture efficiencies from 86% to 92%. Such variability in capture efficiency at flow rates less than 100 cfm shows that the geometry and design of a range hood is a significant factor of its performance at lower air flow rates. For example, Fans A and B were tested at ‘Low’ speed settings with air flow rates < 100 cfm. Fan B performed significantly better than Fan A at similar air flow rates (79-82% capture efficiency compared to 65-67%). Fan B, being 6” wider than Fan A, covered the entire distance of the cooktop burners from end-to-end, resulting in a much greater capture efficiency.

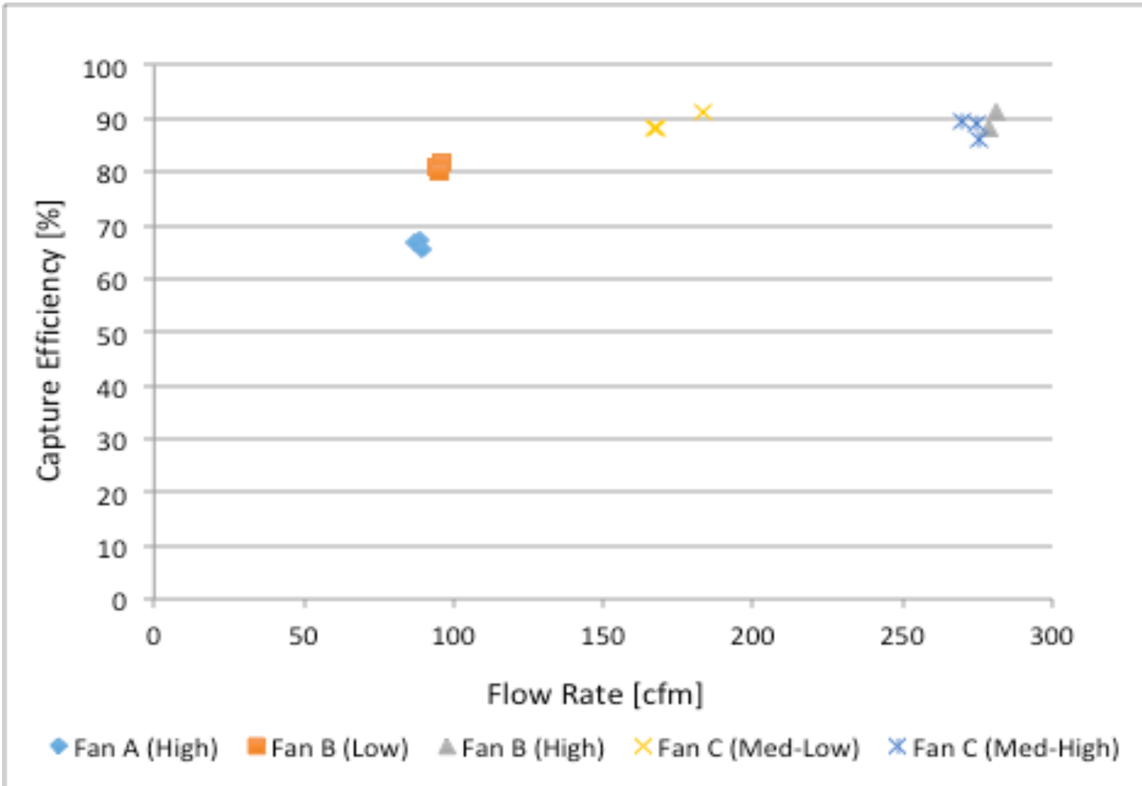

Figure 18: Effects of air flow rate on capture efficiency

6.3 Effects of Mounting Height

Fan G was used to evaluate the effects of mounting height on range hood capture efficiency. Two different mounting heights were used for this analysis; a "Low" mounting height of 21 inches, and a "High" mounting height of 30 inches. For each of the mounting heights, two speed settings were tested, namely "Low" speed and "High" speed. The CO_2 injection rate (0.5% of the range hood flow rate) and surface temperatures of the emitter plates (150 ^{0}C +/- 10 ^{0}C) remained consistent throughout the series of tests.

Figure 19 shows the capture efficiency of each test plotted against the measured air flow rates, and outlines the effects of mounting height on range hood performance.

When operating at “Low” speed, the average capture efficiency was 67.7% and 77.8% for mounting heights of 21 inches and 30 inches, respectively. At “High” speed, the average capture efficiency was 88.2% and 90.3% for mounting heights of 21 inches and 31 inches, respectively. The percent differences in the measured capture efficiency at different mounting heights for “Low” and “High” operating speeds were calculated to be 2.3% and 12.9%. By observation, range hoods mounted at lower mounting heights will have higher capture efficiencies compared to higher mounting heights. The mounting height has a much more significant impact on range hood performance at air flow rates less than 150 cfm.

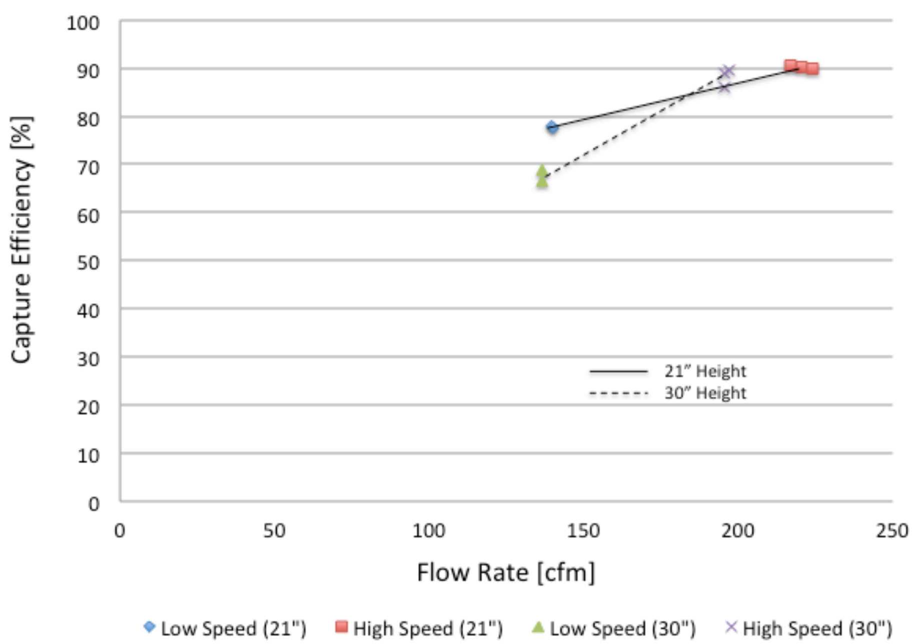

Figure 19: Effects of mounting height on capture efficiency

6.4 Effects of Cooking Surface Temperature

Fan D was used to evaluate the effects of cooking surface temperature on range hood capture efficiency. Surface temperatures of 150 ^{0}C +/- 10 ^{0}C ("Low") and 200 ^{0}C +/- 10 ^{0}C ("High") were used for this analysis. For each of the cooking surface temperatures, two speed settings were used, namely "Low" speed and "High" speed. The CO_2 injection rate (0.5% of the range hood flow rate) and range hood mounting height (16 inches) remained consistent throughout the series of tests.

Figure 20 outlines the effects of cooking surface temperature on range hood capture efficiency at two different speed settings. When operating at "Low" speed, the average capture efficiency measured was 66.4% and 55.6% for surface temperatures of 150 ^{0}C and 200 ^{0}C, respectively. At "High" speed, the average capture efficiency was 79.9% for a surface temperature of 150 ^{0}C, and 74.3% for a surface temperature of 200 ^{0}C. The percent differences in measured capture efficiency at different cooking surface temperatures for "High" and "Low" operating speeds were 7.1% and 16.3%, respectively. By analyzing these results, a range hood will have a higher capture efficiency when using a kitchen's cooking top at lower temperatures. The cooking surface temperature has a more significant impact on range hood performance at low air flow rates, although there is still a significant impact at higher flow rates.

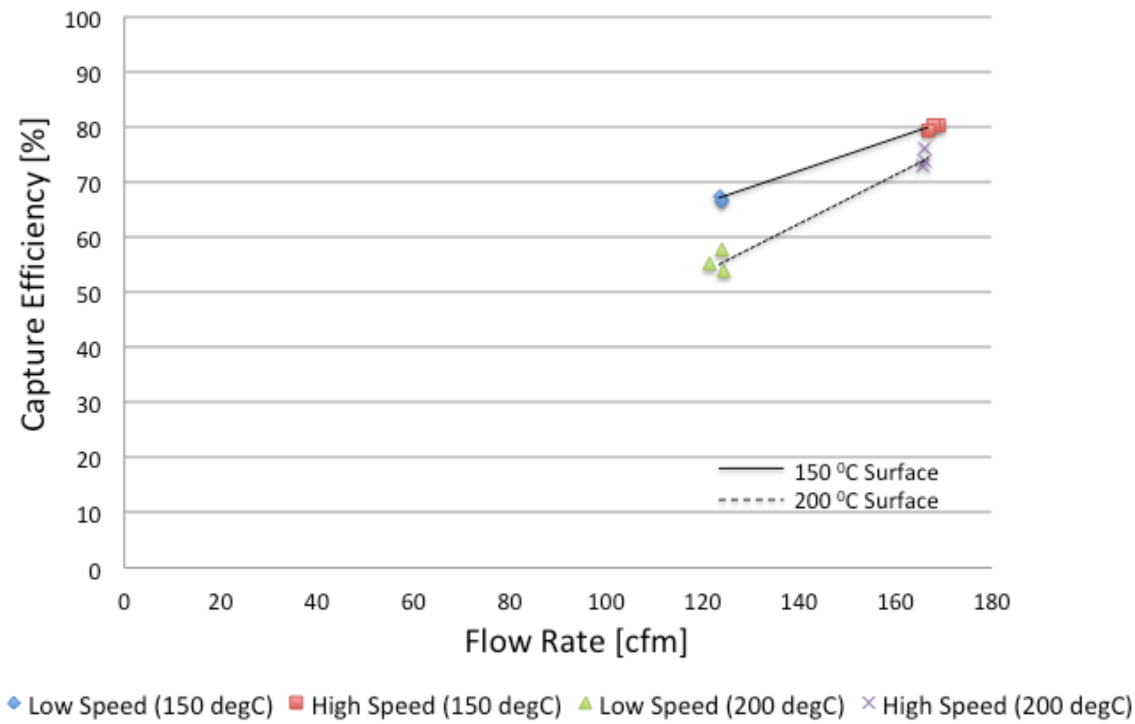

Figure 20: Effects of cooking surface temperature on capture efficiency

6.5 Repeatability

Calculating the standard deviation of repeated tests, although a small sample size, is a good tool to quantify the repeatability of the results. The lower the standard deviation value, the more repeatable the measured results are.

When evaluating the effects of mounting height, flow rate, and cooking surface temperature, multiple tests at the same operating conditions were repeated. Conducting the same test at the same operating conditions allowed our lab to analyze the repeatability of our system and testing process. The detailed results of the different series of tests are obtainable in Appendix B.

When evaluating the range hood flow rates effect on capture efficiency, 5 different series of repeated tests were conducted. Figure 21 shows the quantified repeatability of each series of tests plotted against the measured air flow rate of the range hood. Each symbol represents a different series of tests conducted at a different flow rate. Figure 21 shows a negative effect between air flow rate and quantified repeatability, meaning as the flow rate increased the standard deviation across repeated tests also increased. This means that our system produces more repeatable results at lower flow rates compared to higher flow rates.

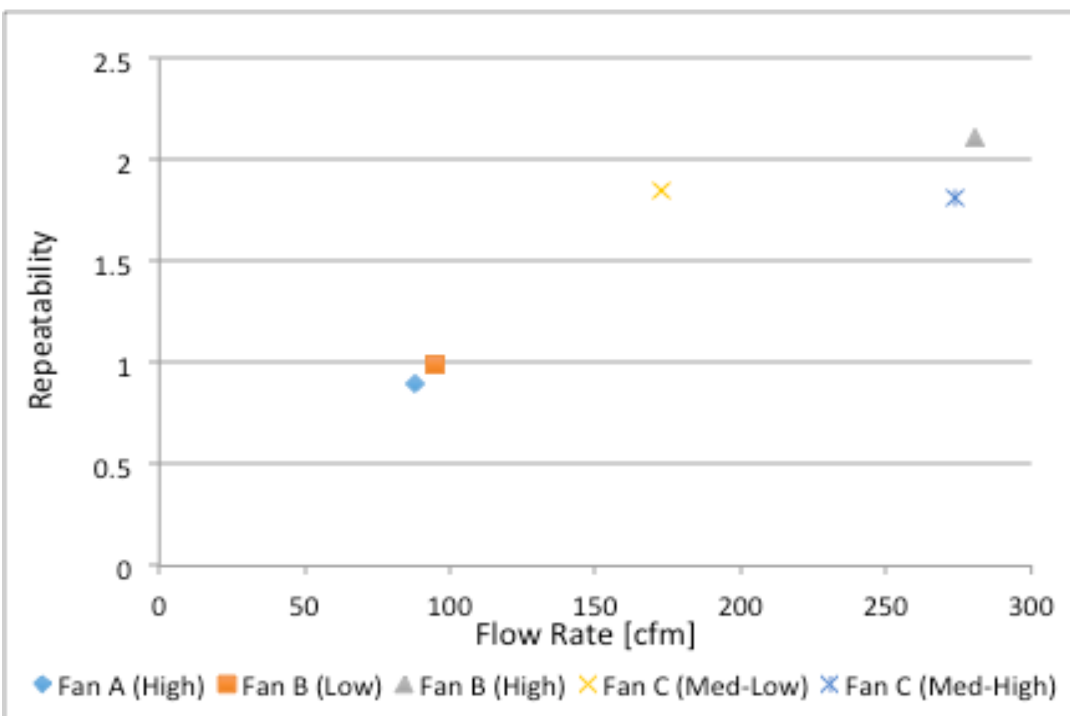

Figure 21: Effects of air flow rate on repeatability of system

When evaluating the effects of mounting height on capture efficiency, 4 different series of repeated tests were conducted. Figure 22 shows the quantified repeatability of each series of tests plotted against the measured air flow rate, and outlines the effect of mounting height on the repeatability of results. From observation, there is a significant increase in quantified repeatability when increasing the mounting height of the range hood. This means that the measured values for range hood capture efficiency are much more consistent at lower mounting heights when all other parameters are held constant.

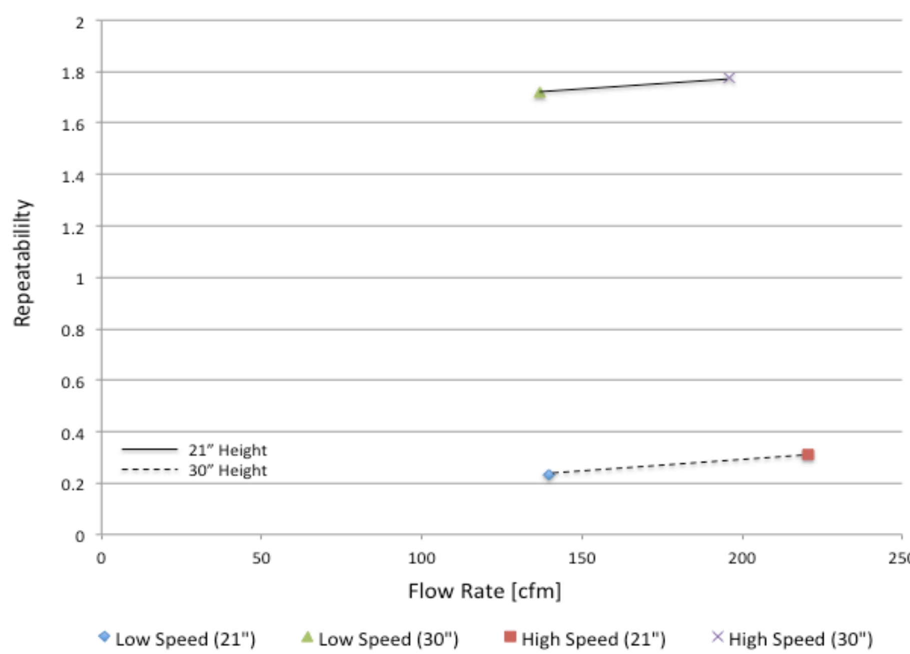

Figure 22: Effects of mounting height on repeatability of system

When evaluating the effects of cooking surface temperature on capture efficiency, four different series of repeated tests were conducted. Figure 23 shows the quantified repeatability of each series plotted against the measured air flow rate, and outlines the effect of surface temperature on the repeatability of results. Similar to the mounting height effects, there is a significant increase in quantified repeatability when increasing the cooking surface temperature. This shows that the measured values for range hood capture efficiency are much more consistent at lower cooking surface temperatures when all other parameters are held constant. An important observation is that the repeatability of the results improves significantly when increasing the air flow rates at the a cooking surface temperature of 200 ^{0}C. This explains that at higher cooking surface temperatures, range hoods operating at higher flow rates are much more consistent at absorbing generated pollutants.

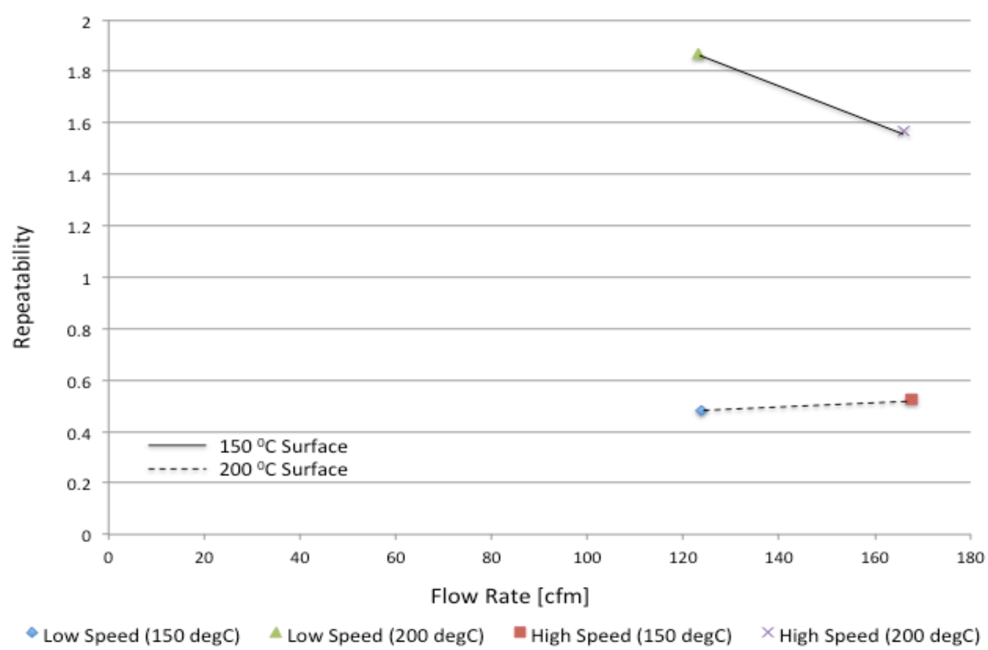

Figure 23: Effects of cooking surface temperature on repeatability of system

It is important to note that only two, three, or four repeated tests were conducted for each series analyzed. A small sample size for each series was recommended due to the availability of CO_2 and other objectives of this research. To further ensure the repeatability of our system and testing procedure, more series of tests with larger sample sizes is recommended.

7. CONCLUSIONS

Lawrence Berkeley National Laboratory (LBNL) has been working in coordination with the American Society for Testing and Materials (ASTM) to develop and publish a test standard for analyzing a kitchen range hood's performance using a metric derived as capture efficiency. The capture efficiency of a range hood is the fraction of pollutants emitted during cooking activities that are vented directly to the outside environment.

RELLIS Energy Efficiency Laboratory (REEL) at Texas A&M University was tasked to design, develop, and construct a new testing facility, resembling a residential kitchen, for range hood capture efficiency. Seven key components of the testing facility were established according to the requirements previously developed by LBNL. The seven components of the test facility are the test chamber, chamber inlet, chamber exhaust, range hood and cabinetry, cooking surface, CO_2 emitter system, and CO_2 detection system.

The walls and structure of the test chamber were built using structurally insulated panels (SIPs) due to their energy efficient and cost effective advantages. The dimensions of the test chamber were designed to be slightly larger than the required dimensions to accommodate for the future development of a test method for island range hoods. The air infiltration of the test chamber was measured to be 1.86 ACH, which satisfies the requirement of 2.5 ACH.

Adjustable rails for both the range hood and cabinetry were used to accommodate for testing various sized range hoods at various mounting heights. The cabinetry, built in-house, meets the depth and width requirements outlined in the test standard. The length of the cabinetry, although exceeding the requirements, was designed so that the cabinetry can make contact with the ceiling while extending lower than range hoods tested at lower mounting heights. A mobile workbench satisfying the dimensional requirements was chosen to represent a cooking surface.

The inlet was sized to 10 inches to accommodate a chamber depressurization of 5 Pa, and a diffuser plate was designed so that incoming air would not disturb the flow pattern of the range hood being tested. A venturi tube was designed with geometric requirements satisfying a maximum flow measurement uncertainty of 5%. An inline fan and damper were installed to allow for the control of range hood flow rates, and the exhaust duct was designed to vent outside of the lab. The measured air infiltration rate of the exhaust system was 1.3 L/s, which satisfies the 2.5 L/s requirement.

Portable electric heaters were selected so that the cooking surface can be positioned according to the range hood width. A variable power transformer was connected in line with the heaters to maintain a power consumption of 1 kW during the course of a test.

Tracer gas emitter assembly plates were designed to the specifications outline by LBNL. A mass flow controller with a range of 0-100 lpm and accuracy of 0.8% was selected, meeting the requirements outlined in the test standard. 6 CO_2 cylindrical tanks are used to supply tracer gas, with both an inline heater and pressure regulator attached for proper safety measurements.

A 0-5,000 ppm CO_2 gas analyzer with an accuracy of 0.3% was selected based on the established requirements and expected exhaust concentrations. A directional control valve was also utilized so that the three sampling locations for CO_2 concentration can be analyzed by using the same device. All instrumentation and data-acquisition equipment was properly calibrated and verified before beginning testing.

From the five range hoods tested, a total of 36 capture efficiency tests were conducted at various air flow rates, mounting heights, and cooking surface temperatures. Measured capture efficiency increased with increasing air flow rates. At flow rates < 100 cfm capture efficiencies were measured to be between 55-82%. Such a large variance in measured capture efficiency suggests that the geometry and design of a range hood is a significant factor of its performance when operating at lower speeds. Design factors were evaluated by analyzing the capture efficiencies of Fans A and B when operating at similar flow rates (~100 cfm). The width of Fans A and B were measured to be 30" and 36", respectively. Fan B, whose width covered the entire area of the cooking surface, yielded capture efficiencies between 79 and 82%. This measured performance was much better than Fan A with its smaller width, which yielded capture efficiencies of 65-67%. At flow rates > 150 cfm, the geometry and design of the range hood proved to be much less of a factor for range hood performance, with measured capture efficiencies between 86% and 92%.

Mounting heights of 21” and 30” were used to analyze the effects of mounting height on range hood performance. At flow rates ~140 cfm, average capture efficiencies were measured to be 77.8% at 21” and 67.7% at 30”, with a percent difference of 12.9%. At flow rates ~190 cfm, capture efficiencies were measured to be 90.3% (21”) and 88.2% (30”) with a percent difference of 2.3%. The large percent difference in measured capture efficiency at flow rates ~140 cfm shows that mounting height has a more significant impact on the performance of range hoods operating at ‘Low’ speeds compared to ‘High’ speeds.

Cooking surface temperatures of 150 ^{0}C of 200 ^{0}C were also used to analyze the effects of cooking temperatures on range hood performance. At air flow rates ~125 cfm, the average capture efficiencies were found to be 66.4% at 150 ^{0}C and 55.6% at 200 ^{0}C, with a percent difference of 16.3%. At air flow rates ~165 cfm, capture efficiencies were measured to be 79.9% and 74.3% at surface temperatures of 150 ^{0}C and 200 ^{0}C, respectively, with a percent difference of 7.1%. Similar to the mounting height, the effects of surface temperature are much more significant at low operating speeds. When comparing the effects of mounting heights and surface temperatures at high flow rates, the percent differences illustrate that cooking temperature has more of an impact on range hood performance.

For each parameter (air flow, mounting height, surface temperature) evaluated, multiple tests were taken under the same conditions to evaluate the repeatability of the system. Measuring the standard deviation for a series of tests is an effective tool to quantify how repeatable the test results are. A standard deviation of 0 means that all test results are identical, thus the smaller the standard deviation, the more repeatable the results are. Measured values of repeatability were more consistent at low air flow rates < 100 cfm. When analyzing the results for different mounting heights, the quantified repeatability at flow rates of ~140 cfm was measured to be 0.23 and 1.72 for mounting heights of 21” and 30”, respectively. At flow rates of ~200 cfm, the repeatability was measured to be 0.31 at 21” mounting heights and 1.78 and 30”. At surface temperatures of 150 ^{0}C and 200 ^{0}C, repeatability was measured to be 0.48 and 1.87 at flow rates of ~125 cfm, and 0.53 and 1.57 at flow rates ~165 cfm, respectively. To further ensure the repeatability of our system and testing procedure, more series of tests with larger samples sizes is recommended.

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APPENDIX A

CAPTURE EFFICIENCY TEST RESULTS

(See next **2** pages)

Test Fan	Speed	Q_{Hood} [cfm]	Mounting Height [in]	Steady -state time [min]	CO_2 injection rate [L/min]	Right Burner T_{avg} [^0C]	Left Burner T_{avg} [^0C]	CE [%]	Uncertainty in CE [%]
A	High	88.5	26	77	13	142.1	148.9	67.14	0.97
A	High	87.3	26	84	13	162.7	159.5	66.83	3.26
A	High	89.4	26	88	13	157.7	153.0	65.45	1.33
B	Low	94.2	27	77	13	148.4	155.8	81.00	1.12
B	Low	95.8	27	81	13	175.0	154.9	81.86	1.3
B	Low	95.1	27	81	13	172.8	151.0	79.88	0.93
B	High	281.6	27	26	35	140.7	137.7	91.21	1.72
B	High	279.1	27	27	35	121.6	153.6	88.23	1.26
C	Med-Low	167.9	27	45	23	156.1	166.1	88.16	0.89
C	Med-Low	167.0	27	48	23	145.3	144.2	88.09	1.32
C	Med-Low	183.7	27	37	23	144.2	153.6	91.32	0.88
C	Med-High	269.9	27	30	35	136.2	147.8	89.58	0.99
C	Med-High	274.8	27	25	35	184.9	185.6	89.08	1.82
C	Med-High	275.7	27	27	35	120.0	151.3	86.22	1.07
D	Low	123.6	16	62	15	154.7	150.0	67.31	2.14
D	Low	124.0	16	60	15	149.6	154.8	66.36	1.24
D	Low	124.0	16	64	15	150.5	151.9	66.72	1.80
D	High	169.0	16	44	20	154.6	160.4	80.38	1.12
D	High	167.7	16	44	20	150.8	156.8	80.16	1.81
D	High	166.7	16	46	20	156.9	173.6	79.38	0.85

Table Continued

Test Fan	Speed	Q_{Hood} [cfm]	Mounting Height [in]	Steady -state time [min]	CO_2 injection rate [L/min]	Right Burner T_{avg} [^0C]	Left Burner T_{avg} [^0C]	CE [%]	Uncertainty in CE [%]
D	Low	121.5	16	62	15	186.4	197.8	55.15	1.61
D	Low	123.9	16	62	15	191.7	197.4	57.68	2.12
D	Low	124.2	16	64	15	212.1	203.0	54.03	1.06
D	High	166.0	16	44	20	181.4	180.4	76.01	1.36
D	High	165.7	16	44	20	204.5	199.3	72.94	1.60
D	High	166.1	16	45	20	214.3	201.5	73.94	1.16
E	Low	139.4	21	59	19	152.1	162.9	77.95	1.49
E	Low	140.2	21	56	19	160.0	151.5	77.62	1.67
E	High	220.6	21	34	28	160.3	153.2	90.30	0.86
E	High	216.8	21	32	28	175.3	159.1	90.57	1.07
E	High	224.0	21	31	28	148.9	152.9	89.95	0.65
E	Low	136.8	30	56	19	160.7	169.7	66.52	0.85
E	Low	136.5	30	56	19	151.8	168.1	68.95	1.43
E	High	195.8	30	36	28	156.8	155.6	86.16	0.91
E	High	197.0	30	36	28	140.4	143.8	89.40	1.24
E	High	195.5	30	38	28	169.2	171.1	89.04	0.74

APPENDIX B

REPEATABILITY RESULTS FOR EACH SERIES OF TESTS

(See next **2** pages)

Test Fan	Speed	Q_{Hood} [cfm]	Mounting Height [in]	Right Burner T_{avg} [^{0}C]	Left Burner T_{avg} [^{0}C]	CE [%]	Average CE [%]	Standard Deviation
A	High	88.5	26	142.1	148.9	67.14	66.47	0.899
A	High	87.3	26	162.7	159.5	66.83		
A	High	89.4	26	157.7	153.0	65.45		
B	Low	94.2	27	148.4	155.8	81.00	80.91	0.99
B	Low	95.8	27	175.0	154.9	81.86		
B	Low	95.1	27	172.8	151.0	79.88		
B	High	281.6	27	140.7	137.7	91.21	89.72	2.11
B	High	279.1	27	121.6	153.6	88.23		
C	Med-Low	167.9	27	156.1	166.1	88.16	89.19	1.84
C	Med-Low	167.0	27	145.3	144.2	88.09		
C	Med-Low	183.7	27	144.2	153.6	91.32		
C	Med-High	269.9	27	136.2	147.8	89.58	88.29	1.81
C	Med-High	274.8	27	184.9	185.6	89.08		
C	Med-High	275.7	27	120.0	151.3	86.22		
D	Low	123.6	16	154.7	150.0	67.31	66.80	0.48
D	Low	124.0	16	149.6	154.8	66.36		
D	Low	124.0	16	150.5	151.9	66.72		
D	High	169.0	16	154.6	160.4	80.38	79.97	0.53
D	High	167.7	16	150.8	156.8	80.16		
D	High	166.7	16	156.9	173.6	79.38		

Table Continued

Test Fan	Speed	Q_{Hood} [cfm]	Mounting Height [in]	Right Burner T_{avg} [^0C]	Left Burner T_{avg} [^0C]	CE [%]	Average CE [%]	Standard Deviation
D	Low	121.5	16	186.4	197.8	55.15	55.62	1.87
D	Low	123.9	16	191.7	197.4	57.68		
D	Low	124.2	16	212.1	203.0	54.03		
D	High	166.0	16	181.4	180.4	76.01	74.30	1.57
D	High	165.7	16	204.5	199.3	72.94		
D	High	166.1	16	214.3	201.5	73.94		
E	Low	139.4	21	152.1	162.9	77.95	77.79	0.23
E	Low	140.2	21	160.0	151.5	77.62		
E	High	220.6	21	160.3	153.2	90.30	90.27	0.31
E	High	216.8	21	175.3	159.1	90.57		
E	High	224.0	21	148.9	152.9	89.95		
E	Low	136.8	30	160.7	169.7	66.52	67.74	1.72
E	Low	136.5	30	151.8	168.1	68.95		
E	High	195.8	30	156.8	155.6	86.16	88.20	1.78
E	High	197.0	30	140.4	143.8	89.40		
E	High	195.5	30	169.2	171.1	89.04		

APPENDIX C

CAPTURE EFFICIENCY TEST AND SOFTWARE INSTRUCTIONS

(See next **3** pages)

CE-001: Capture Efficiency Test Method – Rev.A

Written by: S. Meleika | Approved: J. Sweeney

Date: 1/13/2018 | Date: 1/28/2018

Part 1: Preparation

1. Check chamber air temperature
    a. Temperature should be: **15°C - 30°C (59°F – 86°F)**
    b. Maximum deviation during test: ± **5°C (± 10°F)**
2. Install range hood
    a. Mounted on back wall according to manufacturer's instructions
    b. Minimum distance from top of emitters = **0.5m (19 inches)**
    c. Install filters and seal openings for lights
3. Turn on range hood
    a. Set range hood to desired operating speed (high, med, low, etc.)
4. Turn on Hot Plates
    a. Turn on switch to Variac and set Variac to 71% capacity.
    b. Turn on switch to hotplate and set hotplate to 'High' setting.
5. Wait until temperature of pans reaches 200°C ± 10°C
    a. Can be checked using LabVIEW or IR Thermometer at workstation.
6. Turn on 'Instrumentation Power Strip'
    a. CO2 sensor needs 10 min warm-up time.
7. Open up 'Master LabVIEW File.vi' and 'GAS Software' and complete steps in ***'CE-002: Software Operating Instructions'*** before proceeding to Part 2.

Part 2: Taking Measurements

1. After time greater than Tss, take a minimum of 10 measurements over a 10-minute (minimum) period of the following values (i.e. record each value every minute for 10 minutes).
    a. C_exhaust, C_chamber, C_inlet, Q_hood, Power input to heating elements, pan temperature, chamber temperature.
    b. Reference spreadsheet ***'CE-003: Ten Measurements Template.xls'*** for a guide.
2. Calculate the average of each of the values reported above.
3. Calculate Capture Efficiency (CE)
    a. Calculate CE based on time averaged values using the following formula:

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}}$$

Part 3: Report and Power-off

1. Close CO2 cylinder valve and unplug heater from extension cord
2. Turn off power strip
3. Close LabVIEW and GAS Software
4. Take photos of test set-up.
5. Complete report document by referencing ***'CE-004: Report Template'***

<u>CE-002: Software Operating Instructions – Rev. A</u>

Written by: S. Meleika
Date: 1/19/2017

Approved: J. Sweeney
Date: 1/28/2018

Note: Refer to Sheet 2 of this document for a supplemental graphic that illustrates the locations of fields/buttons mentioned in this document.

1. Create and save an xls (97-2003) Excel workbook
    i. Use following naming conventions "(fan model)_(speed)_(date of test)"
    ii. Close file after creating and saving
2. On the front panel of 'Master LabVIEW File.vi' call the Excel file using the ***'Path'*** button
3. Hit 'Run' on LabVIEW front panel
4. Read range hood flow rate from ***'Range Hood (cfm)'*** field and adjust fan and damper to achieve desired airflow through range hood (i.e. airflow associated with specific rating point or operating condition)
5. Ensure air flow through the range hood does not depressurize the test chamber by more than 0.02 in WC (5 Pa) as measured by ***'Depressurization (i.w.c)'***.
6. Allow ***'Steady State time'*** field to stabilize to (±5 min) and note this time in 'CE Report Template' (See form CE-004 for reference).
7. Update ***'Setpoint'*** field to correspond to ***'CO2 injection (L/min)'*** (±2 L/min) of mass flow controller.
    i. Note: CO2 injection rate shall be 0.5% (or less) of range hood ***'cfm'***.
    ii. Note: 1 cfm = 28.32 L/min
8. Ensure pressure reading on regulator valve is stable.
    i. If necessary reduce pressure supplied to mass flow controller.
9. Plug CO2 Heater into orange extension cable and open valve on CO2 cylinder.
10. Once CO2 cylinder is open, note ***'CO2 start time'*** in 'CE Report Template' (form CE-004)
11. Allow Steady State
    i. Allow the system to reach steady state by waiting ***'Steady State time'*** **(Tss)** that was noted in Step 5 for completion of **<u>four air changes</u>**

$$T_{ss} = 4\frac{V_{chamber}\ (m^3)}{Q_{hood}\ \left(\frac{m^3}{s}\right)}$$

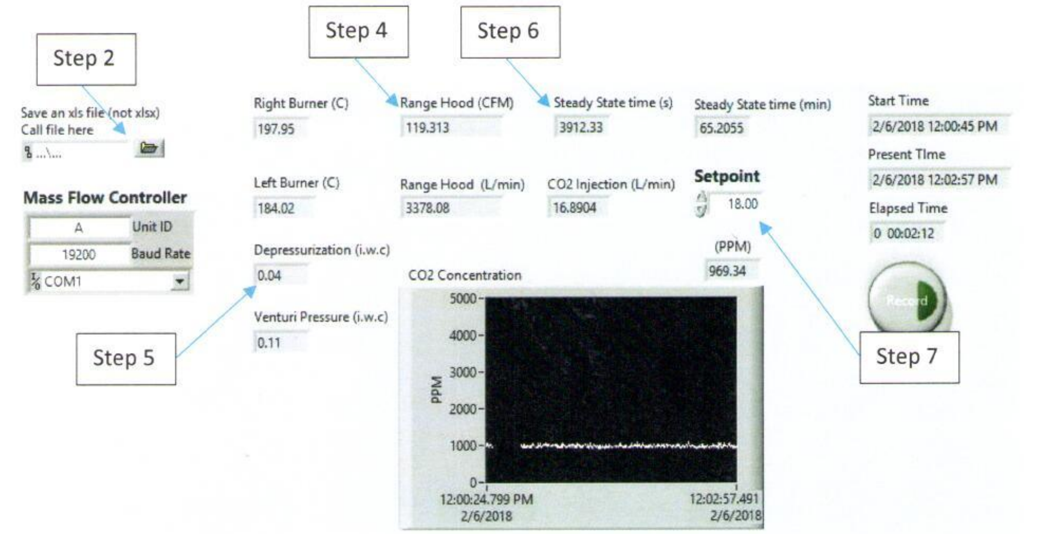
*Note: $V_{chamber} = 56\ m^3$
$1 m^3/s = 2118.88$ cfm

12. After time greater than Tss, refer to 'Part 2: Taking Measurements' in CE-001 for completion of test procedure.

CE-002: Software Operating Instructions – Rev. A

Written by: S. Meleika — Approved: J. Sweeney

Date: 1/19/2017 — Date: 1/28/2018



APPENDIX D

CAPTURE EFFICIENCY MEASUREMENT REPORT TEMPLATE

(See next **1** page)

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	Q_hood (cfm)	Burner Power (W)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1								
2								
3								
4								
5								
6								
7								
8								
9								
10								
AVG.	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!	#DIV/0!
Capture Efficiency Reported:			#DIV/0!					

APPENDIX E

FINAL REPORT TEMPLATE

(See next **1** page)

CHAMBER

Test Start Time: ____________ CO2 Start Time: ______________ Test End Time: ___________

Chamber Temp. at Start:_______°F Chamber Temp. at End: ______ °F

RANGE HOOD

Make: __________________________ Model: _____________________________

Mounting Height: _____ in. Range Hood Width _____ in. Measured Airflow: ________cfm

Operating Speed: ______ (high, med, low) Damper Installed: _____ (y/n) Grill Installed: _____(y/n)

Assist Fan Used: ______ (y/n) Assist Fan Variac Setting: _________ (%) (or N/A if not used)

Damper Adjusted: _______ (y/n) Damper Setting: ________ (k-value) (or N/A if not adjusted)

TRACER GAS

CO2 injection rate: _________ L/min Steady state time calculated: ______ min.

Right burner temp (avg.): ________ °C Left burner temp (avg.): ________ °C

CAPTURE EFFICIENCY

C_inlet (avg.): ______ppm C_chamber (avg.): _______ ppm C_exhaust (avg.): _______ppm

Q_hood (avg.): ______cfm Capture Efficiency: _________ %

*Please also attach completed '10 measurements Report' template to this report

CE Technician: ______________________________ **Date:** ________________

APPENDIX F

CAPTURE EFFICIENCY TESTING AND REPORTING TEMPLATES FOR FANS A - E

(See next **10** pages)

CE-004: CE Report Template – Rev. B

Written by: S. Meleika
Date: 1/19/2018

Approved: J. Sweeney
Date: 2/20/2018

CHAMBER

Test Start Time: 10:40 am CO2 Start Time: 11:36a Test End Time: 12:56p

Chamber Temp. at Start: 70 °F Chamber Temp. at End: 75 °F

RANGE HOOD

Make: Test Fan A Model: Test #1

Mounting Height: 26 in. Range Hood Width 30 in. Measured Airflow: 100 cfm

Operating Speed: high (high, med, low) Damper installed: N (y/n) Grill installed: Y (y/n)

Assist Fan Used: N (y/n) Assist Fan Variac Setting: N/A (%) (or N/A if not used)

Damper Adjusted: N (y/n) Damper Setting: N/A (k-value) (or N/A if not adjusted)

TRACER GAS

CO2 injection rate: 13 L/min Steady state time calculated: 77 min. (waited 50 min) SM

Right burner temp (avg.): 142.1 °C Left burner temp (avg.): 148.9 °C

CAPTURE EFFICIENCY

C_inlet (avg.): 630.5 ppm C_chamber (avg.): 1940 ppm C_exhaust (avg.): 4616 ppm

Q_hood (avg.): 88.5 cfm Capture Efficiency: 67.14 %

*Please also attach completed '10 measurements Report' template to this report

CE Technician: SM **Date:** 3/14/2018

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	Q_hood (cfm)	Right Burner Power (W)	Left Burner Power (W)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1	645	1910	4620	84	1000	1000	145	147	73
2	640	1920	4700	88	1000	1000	145	148	73
3	647	1890	4600	87	1000	1000	145	148	74
4	638	1865	4630	90	1000	1000	143	148	74
5	640	2010	4550	88	1000	1000	142	149	74
6	610	1910	4620	90	1000	1000	141	149	74
7	630	1965	4500	93	1000	1000	140	150	74
8	625	1960	4550	87	1000	1000	140	150	74
9	620	1990	4700	88	1000	1000	140	150	74
10	610	1980	4690	90	1000	1000	140	150	75
AVG.	630.5	1940.0	4616.0	88.5	1000.0	1000.0	142.1	148.9	73.9
Capture Efficiency Reported:			67.14						

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} X\, 100\%$$

CE-004: CE Report Template – Rev. B

Written by: S. Meleika
Date: 1/19/2018

Approved: J. Sweeney
Date: 2/20/2018

CHAMBER

Test Start Time: 12:04pm CO2 Start Time: 12:32p Test End Time: 1:34p

Chamber Temp. at Start: 78 °F Chamber Temp. at End: 79 °F

RANGE HOOD

Make: Test fan B Model: Test #4

Mounting Height: 27 in. Range Hood Width 36 in. Calculated Airflow: 290 cfm

Operating Speed: High (high, med, low) Damper installed: Y (y/n) Grill installed: Y (y/n)

Assist Fan Used: Y (y/n) Assist Fan Variac Setting: 100% (%) (or N/A if not used)

Damper Adjusted: – (y/n) Damper Setting: – (k-value) (or N/A if not adjusted)

Light on: Y (Y/N) power usage: 255 W

TRACER GAS

CO2 injection rate: 35 L/min Steady state time calculated: 26 min. (waited 26min)

Right burner temp (avg.): 140.7 °C Left burner temp (avg.): 137.7 °C

CAPTURE EFFICIENCY

C_inlet (avg.): 636 ppm C_chamber (avg.): 901.5 ppm C_exhaust (avg.): 3655 ppm

Q_hood (avg.): 281.6 cfm Capture Efficiency: 91.21 %

*Please also attach completed '10 measurements Report' template to this report

CE Technician: SM **Date:** 3/22/2018

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	Q_hood (cfm)	Right Burner Power (W)	Left Burner Power (W)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1	620	890	3730	281	1000	1000	145	140	78
2	660	885	3670	282	1000	1000	144	139	78
3	630	890	3740	279	1000	1000	143	139	78
4	640	865	3550	280	1000	1000	141	138	78
5	650	920	3600	282	1000	1000	141	137	78
6	610	900	3800	281	1000	1000	140	138	78
7	670	920	3750	282	1000	1000	139	137	78
8	660	910	3430	281	1000	1000	137	137	78
9	630	935	3560	283	1000	1000	138	136	78
10	590	900	3720	285	1000	1000	139	136	79
AVG.	636.0	901.5	3655.0	281.6	1000.0	1000.0	140.7	137.7	78.1
Capture Efficiency Reported:			91.21						

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \ X\ 100\%$$

CE-004: CE Report Template – Rev. B
Written by: S. Meleika
Date: 1/19/2018

Approved: J. Sweeney
Date: 2/20/2018

CHAMBER

Test Start Time: 3:20p CO2 Start Time: 3:58p Test End Time: 5:05p

Chamber Temp. at Start: 79 °F Chamber Temp. at End: 79 °F

RANGE HOOD

Make: Test Fan C Model: Test #1

Mounting Height: 27 in. Range Hood Width 35 3/8 in. Calculated Airflow: 170 cfm

Operating Speed: 2 of 4 (high, med, low) Damper installed: Y (y/n) Grill installed: Y (y/n)

Assist Fan Used: N (y/n) Assist Fan Variac Setting: – (%) (or N/A if not used)

Damper Adjusted: N (y/n) Damper Setting: – (k-value) (or N/A if not adjusted)

Lights on: Y (y/n) Power usage: 55 W

TRACER GAS

CO2 injection rate: 23 L/min Steady state time calculated: 45 min. (waited 40 min)

Right burner temp (avg.): 156.1 °C Left burner temp (avg.): 166.1 °C

CAPTURE EFFICIENCY

C_inlet (avg.): 444.4 ppm C_chamber (avg.): 925.0 ppm C_exhaust (avg.): 4505.0 ppm

Q_hood (avg.): 167.9 cfm (*) Capture Efficiency: 88.16 %

*Please also attach completed '10 measurements Report' template to this report

CE Technician: SM **Date:** 3/23/2018

(*) Note: CO_2 sensor was not placed in accordance with ASTM standard (was bumped during set-up). Will re-run & send results.

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	Q_hood (cfm)	Right Burner Power (W)	Left Burner Power (W)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1	450	850	4480	161	1000	1000	156	166	79
2	440	950	4550	175	1000	1000	156	167	79
3	475	940	4510	167	1000	1000	156	166	79
4	430	870	4480	162	1000	1000	156	166	79
5	430	890	4600	161	1000	1000	157	166	79
6	450	950	4540	158	1000	1000	156	166	79
7	445	960	4440	178	1000	1000	156	166	79
8	449	920	4450	174	1000	1000	156	166	79
9	435	930	4620	173	1000	1000	156	166	79
10	440	990	4380	170	1000	1000	156	166	79
AVG.	444.4	925.0	4505.0	167.9	1000.0	1000.0	156.1	166.1	79.0
Capture Efficiency Reported:			88.16						

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \ X\ 100\%$$

Fan C, Test 1

CE-004: CE Report Template – Rev. B

Written by: S. Meleika | Approved: J. Sweeney
Date: 1/19/2018 | Date: 2/20/2018

CHAMBER

Test Start Time: 2:20 p CO2 Start Time: 2:46 p Test End Time: 3:50 p

Chamber Temp. at Start: 80 °F Chamber Temp. at End: 81 °F

RANGE HOOD

Make: Test Fan D Model: Test #2

Mounting Height: 16 in. Range Hood Width 30 in. Calculated Airflow: 175 cfm

Operating Speed: Super (High) (high, med, low) Damper installed: y (y/n) Grill installed: y (y/n)

Assist Fan Used: N (y/n) Assist Fan Variac Setting: – (%) (or N/A if not used)

Damper Adjusted: N (y/n) Damper Setting: – (k-value) (or N/A if not adjusted)

Lights on: y (y/n) Power usage: 214 W

TRACER GAS

CO2 injection rate: 20 L/min Steady state time calculated: 44 min.

Right burner temp (avg.): 154.6 °C Left burner temp (avg.): 160.4 °C

CAPTURE EFFICIENCY

C_inlet (avg.): 468 ppm C_chamber (avg.): 1104 ppm C_exhaust (avg.): 3709 ppm

Q_hood (avg.): 169 cfm Capture Efficiency: 80.38 %

*Please also attach completed '10 measurements Report' template to this report

CE Technician: SM **Date:** 5/24/2018

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	Q_hood (cfm)	Right Burner Power (W)	Left Burner Power (W)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1	471	1154	3635	169	1000	1000	155	160	81
2	473	1099	3745	170	1000	1000	155	161	81
3	470	1137	3770	170	1000	1000	155	161	81
4	470	1088	3718	167	1000	1000	155	161	81
5	462	1075	3756	168	1000	1000	155	161	81
6	463	1105	3580	169	1000	1000	155	160	81
7	459	1085	3713	169	1000	1000	155	160	81
8	472	1100	3830	168	1000	1000	154	160	81
9	471	1085	3597	172	1000	1000	154	160	81
10	468	1112	3750	170	1000	1000	153	160	81
AVG.	467.9	1104.0	3709.4	169.2	1000.0	1000.0	154.6	160.4	81.0
Capture Efficiency Reported:			80.38						

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} X\, 100\%$$

Fan C, Test 2

CE-004: CE Report Template – Rev. B
Written by: S. Meleika
Date: 1/19/2018

Approved: J. Sweeney
Date: 2/20/2018

CHAMBER

Test Start Time: 9:12 am CO2 Start Time: 9:26 am Test End Time: 10:49 am

Chamber Temp. at Start: 78 °F Chamber Temp. at End: 81 °F

RANGE HOOD

Make: Test Fan E Model: Test #4

Mounting Height: 21 in. Range Hood Width 29 in. Calculated Airflow: 133 cfm

Operating Speed: Low (high, med, low) Damper installed: N (y/n) Grill installed: Y (y/n)

Assist Fan Used: Y (y/n) Assist Fan Variac Setting: 65% (%) (or N/A if not used)

Damper Adjusted: N (y/n) Damper Setting: - (k-value) (or N/A if not adjusted)

Lights on: N (y/n) Power usage: 47 W

TRACER GAS

CO2 injection rate: 19 L/min Steady state time calculated: 59 min.

Right burner temp (avg.): 152.1 °C Left burner temp (avg.): 162.9 °C

CAPTURE EFFICIENCY

C_inlet (avg.): 429 ppm C_chamber (avg.): 1266 ppm C_exhaust (avg.): 4224 ppm

Q_hood (avg.): 139.4 cfm Capture Efficiency: 77.95 %

*Please also attach completed '10 measurements Report' template to this report

CE Technician: [signature] **Date:** 6/11/2018

No.	C_inlet (ppm)	C_chamber (ppm)	C_exhaust (ppm)	Q_hood (cfm)	Right Burner Power (W)	Left Burner Power (W)	Right Burner Temp. (°C)	Left Burner Temp. (°C)	Chamber Temp. (°F)
1	420	1263	4170	140	1000	1000	152	167	80
2	428	1252	4313	145	1000	1000	151	166	80
3	431	1320	4203	140	1000	1000	152	165	80
4	436	1242	4260	133	1000	1000	152	165	80
5	435	1285	4356	137	1000	1000	152	164	80
6	437	1265	4278	136	1000	1000	153	163	81
7	429	1254	3980	138	1000	1000	154	162	81
8	430	1223	4013	140	1000	1000	152	159	81
9	422	1276	4321	141	1000	1000	151	159	81
10	426	1280	4346	143	1000	1000	152	159	81
AVG.	429.4	1266.0	4224.0	139.3	1000.0	1000.0	152.1	162.9	80.5
Capture Efficiency Reported:			77.95						

$$CE = \frac{C_{exhaust} - C_{chamber}}{C_{exhaust} - C_{inlet}} \; X\, 100\%$$

APPENDIX G

CALIBRATION CERTIFICATION

(See next **14** pages)

Calibration Certificate

Copy

Part No:	2641003WD11T1F	Serial No:	8420843	Tech.:	NN SK
Range:	0 to 3 IN WC	Work Order:	24303960	Model:	264
Output:	4 to 20 mA	Date:	03/15/2017	Supply:	24 VDC

CALIBRATION DATA

APPLIED PRESSURE (IN WC)	TRANSDUCER OUTPUT (mA)	NONLINEARITY ERRORS (% FS)	EXTRAPOLATED ERRORS (% FS)
0.0279	4.1404	0.176	Zero -0.054
0.3352	5.7461	-0.041	
0.6089	7.1915	-0.137	Span 0.071
0.9302	8.9005	-0.176	
1.2100	10.3947	-0.171	
1.5262	12.0940	-0.098	
1.8384	13.7736	-0.016	
2.1077	15.2244	0.065	
2.4362	16.9886	0.132	
2.7280	18.5530	0.176	
3.0238	20.1298	0.162	

3/23/2017 OFS

SPECIFICATIONS
1. Nonlinearity: +/- 0.25 %FS, BEST FIT STRAIGHT LINE method, ISA.#S-37.1
2. Zero pressure output: 4 mA +/- 0.5 %FS
3. Full Scale output: 16 mA +/- 0.5 %FS
4. This unit meets the specifications defined above.

NOTES
1. All errors are expressed as: Percent Full-Scale output.
2. Consult specification sheet for additional specifications.
3. This calibration is certified per N.I.S.T. traceable primary standards.
   NIST# FlukeRpt#1500202048
   Transfer standard: 23908D20.4, Location of cal.: PCZD20
4. This part uses spec. record number: 2641003WD11T1F.4
5. This certificate cannot be reproduced except in full, without the writte
   approval of Setra Systems, Inc.

159 Swanson Road, Boxborough, MA 01719/Telephone 1-800-257-3872, (978) 263-1400

SS0513-2 Rev. 1/99

3330 E. 83rd Place
Merrillville, IN 46410
Phone: 800-373-1759
www.callabco.com
in@callabco.com

CAL LAB

LABORATORY ACCREDITATION BUREAU ACCREDITED

Certificate #L2215 Calibration/Dimensional Inspection

Calibration Certificate

#1802470

Copy

(Level 3) ISO/IEC 17025:2005 Accredited Calibration with Measurement Uncertainty

Customer

Riverside Energy Efficiency Lab (620241)
Riverside Energy Lab Bldg 6502
3100 State Highway 47
Bryan, Texas 77807
PO Number: CREDIT CARD

Instrument Profile

Manufacturer: *Setra*
Model: *264 0-1.0 INH²O*
Asset ID: *8134644*
Serial: *8134644*
Description: *Pressure Transducer, 0-1.0 inH²O*

Calibration Information

†Requested Interval: *12 Months*
Calibration Date: *10/25/2017*
†Due Date: *10/25/2018*
Temperature: *68.0 °F (20.0 °C)*
Batch #: *1692245*
Calibration Location: *Indiana Physical Lab*
Calibration Procedure: *CP-0096*
Relative Humidity: *38.6 %*

Instrument Condition

As Received: *In Tolerance*
As Returned: *In Tolerance*
JPJ 10/31/2017
Tolerance(s): *Manufacturer specification(s) unless otherwise specified.*
Phys. Damage: *No apparent evidence of physical or cosmetic damage noted during this calibration.*

Quality & Traceability Statements

Level ❸ Calibration

The results reported herein apply only to the calibration of the item described above. All calibration standards used in this calibration are traceable to the International System of Units (SI) through NIST or equivalent National Measurement Institute signatories to the CIPM MRA. Supporting documentation relating to this traceability is initiated by the Trace Number listed in the Calibration Standards section of this certificate. Additional documentation is available for review by a scheduled appointment. Our Quality System is accredited to ISO/IEC 17025:2005, ANSI/NCSL Z540-1:1994 and ANSI/NCSL Z540.3:2006 via the Laboratory Accreditation Bureau. Details of our scope of accreditation are available at www.L-A-B.com.

†Per the requirements of ISO-17025:2005, Cal Lab does not make recommendations for recall therefore the listed Due Date is dictated by the owner of this equipment. Although the item calibrated meets the conditions or specifications at the time of the calibration, due to a number of factors the due date of the item calibrated does not imply continuing conformance during the calibration interval.

*The parameters of this calibration are directly or indirectly covered under our current scope of accreditation unless otherwise noted. The reported expanded uncertainty of measurement is reported at a coverage factor of k=2, which for a normal distribution corresponds to a coverage of approximately 95%. The EMU **does** include the resolution of the instrument calibrated, which in some cases, may be a dominate source of error, but does not include Type A contributors (repeatability/reproducibility studies) of the instrument calibrated unless specifically requested by the customer. The uncertainty values reflect the measurement processes uncertainty and may not reflect the measurement uncertainty listed on our scope of accreditation. The reported measurement uncertainty **is not** considered (i.e. measured value ± EMU) when making statements of compliance to specification (i.e. In tolerance, OOT, Pass/Fail, etc.) unless requested by the customer.*

For purposes of determining conformance with the listed specifications (tolerances), the observed value or a calculated value has been rounded "to the nearest unit" in the last right-hand digit used in expressing the specification limit, in accordance with the rounding method of ASTM Practice E 29 for Using Significant Digits in Test Data to Determine Conformance with Specifications.

This certificate may contain calibration data with results listed as either Pass or Fail. These attributes are typically listed as a functional check based on an applied measurand or verification, however, this is strictly Qualitative and should not be interpreted as a Quantitative measurement.

Kyle Hilburger
Calibration Technician
Kyle Hilburger
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Jeff Breidigan
Review & Approval
Jeff Breidigan
Operations Director
jeffb@callabco.com

QA

CAL LAB

Calibration Standard(s)

Description	Manufacturer	Model	ID#	Due Date	Traceability #
Micromanometer, 10 inch	Meriam Instrument	34FB2TM	1598	10/31/2019	1714640
Thermohygrometer, (Environmental Only)	Dickson	TM320	2392	03/31/2018	1797912
Multimeter-Digital	Agilent	34401A	2512	09/30/2018	1798913

Indicates that this equipment is only used to monitor & record environmental conditions as listed in the Calibration Information Section.

Calibration Data

>>> For quick review, any Function/Attribute with an Out-of-Tolerance reading (OOT) has been highlighted. <<<

Function / Attribute	Nominal Value	As Found	OOT	As Left	OOT	Tolerance
0.1 inH²0 mA Output (0.4%)	5.60 mA	5.60		5.60		5.54 to 5.66 mA [EMU 37.5 µA]
0.3 inH²0 mA Output (0.4%)	8.80 mA	8.81		8.81		8.74 to 8.86 mA [EMU 37.7 µA]
0.5 inH²0 mA Output (0.4%)	12.00 mA	12.02		12.02		11.94 to 12.06 mA [EMU 38.8 µA]
0.7 inH²0 mA Output (0.4%)	15.20 mA	15.22		15.22		15.14 to 15.26 mA [EMU 39.3 µA]
0.9 inH²0 mA Output (0.4%)	18.40 mA	18.42		18.42		18.34 to 18.46 mA [EMU 39.8 µA]
0.7 inH²0 mA Output (0.4%)	15.20 mA	15.19		15.19		15.14 to 15.26 mA [EMU 39.3 µA]
0.5 inH²0 mA Output (0.4%)	12.00 mA	11.99		11.99		11.94 to 12.06 mA [EMU 38.8 µA]
0.3 inH²0 mA Output (0.4%)	8.80 mA	8.78		8.78		8.74 to 8.86 mA [EMU 37.7 µA]
0.1 inH²0 mA Output (0.4%)	5.60 mA	5.58		5.58		5.54 to 5.66 mA [EMU 37.5 µA]

3330 E. 83rd Place
Merrillville, IN 46410
Phone: 800-373-1759
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CAL LAB

LABORATORY ACCREDITATION BUREAU ACCREDITED

Certificate #L2215 Calibration/Dimensional Inspection

Calibration Certificate

Copy

#1802471

(Level 3) ISO/IEC 17025:2005 Accredited Calibration with Measurement Uncertainty

Customer

Riverside Energy Efficiency Lab (620241)
Riverside Energy Lab Bldg 6502
3100 State Highway 47
Bryan, Texas 77807
PO Number: CREDIT CARD

Instrument Profile

Manufacturer: *Monarch*
Model: *ACT-3*
Asset ID: *1444710*
Serial: *1444710*
Description: *Panel Meter, RPM*

Calibration Information

†Requested Interval: *12 Months*
Calibration Date: *10/20/2017*
†Due Date: *10/20/2018*
Temperature: *70.6 °F (21.4 °C)*
Batch #: *1692245*
Calibration Location: *Indiana Electronics Lab*
Calibration Procedure: *CP-0021*
Relative Humidity: *40.6 %*

Instrument Condition

As Received: *In Tolerance*
As Returned: *In Tolerance*

JPJ 10/31/2017.

Tolerance(s): *Manufacturer specification(s) unless otherwise specified.*
Phys. Damage: *Evidence of physical and/or cosmetic damage was noted during this calibration. See Technician Remarks for details.*

Quality & Traceability Statements

Level ❸ Calibration

The results reported herein apply only to the calibration of the item described above. All calibration standards used in this calibration are traceable to the International System of Units (SI) through NIST or equivalent National Measurement Institute signatories to the CIPM MRA. Supporting documentation relating to this traceability is initiated by the Trace Number listed in the Calibration Standards section of this certificate. Additional documentation is available for review by a scheduled appointment. Our Quality System is accredited to ISO/IEC 17025:2005, ANSI/NCSL Z540-1:1994 and ANSI/NCSL Z540.3:2006 via the Laboratory Accreditation Bureau. Details of our scope of accreditation are available at www.L-A-B.com.

†Per the requirements of ISO-17025:2005, Cal Lab does not make recommendations for recall therefore the listed Due Date is dictated by the owner of this equipment. Although the item calibrated meets the conditions or specifications at the time of the calibration, due to a number of factors the due date of the item calibrated does not imply continuing conformance during the calibration interval.

*The parameters of this calibration are directly or indirectly covered under our current scope of accreditation unless otherwise noted. The reported expanded uncertainty of measurement is reported at a coverage factor of k=2, which for a normal distribution corresponds to a coverage of approximately 95%. The EMU **does** include the resolution of the instrument calibrated, which in some cases, may be a dominate source of error, but does not include Type A contributors (repeatability/reproducibility studies) of the instrument calibrated unless specifically requested by the customer. The uncertainty values reflect the measurement processes uncertainty and may not reflect the measurement uncertainty listed on our scope of accreditation. The reported measurement uncertainty **is not** considered (i.e. measured value ± EMU) when making statements of compliance to specification (i.e. In tolerance, OOT, Pass/Fail, etc.) unless requested by the customer.*

For purposes of determining conformance with the listed specifications (tolerances), the observed value or a calculated value has been rounded "to the nearest unit" in the last right-hand digit used in expressing the specification limit, in accordance with the rounding method of ASTM Practice E 29 for Using Significant Digits in Test Data to Determine Conformance with Specifications.

This certificate may contain calibration data with results listed as either Pass or Fail. These attributes are typically listed as a functional check based on an applied measurand or verification, however, this is strictly Qualitative and should not be interpreted as a Quantitative measurement.

Timothy Namovice
Calibration Technician
Timothy Namovice
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Jeff Breidigan
Review & Approval
Jeff Breidigan
Operations Director
jeffb@callabco.com

QA

CAL LAB

Calibration Standard(s)

Description	Manufacturer	Model	ID#	Due Date	Traceability #
Calibrator, Multi-Function, 1.1 GHz	Fluke	5520A-SC1100	1507	08/31/2018	1788759
Thermohygrometer, (Environmental Only)	Dickson	TM320	2314	12/31/2017	1783530

Indicates that this equipment is only used to monitor & record environmental conditions as listed in the Calibration Information Section.

Technician Remarks

Face plate is held on with tape and power input terminals are damaged.

Calibration Data

>>> For quick review, any Function/Attribute with an Out-of-Tolerance reading (OOT) has been highlighted. <<<

Function / Attribute	Nominal Value	As Found	OOT	As Left	OOT	Tolerance
Revolutions Per Minute	60.000 rpm	59.999		59.999		59.900 to 60.100 rpm [EMU 0.00067 rpm]
Revolutions Per Minute	600.00 rpm	600.00		600.00		599.00 to 601.00 rpm [EMU 0.0059 rpm]
Revolutions Per Minute	6000.0 rpm	6000.0		6000.0		5999.0 to 6001.0 rpm [EMU 0.059 rpm]
Revolutions Per Minute	60000 rpm	60000		60000		59998 to 60002 rpm [EMU 0.58 rpm]

Cole Parmer Instrument Co.

Calibration Data Sheet

Certification Number: 163487

Sales Order Number:	SO335458
Serial Number:	150155
Model Number:	32907-75
Software Version:	5v13.0-R22
P/D/I Values:	300 / 5000 / 0
Process Gas:	Selectable
Calibration Gas:	Air
Range:	100.0 SLPM
Gas Temperature:	25.98°C
Ambient Humidity:	35.69%
Calibration Procedure/Rev. #:	DOC-AUTOCAL-GASFLOW/Rev. 92
Calibrated By:	Kenyon Ellefson
Calibration Date:	4/28/2017
Full Scale Pressure:	160.00 PSIA
Pressure Accuracy:	+/-0.5% of Full Scale
Temperature Accuracy:	+/-1.5°C
Standard Temp. & Pressure:	25.00°C, 14.69595 PSIA
Calibration due 1 yr. after receipt:	

Equipment Used

Temperature: TOOL-TEMP18
Tool Due Date: 6/8/2017
Manufacturer/Model: SELCO
Device Uncertainty: +/- 0.75°C

Pressure: TOOL-PRESSURE8
Tool Due Date: 3/9/2018
Manufacturer/Model: Alicat / P-100PSIG-D
Device Uncertainty: +/- 0.2% of full scale

Flow: TOOL-FLOW43
Tool Due Date: 7/11/2017
Manufacturer/Model: Alicat / MCRM-120SLPM-D
Device Uncertainty: +/- (0.3% Reading + 0.2% F.S.)

Voltage: TOOL-CMTR20
Tool Due Date: 7/19/2017
Manufacturer/Model: Fluke / 87V
Device Uncertainty: +/- (0.1% + 1 digit)

All test equipment used for calibration is NIST traceable.

Calibration

Uncertainty: +/- (0.8% of Reading + 0.2% of Full Scale)
Units of measure: SLPM

Calibration Pressure: Inlet: 25 PSIG
Outlet: 0 PSIG

Output 1 Configuration
mini-DIN Pin #6

Output 2 Configuration
mini-DIN Pin #2

D.U.T.	Actual	In Tolerance	Output 1	Output 2
0.0	0.0	Yes	0.000 Vdc	5.12 Vdc
25.0	25.1	Yes	1.250 Vdc	5.12 Vdc
50.0	49.7	Yes	2.500 Vdc	5.12 Vdc
75.0	74.6	Yes	3.750 Vdc	5.12 Vdc
100.0	100.2	Yes	5.00 Vdc	5.12 Vdc

Notes: 0-5V set-point.

Tech Signature: K Elle

QC Signature:

CS1 Rev 16 Last Modified 01/18/2013

ACCREDITED
Calibration Cert# 2166.01

FLUKE ®

Certificate of Calibration

Everett Service Center

Certificate Number:	EVL401467		
Data Type:	Found-Left	**Calibration Date:**	28-Nov-2017
Result Summary:	Measurement Results < Limits	**Calibration Due:**	28-Nov-2018
Manufacturer:	Fluke	**Certificate Date:**	28-Nov-2017
Model:	717 1G	**Temperature:**	22.9 °C
Serial Number:	1022069	**Humidity:**	29.8 %
Description:	PRESSURE CALIBRATOR		

OK
[signature]
12/6/2017

Procedure:	Fluke 717-1G: (1 year) ZCAL/ACAL VER/7250LP/5500A	**Revision:**	4.2
Customer:	TEXAS A & M UNIVERSITY		
City:	BRYAN	**Country:**	US
State:	TX		
Purchase Order:	112217KW	**RMA:**	31403263
Asset ID:	1022069		

This calibration is traceable to the International System of Units (SI), through National Metrology Institutes (NIST, PTB, NRC, NPL, etc.), ratiometric techniques, or natural physical constants. This certificate applies only to the item identified and shall not be reproduced other than in full, without the specific written approval by Fluke Corporation. Calibration certificates without signature are not valid. The calibration has been completed in accordance with Fluke Electronics Corporation Quality System Document 111.0 Revision 121 7/2017 and/or Fluke 17025 Quality Manual QSD 111.41 Revision 005 9/2014.

The Data Type found in this certificate must be interpreted as:

- As - Found Calibration data collected before the unit is adjusted and / or repaired.
- As - Left Calibration data collected after the unit has been adjusted and / or repaired.
- Found-Left Calibration data collected without any adjustment and / or repair performed.

This calibration conforms to the requirements of ISO/IEC 17025:2005 and ANSI/NCSL Z540-1-1994 (R2002).
In the attached measurement results, deviation may be expressed with units, Measured Value (MV) - Nominal Value (NV) or as a proportion of the nominal value ((MV-NV)/NV), expressed without units with a scalar multiplier such as % (0.01), or as a ratio of the units (mA/A, μV/V, etc.) Descriptions such as μA/A, μV/V, and others, where used to annotate results or column headings are the preferred replacements for what was historically labeled as "ppm" or parts-per-million and described the results in that column, unless otherwise noted by units symbols.

Where applicable, the expanded uncertainty of measurement at the time of test is given in the following pages. They are calculated in accordance with the method described in the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k, such that the confidence level approximates 95%.

This calibration certificate may contain data that is not covered by the A2LA Scope of Accreditation. Unaccredited material, where applicable is indicated by an asterisk (*), or confined to clearly marked sections. Functional (Pass / Fail) tests are not accredited.

No statement of compliance with specifications is made or implied on this certificate. However, measurement results are reviewed, where applicable, to establish where any measurement result exceeded the manufacturer's specifications.

Measurement results greater than limits of error are indicated by '!'.

Cert # : EVL401467
Date: 28-Nov-2017
Due: 28-Nov-2018
www.fluke.com

[signature]
Holly Shelvock
Calibration Technician

FLUKE.

Certificate Number: EVL401467 **Date of Calibration:** 28-Nov-2017

Standards Used

Asset	Description	Cal-Date	Cal-Due
13602	Fluke 5500A Calibrator	07-Mar-2017	07-Mar-2018
15376	Fluke 7250LP Low Pressure Controller / Calibrator	08-Jun-2017	08-Jun-2018

FLUKE.

Certificate Number: EVL401467 **Date of Calibration:** 28-Nov-2017

Calibration Data

Parameter	Nominal Value	Measurement Result	Limits of Error Lower Limit	Limits of Error Upper Limit	Expanded Uncertainty
PRESSURE VERIFICATION TESTS					
-1.0 psig	-1.00000	-0.9997	-1.0005	-0.9995	1.1e-004 psig
-0.8 psig	-0.80000	-0.7999	-0.8005	-0.7995	9.9e-005 psig
-0.6 psig	-0.59999	-0.6000	-0.6005	-0.5995	9.1e-005 psig
-0.4 psig	-0.40000	-0.4001	-0.4005	-0.3995	9.4e-005 psig
-0.2 psig	-0.19998	-0.2001	-0.2005	-0.1995	8.8e-005 psig
0.0 psig	0.00000	-0.0003	-0.0005	0.0005	5.9e-005 psig
0.2 psig	0.20000	0.1998	0.1995	0.2005	6.5e-005 psig
0.4 psig	0.40000	0.3998	0.3995	0.4005	7.7e-005 psig
0.6 psig	0.60001	0.5998	0.5995	0.6005	8.5e-005 psig
0.8 psig	0.80000	0.7998	0.7995	0.8005	9.6e-005 psig
1.0 psig	1.00000	0.9997	0.9995	1.0005	1.1e-004 psig
mA MEASURE TEST					
4.000 mA	4.0000	4.000	3.997	4.003	7.3e-007 A
12.000 mA	12.0000	12.000	11.996	12.004	1.1e-006 A
20.000 mA	20.0000	20.000	19.995	20.005	1.5e-006 A

Certificate of Conformance

I hereby certify that on 29-NOV-2017 (date) , Fluke Corporation, furnished the supplies or services called for by Contract / P.O.Number 112217KW , via UPSG.STD UPS GROUND (carrier), on 36486314 / 31403263 (invoice / order number) in accordance with all applicable requirements. I furthur certify that the supplies or services are of the quality specified and conform in all respects with the contract requirements, including specifications, drawings, preservation, packaging, packing, making requirements, and physical item identification (part Number), and are in the quality shown on this or on the attached acceptance document.

Date of Execution : 29-NOV-2017

Jason Shaffer, Corporate Quality Assurance Manager

Note: Fluke Corporation does not always manufacture every component or spare supplied; therefore all components/spares may not reflect the Fluke part number, but only the true Manufacturer's part number(s).

Fluke Corporation	Telephone	Fax	Internet
PO Box 9090 Everett, WA 98206-9090USA	425.347.6100	425.446.5116	www.fluke.com

FLUKE ®

ACCREDITED
Calibration Cert# 2166.01

Certificate of Calibration

Beaverton Service Center

Certificate Number:	BVL405240		
Data Type:	Found-Left	**Calibration Date:**	09-Dec-2017
Result Summary:	Measurement Results < Limits	**Calibration Due:**	09-Dec-2018
Manufacturer:	Fluke	**Certificate Date:**	12-Dec-2017
Model:	87 V	**Temperature:**	22.7 °C
Serial Number:	40380203	**Humidity:**	18.4 %
Description:	Multimeter		
Procedure:	Fluke 87 V (1 Year) ACAL/ZCAL Ver /5520	**Revision:**	1.1
Customer:	TEXAS A & M UNIVERSITY		
City:	BRYAN	**Country:**	US
State:	TX		
Purchase Order:	1252017KW	**RMA:**	31410960

ok JRS 12/20/2017

This calibration is traceable to the International System of Units (SI), through National Metrology Institutes (NIST, PTB, NRC, NPL, etc.), ratiometric techniques, or natural physical constants. This certificate applies only to the item identified and shall not be reproduced other than in full, without the specific written approval by Fluke Corporation. Calibration certificates without signature are not valid. The calibration has been completed in accordance with Fluke Electronics Corporation Quality System Document 111.0 Revision 121 7/2017 and/or Fluke 17025 Quality Manual QSD 111.41 Revision 005 9/2014.

The Data Type found in this certificate must be interpreted as:

- As - Found Calibration data collected before the unit is adjusted and / or repaired.
- As - Left Calibration data collected after the unit has been adjusted and / or repaired.
- Found-Left Calibration data collected without any adjustment and / or repair performed.

This calibration conforms to the requirements of ISO/IEC 17025:2005 and ANSI/NCSL Z540-1-1994 (R2002).
In the attached measurement results, deviation may be expressed with units, Measured Value (MV) - Nominal Value (NV) or as a proportion of the nominal value ((MV-NV)/NV), expressed without units with a scalar multiplier such as % (0.01), or as a ratio of the units (mA/A, µV/V, etc.) Descriptions such as µA/A, µV/V, and others, where used to annotate results or column headings are the preferred replacements for what was historically labeled as "ppm" or parts-per-million and described the results in that column, unless otherwise noted by units symbols.

Where applicable, the expanded uncertainty of measurement at the time of test is given in the following pages. They are calculated in accordance with the method described in the ISO Guide to the Expression of Uncertainty in Measurement (GUM). The reported expanded uncertainty of measurement is stated as the standard uncertainty of measurement multiplied by the coverage factor k, such that the confidence level approximates 95%.

This calibration certificate may contain data that is not covered by the A2LA Scope of Accreditation. Unaccredited material, where applicable is indicated by an asterisk (*), or confined to clearly marked sections. Functional (Pass / Fail) tests are not accredited.

No statement of compliance with specifications is made or implied on this certificate. However, measurement results are reviewed, where applicable, to establish where any measurement result exceeded the manufacturer's specifications.

Measurement results greater than limits of error are indicated by '!'.

Cert #: BVL405240
Date: 09-Dec-2017
Due: 09-Dec-2018
www.fluke.com

Michael Griffiths
Production Manager

FLUKE.

Certificate Number: BVL405240 **Date of Calibration:** 09-Dec-2017

Standards Used

Asset	Description	Cal-Date	Cal-Due
9899	Fluke 5520A Calibrator	10-May-2017	10-May-2018

FLUKE.

Certificate Number: BVL405240 **Date of Calibration:** 9-Dec-2017

Calibration Data

Parameter	Nominal Value	Measurement Result	Limits of Error Lower Limit	Limits of Error Upper Limit	Expanded Uncertainty
30.00 MOhm	30.000	30.01	29.67	30.33	9.7e+003 Ω
Conductance Test					
Open circuit reading: -0.01nS		Pass			
10.00 nS	10.000	9.99	9.60	10.40	7.1e-012 S
Diode Test					
3.000 V	3.0000	2.999	2.939	3.061	5.8e-004 V
Current Test					
A Range					
3.000 A @ 60 Hz	3.0000	2.999	2.968	3.032	3.0e-003 A
3.000 A	3.0000	3.001	2.990	3.010	1.7e-003 A
10.00 A	10.000	10.00	9.96	10.04	7.2e-003 A
mA Range					
33.00 mA @ 60 Hz	33.000	32.99	32.65	33.35	2.6e-005 A
330.0 mA @ 60 Hz	330.00	330.0	326.5	333.5	2.1e-004 A
33.00 mA	33.000	33.01	32.89	33.11	7.3e-006 A
330.0 mA	330.00	330.0	329.1	330.9	1.0e-004 A
uA Range					
330.0 µA @ 60 Hz	330.00	329.9	326.5	333.5	3.8e-007 A
3300 µA @ 60 Hz	3300.0	3300	3265	3335	2.6e-006 A
330.0 µA	330.00	330.0	328.9	331.1	8.6e-008 A
3300 µA	3300.0	3300	3291	3309	7.3e-007 A
Capacitance Test					
Open circuit reading: 0.26nF		Pass			
5.0 nF	5.00	4.8	4.7	5.3	6.0e-011 F
9.5 µF	9.50	9.5	9.2	9.8	6.3e-008 F
Low Pass Filter Test					
LPF inactive at 400Hz		Pass			
LPF active at 800Hz		Pass			
Min Max Test					
Max Hold Function Test		Pass			
Min Hold Function Test		Pass			
Temperature Test					
0.0 °C	0.00	-0.5	-1.0	1.0	1.4e-001 °C
100.0 °C	100.00	99.5	98.0	102.0	1.4e-001 °C

FLUKE

Certificate Number: BVL405240 **Date of Calibration:** 9-Dec-2017

Calibration Data

Parameter	Nominal Value	Measurement Result	Limits of Error Lower Limit	Limits of Error Upper Limit	Expanded Uncertainty
AC Voltage Test					
330.0 mV @ 60 Hz	330.00	330.0	327.3	332.7	1.0e-004 V
600.0 mV @ 13 kHz	600.00	604.7	586.0	614.0	1.5e-004 V
3.300 V @ 60 Hz	3.3000	3.299	3.275	3.325	1.0e-003 V
3.300 V @ 20 kHz	3.3000	3.292	3.214	3.386	1.2e-003 V
33.00 V @ 60 Hz	33.000	32.99	32.75	33.25	8.6e-003 V
33.00 V @ 20 kHz	33.000	32.91	32.14	33.86	1.2e-002 V
330.0 V @ 60 Hz	330.00	329.9	327.5	332.5	1.0e-001 V
330.0 V @ 2.5 kHz	330.00	330.3	323.0	337.0	9.2e-002 V
500 V @ 60 Hz	500.0	500	494	506	5.9e-001 V
1000 V @ 1 kHz	1000.0	1002	986	1014	6.1e-001 V
Frequency Test					
99.95 kHz @ 150 mV	99.950	99.95	99.93	99.97	5.8e+000 Hz
199.50 kHz @ 150 mV	199.500	199.50	199.48	199.52	5.8e+000 Hz
Frequency Sensitivity Test					
99.95 kHz @ 0.7 V	99.950	99.95	99.93	99.97	5.8e+000 Hz
99.95 kHz @ 7 V	99.950	99.95	99.93	99.97	5.8e+000 Hz
Trigger Level Test					
1000.0 Hz @ 3.4 V	1000.00	1000.0	999.8	1000.2	5.8e-002 Hz
Duty Cycle Test					
50.0 % @ 1 kHz	50.00	50.1	49.7	50.3	5.9e-002 %
DC Voltage Test					
3.300 V	3.3000	3.300	3.297	3.303	5.8e-004 V
33.00 V	33.000	33.00	32.97	33.03	5.8e-003 V
330.0 V	330.00	330.0	329.7	330.3	5.8e-002 V
1000 V	1000.0	1000	998	1002	5.8e-001 V
mV DC Test					
33.0 mV	33.00	33.0	32.9	33.1	5.8e-005 V
330.0 mV	330.00	330.0	329.6	330.4	5.8e-005 V
Ohms Test					
330.0 Ohm	330.00	330.0	329.1	330.9	5.9e-002 Ω
3.300 kOhm	3.3000	3.300	3.292	3.308	5.9e-001 Ω
33.00 kOhm	33.000	33.00	32.92	33.08	5.9e+000 Ω
330.0 kOhm	330.00	330.1	327.9	332.1	5.9e+001 Ω
3.300 MOhm	3.3000	3.300	3.279	3.321	6.9e+002 Ω

APPENDIX H

CHAMBER LEAKAGE REPORT

(See next **2** pages)

Blower Door / Duct Blaster

1511954

DPIS Engineering, LLC
The Builders Solution

Date: 1/24/2018 Plan# Po # Wo # 220560

Builder: James F. Sweeney

Address: 3100 State Highway 47 - Building 6502

Subdivision: Bryan

L/B/S // City Bryan Zip: 77807

Signature:

Inspector: BRIAN COOK

- [ ] Pass
- [x] Fail
- [ ] NRI
- [ ] Correct & Proceed
- [ ] Cancelled w/o Notification

[x] **Re-inspection Required**

Home Start Date: 01/23/2018

Duct Blaster

Is this a reinspection? False Inspection # 1

Supt. Name: **James Sweeney** Phone: **979-575-5182** Called? [x] Y [ ] N On Site? [x] Y [ ] N

Inspection Status Summary **Meter#:** Na

Building Type : **Single Family** Utility Co.: HVAC Contractor:

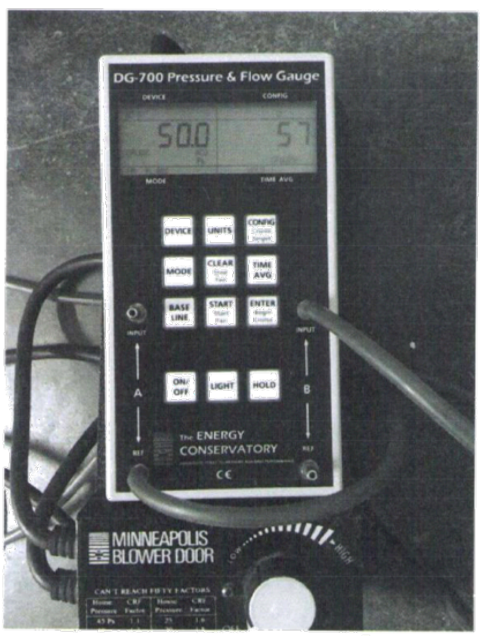
	NA	Pass	Fail	NRI	Correct & Proceed
Duct Blaster			✔		
Blower Door		✔			

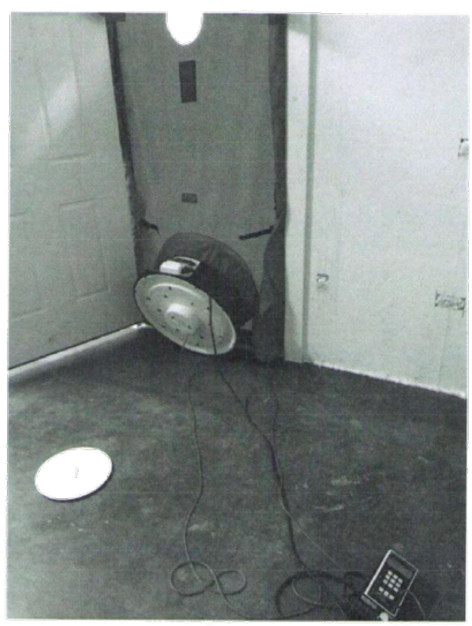
CFM50 Target	
CFM50 Test	57
BD Location	Front Door

Wind Condition [ ] Yes [x] No

Blower Door Location During Test

Comments:





DPIS Engineering, LLC
The Builder's Solution

Blower Door / Duct Blaster

1511954

Date: 1/24/2018 WO# 220560 Job: PO# Plan#

Builder: James F. Sweeney Home Start Date: 01/23/2018

Address: 3100 State Highway 47 - Buildin

Subdivision: Bryan

City: Bryan State TX Zip:

Lot / Block / Section: //

Duct Blaster

Status

		TDL	Target	LTO	Target
Unit 1		31	5		
Unit 2					
Unit 3					
Unit 4					
Unit 5					

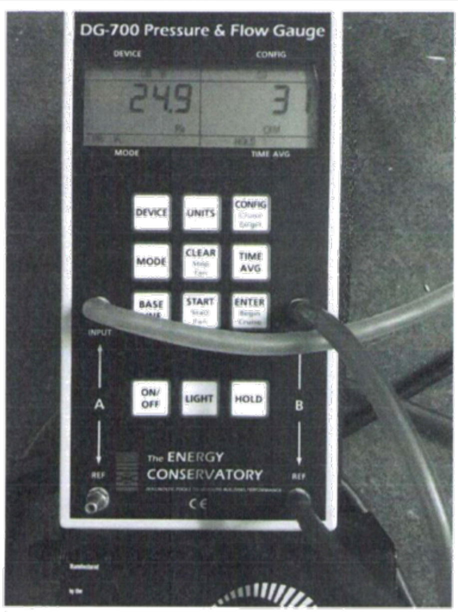
TDL = Total Duct Leakage LTO = Leakage to Outside

Blower Unit Location

Duct Blaster Location During Test Unit

Are all HVAC connections sealed properly? ○ YES ● NO

Comments:



APPENDIX I

EXHAUST DUCT LEAKAGE REPORT

(See next **3** pages)

DPIS Engineering, LLC
The Builder's Solution

Blower Door / Duct Blaster

1512699

1 of 3

Date: 1/25/2018 Plan# Po # Wo # 220560

Builder: James F. Sweeney

Address: 3100 State Highway 47 - Building 6502

Subdivision: Bryan

L/B/S // City Bryan Zip: 77807

Signature:

Inspector: BRIAN COOK

- [x] Pass
- [ ] Fail
- [ ] NRI
- [ ] Correct & Proceed
- [ ] Cancelled w/o Notification

Home Start Date: 01/23/2018

Is this a reinspection? True Inspection # 2

Supt. Name: **James Sweeney** Phone: **979-575-5182** Called? ✔ Y ☐ N On Site? ✔ Y ☐ N

Inspection Status Summary Meter#: Na

Building Type : **Single Family** Utility Co.: HVAC Contractor:

Duct Blaster	☐ NA	✔ Pass	☐ Fail	☐ NRI	☐ Correct & Proceed
Blower Door	✔ NA	☐ Pass	☐ Fail	☐ NRI	☐ Correct & Proceed

CFM50 Target

CFM50 Test

BD Location

Wind Condition ☐ Yes ☐ No

Blower Door Location During Test

Comments: **Blower door previously completed**

DPIS Engineering, LLC
The Builder's Solution

Blower Door / Duct Blaster

1512699

Date: 1/25/2018 WO# 220560 Job: PO# Plan#

Builder: James F. Sweeney Home Start Date: 01/23/2018

Address: 3100 State Highway 47 - Buildin

Subdivision: Bryan

City: Bryan State TX Zip:

Lot / Block / Section: //

Duct Blaster

Status Pass

		TDL	Target	LTO	Target
Unit 1		2.7	5		
Unit 2					
Unit 3					
Unit 4					
Unit 5					

TDL = Total Duct Leakage LTO = Leakage to Outside

Blower Unit Location

Duct Blaster Location During Test **Interior**

Are all HVAC connections sealed properly? (●) YES ( ) NO

See Next Page---->>

Comments:

Converted from pascals to cfms, see Ring 4 Flow Table below for results.

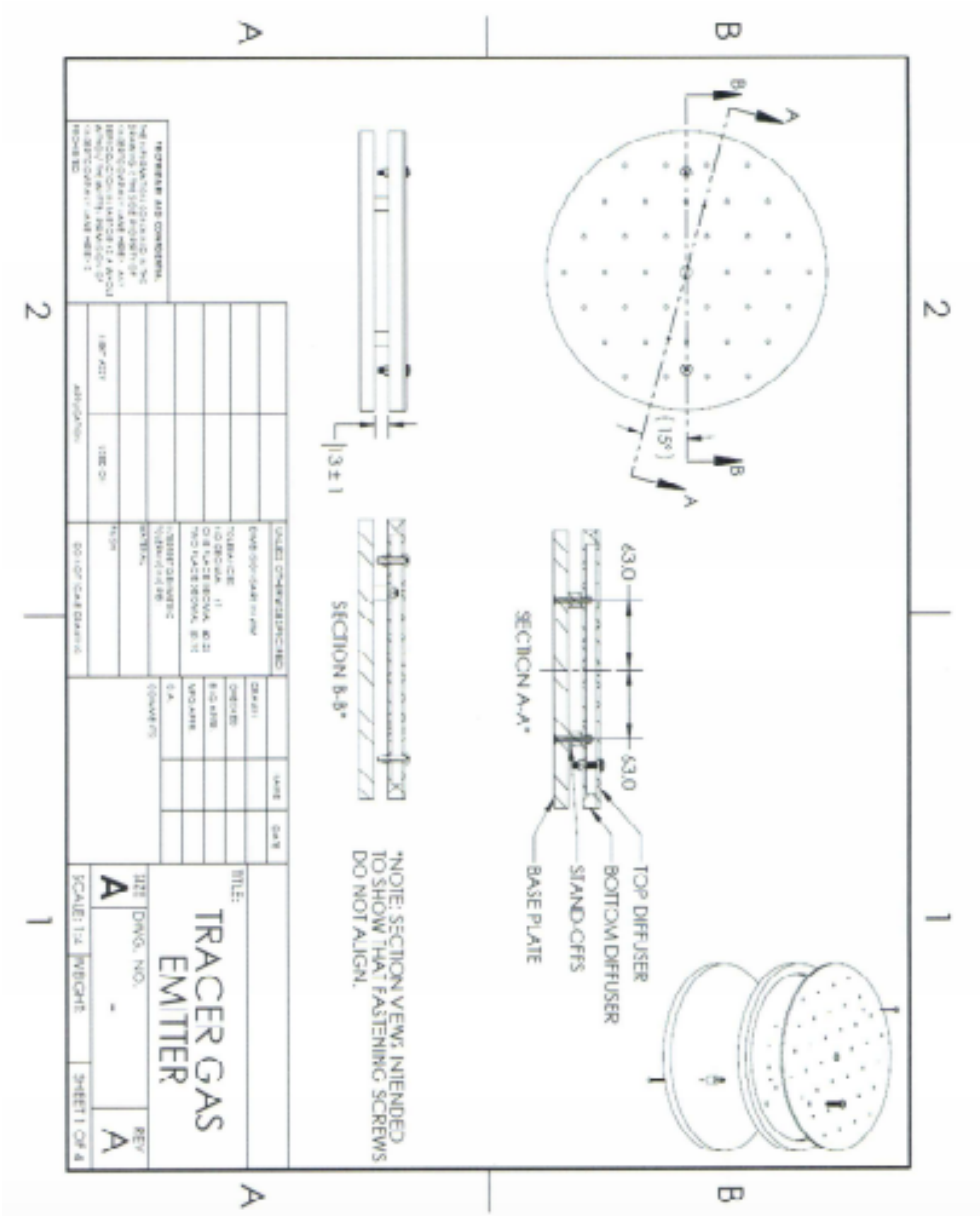
Ring 4 Flow Table

Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)	Fan Pressure (Pa)	Flow (cfm)
5	2.4	105	11.0	205	15.4	305	18.8	405	21.7
10	3.4	110	11.3	210	15.6	310	18.9	410	21.8
15	4.1	115	11.5	215	15.8	315	19.1	415	21.9
20	4.8	120	11.8	220	16.0	320	19.3	420	22.1
25	5.4	125	12.0	225	16.1	325	19.4	425	22.2
30	5.9	130	12.3	230	16.3	330	19.6	430	22.3
35	6.3	135	12.5	235	16.5	335	19.7	435	22.5
40	6.8	140	12.7	240	16.7	340	19.8	440	22.6
45	7.2	145	12.9	245	16.8	345	20.0	445	22.7
50	7.6	150	13.2	250	17.0	350	20.1	450	22.8
55	8.0	155	13.4	255	17.2	355	20.3	455	23.0
60	8.3	160	13.6	260	17.3	360	20.4	460	23.1
65	8.7	165	13.8	265	17.5	365	20.6	465	23.2
70	9.0	170	14.0	270	17.7	370	20.7	470	23.4
75	9.3	175	14.2	275	17.8	375	20.8	475	23.5
80	9.6	180	14.4	280	18.0	380	21.0	480	23.6
85	9.9	185	14.6	285	18.2	385	21.1	485	23.7
90	10.2	190	14.8	290	18.3	390	21.3	490	23.8
95	10.5	195	15.0	295	18.5	395	21.4	495	24.0
100	10.7	200	15.2	300	18.6	400	21.5	500	24.1

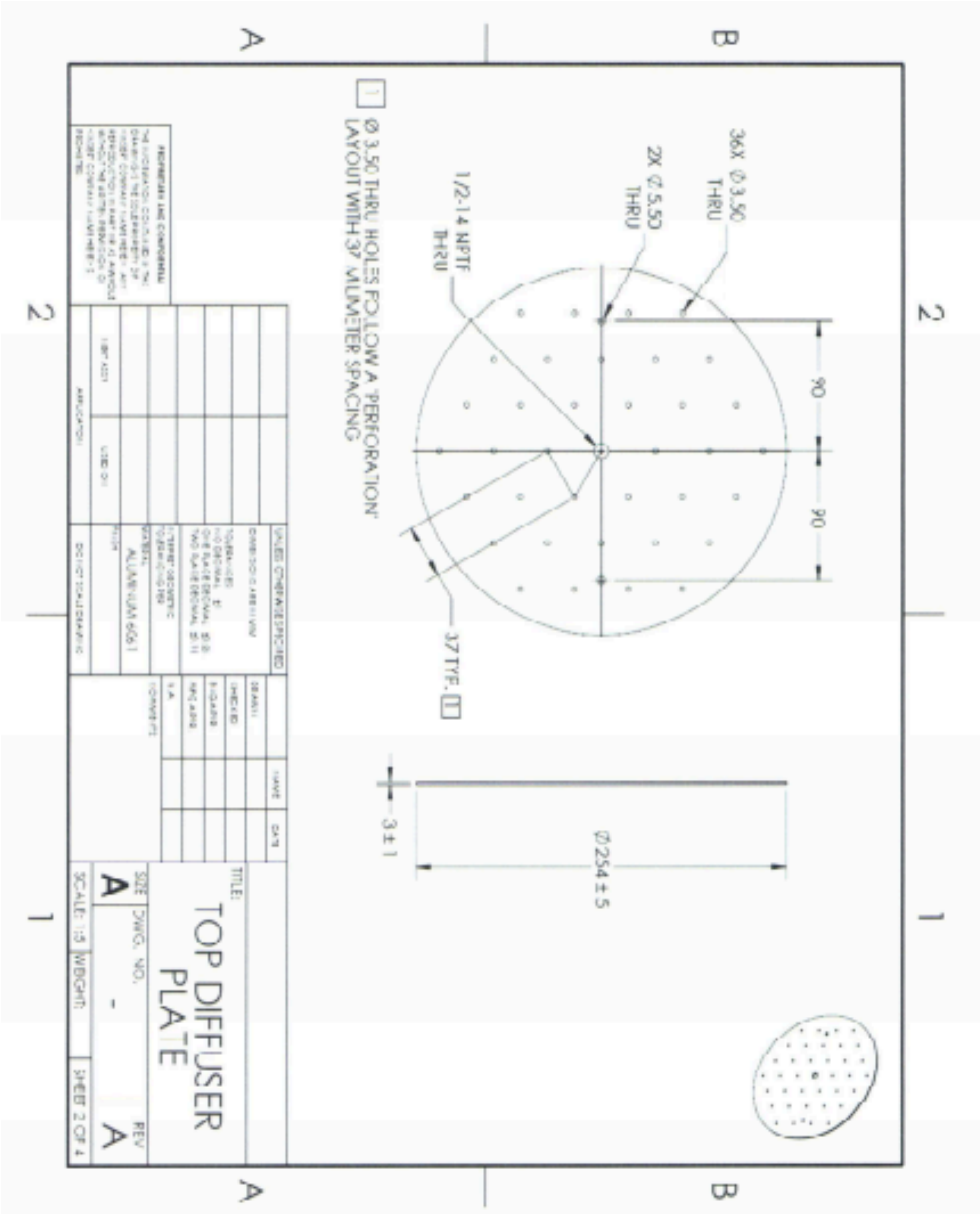
APPENDIX J

DIMENSIONAL DRAWINGS FOR TRACER GAS EMITTER PLATES

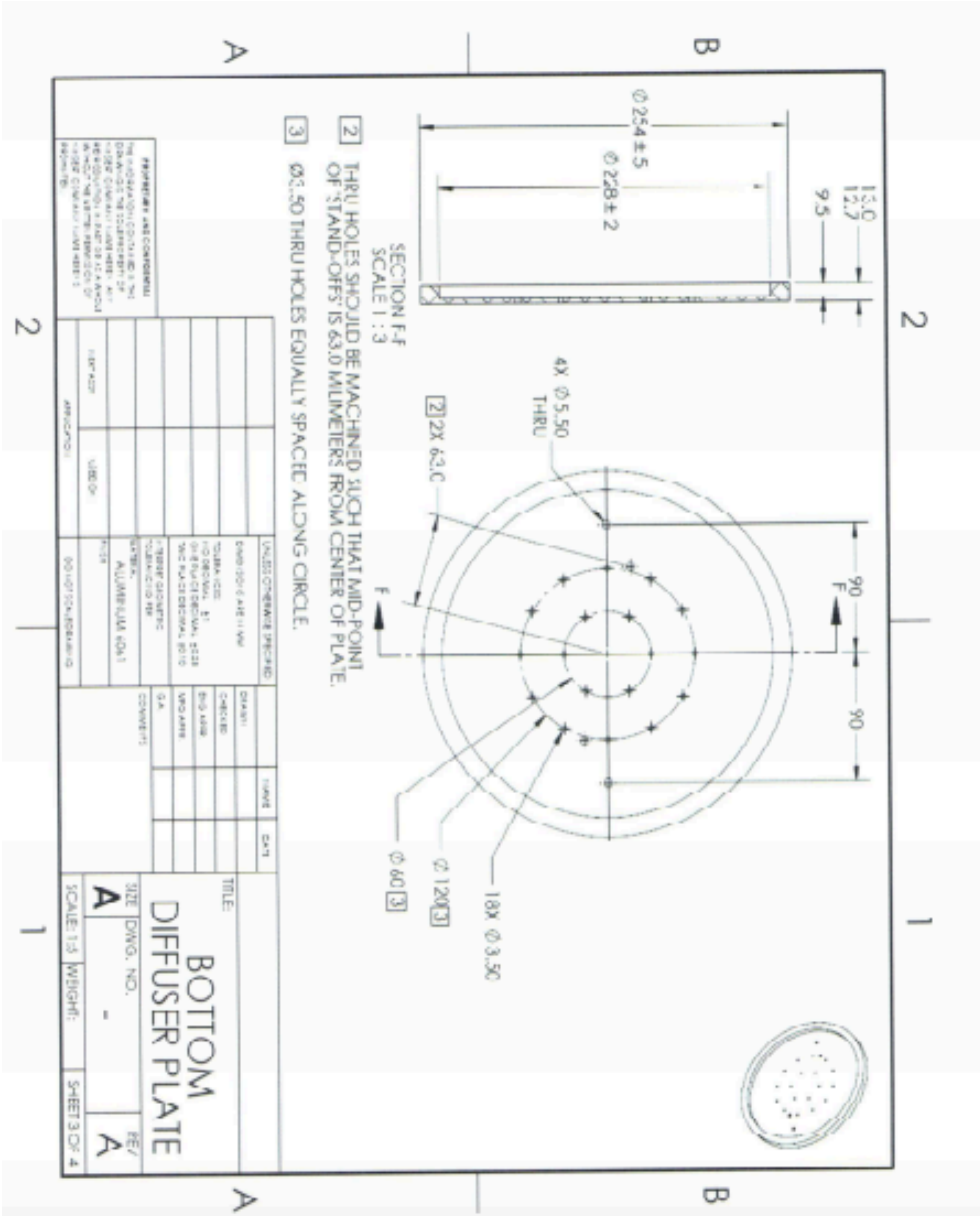
(See next **4** pages)



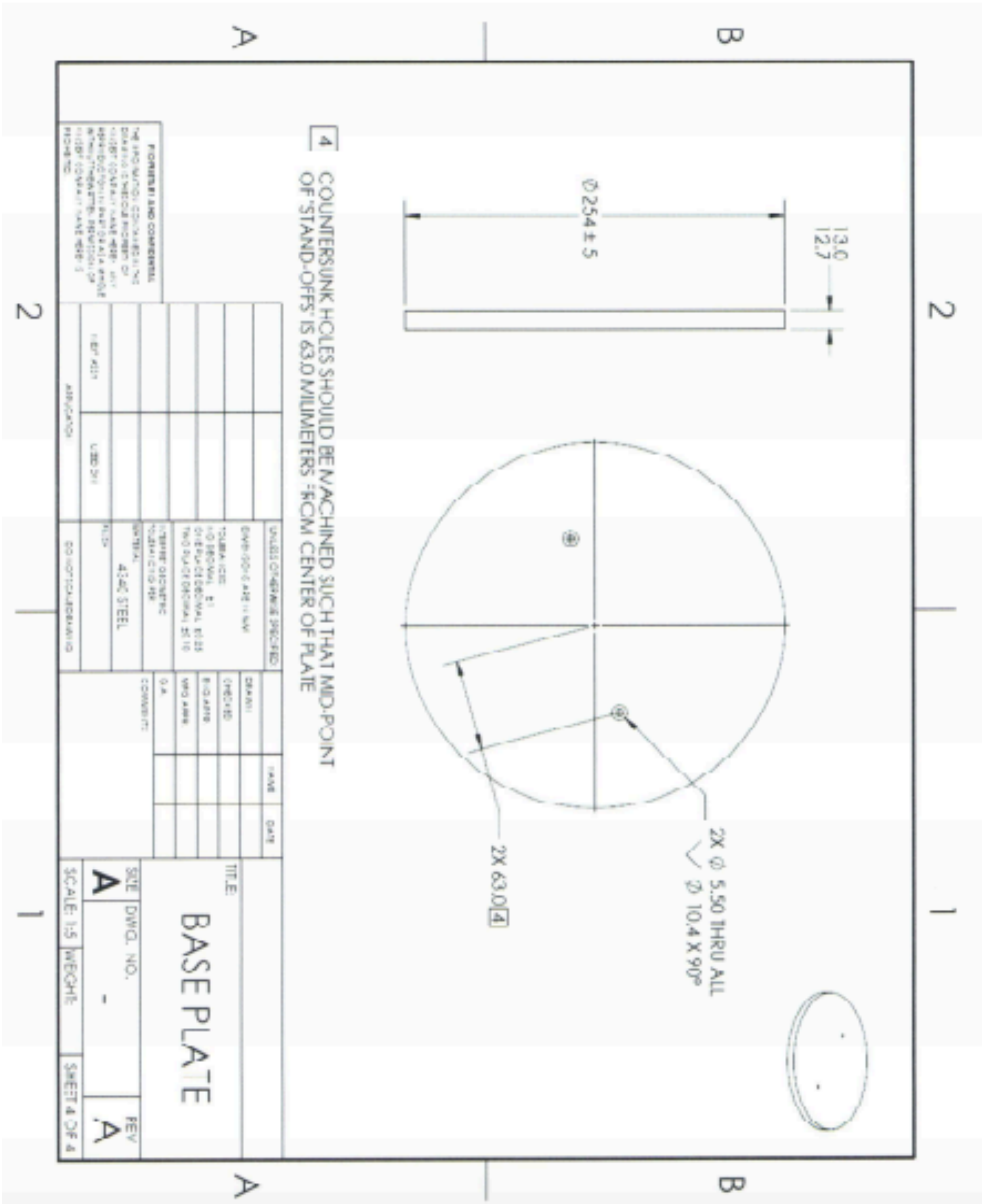
TRACER GAS EMITTER
TITLE:
SIZE
A
DWG. NO.
REV
A
SCALE: 1:4
WEIGHT:
SHEET 1 OF 4
SECTION A-A*
SECTION B-B*
*NOTE: SECTION VIEWS INTENDED TO SHOW THAT FASTENING SCREWS DO NOT ALIGN.
TOP DIFFUSER
BOTTOM DIFFUSER
STAND-OFFS
BASE PLATE
63.0
63.0
13 ± 1
(15°)



TOP DIFFUSER PLATE
36X Ø3.50 THRU
2X Ø5.50 THRU
1/2-14 NPTF THRU
Ø3.50 THRU HOLES FOLLOW A 'PERFORATION' LAYOUT WITH 37 MILIMETER SPACING
37 TYP.
90
90
Ø254 ± 5
3 ± 1
ALUMINUM 6061
SIZE A
DWG. NO. -
REV A
SCALE: 1:5 WEIGHT:
SHEET 2 OF 4



Ø 254 ± 5
Ø 228 ± 2
13.0
12.7
9.5
SECTION F-F
SCALE 1 : 3
4X Ø 5.50
THRU
2 2X 63.0
90
90
F
F
18X Ø 3.50
Ø 120 3
Ø 60 3
2 THRU HOLES SHOULD BE MACHINED SUCH THAT MID-POINT OF 'STAND-OFFS' IS 63.0 MILIMETERS FROM CENTER OF PLATE.
3 Ø3.50 THRU HOLES EQUALLY SPACED ALONG CIRCLE.
ALUMINIUM 6061
TITLE:
BOTTOM DIFFUSER PLATE
SIZE
A
DWG. NO.
-
REV
A
SCALE: 1:5
WEIGHT:
SHEET 3 OF 4

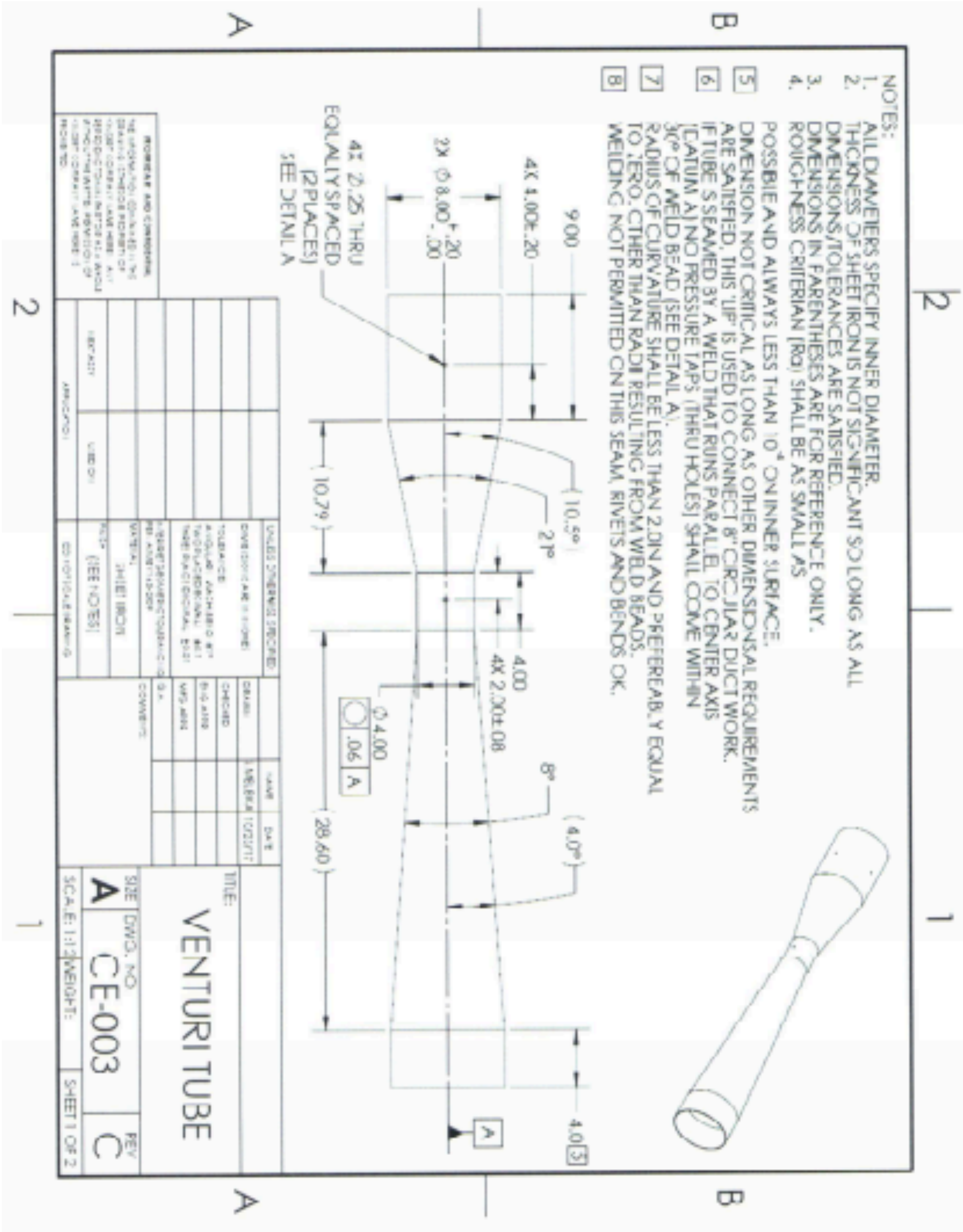


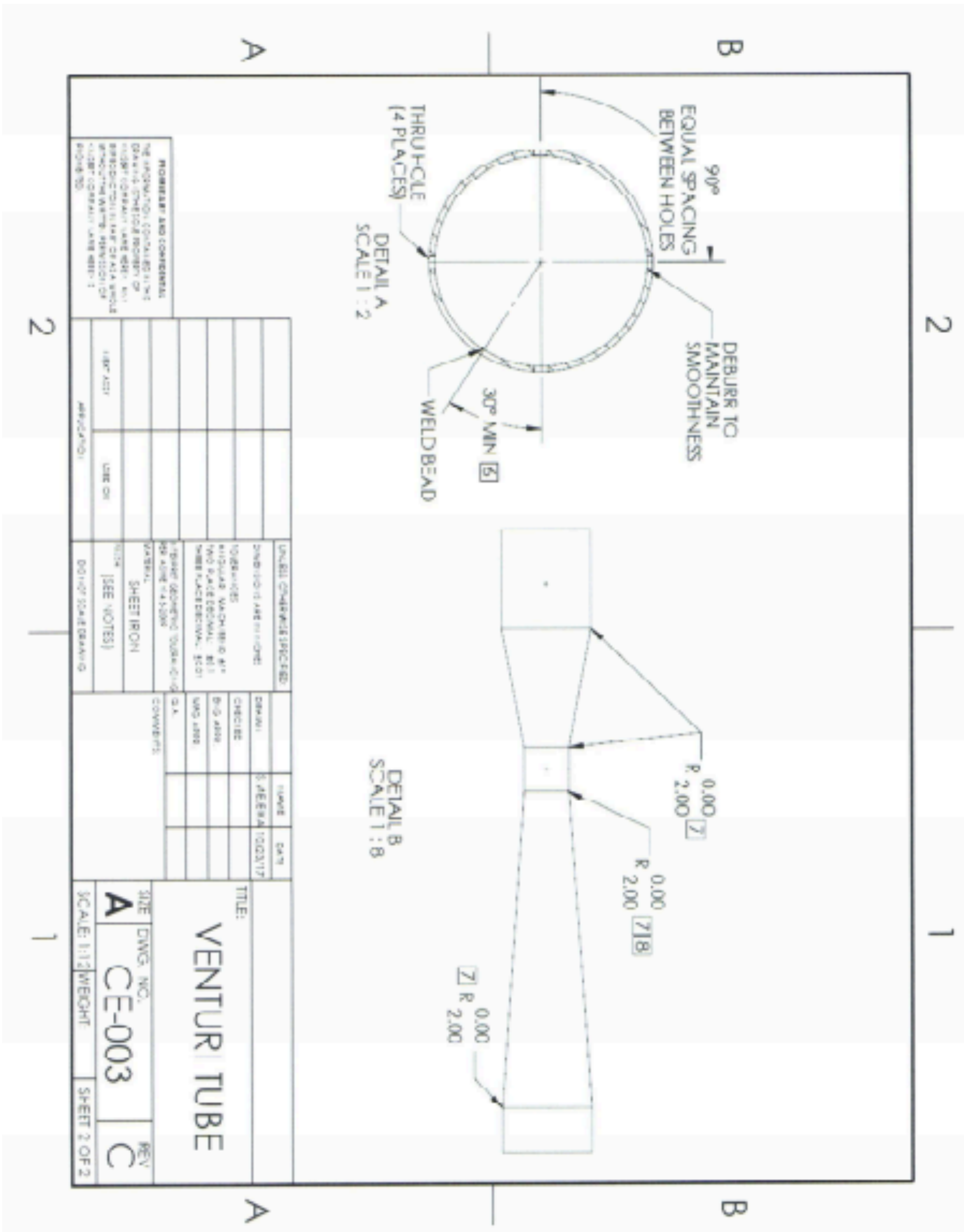
4 COUNTERSUNK HOLES SHOULD BE MACHINED SUCH THAT MID-POINT OF "STAND-OFFS" IS 63.0 MILIMETERS FROM CENTER OF PLATE
Ø254 ± 5
13.0
12.7
2X Ø 5.50 THRU ALL
Ø 10.4 X 90°
2X 63.0 4
TITLE:
BASE PLATE
SIZE
A
DWG. NO.
REV
A
SCALE: 1:5
WEIGHT:
SHEET 4 OF 4
MATERIAL
4340 STEEL
DO NOT SCALE DRAWING

APPENDIX K

DIMENSIONAL DRAWINGS FOR VENTURI TUBE

(See next **2** pages)


NOTES:
1. ALL DIAMETERS SPECIFY INNER DIAMETER.
2. THICKNESS OF SHEET IRON IS NOT SIGNIFICANT SO LONG AS ALL DIMENSIONS/TOLERANCES ARE SATISFIED.
3. DIMENSIONS IN PARENTHESES ARE FOR REFERENCE ONLY.
4. ROUGHNESS CRITERIAN [Ra] SHALL BE AS SMALL AS POSSIBLE AND ALWAYS LESS THAN 10^-4 ON INNER SURFACE.
5 DIMENSION NOT CRITICAL AS LONG AS OTHER DIMENSIONAL REQUIREMENTS ARE SATISFIED. THIS 'LIP' IS USED TO CONNECT 8" CIRCULAR DUCT WORK.
6 IF TUBE IS SEAMED BY A WELD THAT RUNS PARALLEL TO CENTER AXIS [DATUM A] NO PRESSURE TAPS (THRU HOLES) SHALL COME WITHIN 30° OF WELD BEAD (SEE DETAIL A).
7 RADIUS OF CURVATURE SHALL BE LESS THAN 2.0IN AND PREFEREABLY EQUAL TO ZERO, OTHER THAN RADII RESULTING FROM WELD BEADS.
8 WELDING NOT PERMITED ON THIS SEAM, RIVETS AND BENDS OK.
9.00
4X 1.00±.20
2X ⌀8.00 +.20 -.00
4X ⌀.25 THRU EQUALLY SPACED (2 PLACES) SEE DETAIL A
(10.79)
(10.5°)
21°
4.00
4X 2.00±.08
⌀4.00
.06 A
8°
(4.0°)
(28.60)
4.0 3
A
SHEET IRON
(SEE NOTES)
TITLE:
VENTURI TUBE
SIZE A
DWG. NO. CE-003
REV C
SCALE: 1:12
WEIGHT:
SHEET 1 OF 2
A
B
2
1


90° EQUAL SPACING BETWEEN HOLES
DEBURR TO MAINTAIN SMOOTHNESS
THRU-HOLE (4 PLACES)
DETAIL A SCALE 1 : 2
30° MIN
WELD BEAD
DETAIL B SCALE 1 : 8
SHEET IRON
[SEE NOTES]
TITLE:
VENTURI TUBE
SIZE
A
DWG. NO.
CE-003
REV
C
SHEET 2 OF 2