Comparison of Low-Cost CO2 Non-Dispersive Infrared (NDIR) Sensors for Ambient Greenhouse Gas Monitoring

Annaliese Keimel

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Comparison of Low-Cost CO₂ Non-Dispersive Infrared (NDIR) Sensors for Ambient Greenhouse Gas Monitoring

An Analysis of SenseAir K30 Fast Response and K33 ELG Sensors for Deployment on Unmanned Aerial Vehicles (UAVs)

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Undergraduate Honors Thesis
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Acknowledgements

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Abstract

This thesis centers around an analysis of two low-cost, small footprint non-dispersive infrared (NDIR) CO₂ sensors for incorporation to lightweight drone-based sensing applications. The sensors of interest are produced by SenseAir and are the models K30 1% FR and K33 10,000ppm ELG. Low-cost portable sensors such as these are becoming increasingly common, but require thorough analysis of their accuracy, sensitivity to environmental noise, and response time in order to increase their reliability for accurate CO₂ measurement applications. The sensors were tested against benchmark instruments in a flow through chamber. The goals of this project were to increase understanding of both sensors’ characteristics, especially sensitivity to ambient temperature and relative humidity conditions. It was found that the influence of humidity on the CO₂ concentration produced contradicting trends within the two different humidity sensitivity tests conducted. It was also found that the relative humidity readings of the K33 were higher than the Hobo benchmark logger by 11 – 15 % throughout the tests. Additionally, the CO₂ concentrations were offset from benchmark readings by a consistent amount in the tests conducted. This offset ranged from 70 - 90 ppm higher for the K30 and 80-100 ppm higher for the K33. This suggests that an algorithm could be applied to correct for this offset. In order to determine this correction procedure, the sensors’ should be tested following calibration and in greater quantities, meaning more sensors of the same model. For all tests conducted here, the manufacturer’s Automatic Baseline Correction (ABC) algorithm was not applied, leaving the opportunity to further analyze this calibration method.
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1.0 Introduction

Global climate change poses a great threat to environmental health, human security, and the future health of our planet. One of the driving forces behind this crisis are anthropogenic greenhouse gases (GHGs). These gases have the capability of trapping heat in the atmosphere and consist of carbon dioxide (CO$_2$), methane (CH$_4$), nitrous oxide (N$_2$O), water vapor (H$_2$O) and fluorinated gases. CO$_2$ specifically receives a lot of attention as a key contributor to the issue, as CO$_2$ alone was estimated to account for 81% of the total United States GHGs emissions in 2016. The global average ambient concentration of CO$_2$ is just above 400 ppm and has been steadily rising since the early 1900s. Further, while CO$_2$ has low global warming potential compared to other GHGs, CO$_2$ has an extremely long atmospheric lifetime. It was estimated that after 100 years of a pulse release of CO$_2$ gas 40% remains, after 1000 years, 20% remains, and after 10,000 years 10% remains. This long lifetime is mostly due to the complex nature of the carbon cycle and the sequestering of CO$_2$ in the ocean. This long lifetime along with representing the greatest GHG emissions percentage makes CO$_2$ a primary concern in relation to climate change.

CO$_2$ is regulated in the United States in two main sectors, transportation and industry. In the transportation sector, CO$_2$ regulations have been placed on specific model year (MY) vehicles. On light-duty vehicles (passenger cars & trucks), MY 2012-2016 and MY 2017-2025 have specific regulations placed on manufacturers, in terms of fuel economy standards. The EPA regulates industry CO$_2$ emissions through Prevention of Significant Deterioration (PSD) and Title V Operating Permit Programs enforced by the Clean Air Act of 1963. Industry GHG emissions are regulated by the EPA based upon best available control technology (BACT). This is based on the maximum degree of control that can be achieved, and considers environmental, economic, and energy impacts.

Reduction of GHG emissions is at the forefront of research aimed at mitigating climate change. In order to understand the full extent of the problem, accurate emissions quantifications via real-world measurements are necessary. CO$_2$ is found to be released by sources or stored in sinks on our planet. The three main natural sinks in the earth’s biosphere are the ocean, forests, and soil. The two main sources of CO$_2$ emissions are transportation and industry and other notable sources are agriculture and the residential emissions. These sources can be point sources and non-point...
sources. Point sources are easily identifiable and typically consist of industry emissions. Non-point sources are not easily identified and range from vehicles to agricultural emissions. There are no easy methods for quantifying non-point sources. As a result, measuring CO$_2$ reliably from these sources is crucial for emission identifications and for environmental health purposes.

1.1 Background and Literature

There are a multitude of measurement technologies available for CO$_2$ and GHGs. The methods largely depend on one’s application, whether it be safety, research, or ambient concentration recordings. The application often determines the detection range, resolution, and accuracy needed. One way to break down the type of measuring technologies is to organize them into two groups, methods that use electrical properties and methods that use “other” properties to detect gases$^8$. Sensors that use electrical properties consist of metal oxide semiconductors, carbon nanotubes, and polymer sensors. The principle method of measurement for sensors in this group is based upon electrical variation of a physical materials properties in the presence of the gas species of interest$^8$. Sensors in the “other” properties category may consist of optical methods, acoustic methods, and gas chromatography methods$^8$.

In-lab benchtop equipment that uses gas chromatography has proven to be one of the most accurate measurement methods, often providing high sensitivity and selectivity to a given gas$^8$. These units however, are often large and expensive$^9$, necessitating methods that are cost-effective and mobile, while retaining accuracy. There has been a significant amount of research dedicated to developing and analyzing portable measurement technologies for GHGs. The ambient CO$_2$ concentration of 400 ppm is not universal; to better identify emission sources and hotspots it has become important to increase the spatial resolution of CO$_2$ measurements. Picarro, a company producing GHGs measurement technologies, has deployed its instruments in cars, aircrafts, and on buildings to mobilize their units and increase spatial resolution, with the objective of developing greenhouse gas monitoring networks$^{10}$. In Finland, there have been efforts to integrate CO$_2$ sensors on cell phones using optical technologies such as a Fabry-Perot interferometer (FPI) during the wafer (phone chip) development phase of manufacturing$^{11}$. Non-Dispersive Infrared (NDIR) CO$_2$ sensors have been deployed in agricultural settings for spatial field monitoring of CO$_2$ concentrations in a dairy cow house$^{12}$. Another technology that is a
popular mobile alternative is metal oxide semiconductor sensing. These units are very low-cost and small, however there are inherent problems with the technology. The material properties of the sensing mechanism and surface interactions result in a working range of 2,000 – 10,000 ppm frequently found in the literature for CO$_2$ metal oxide sensors $^{13}$. The lower end of this range is roughly 5 times greater than the ambient CO$_2$ concentration making these sensors unreliable for monitoring CO$_2$ in the ambient environment.

There have been further efforts to improve upon deviations in CO$_2$ measurements using low-cost methods. In an effort to develop a portable device that does not require exhaustive calibration, Yasuda et al. tested two low-cost CO$_2$ sensors in order to determine an algorithm to correct their true concentration $^{14}$. The portable device finally developed allows for CO$_2$ measurement while walking, biking, and measuring CO$_2$ distribution in urban areas $^{14}$. Other research efforts have used monitoring towers typically used for global CO$_2$ monitoring to develop networks for observations in urban areas. These towers increase the density of CO$_2$ measurements by implementing 3 to 12 sites in a metropolitan area, and estimate GHGs from the covered land $^{15}$. These are still expensive, but further experiments found that a higher spatial resolution of CO$_2$ observations produce reasonable GHG estimates, even though the error is still higher than the research grade technologies $^{15}$. This indicates that an increase in measurements over a broad area can produce reasonable CO$_2$ estimates, even if the CO$_2$ reading from an individual observation is not highly accurate.

The move to reduce the cost and size of CO$_2$ technologies stems from a desire to mobilize CO$_2$ measurement. Mobilization of measurements will increase spatial resolution, enabling more comprehensive data collection and understanding of CO$_2$ emissions over a broad area and ideally help identify non-point sources. While the technologies are available to reduce size, cost, and mobilize measurements, complete understanding of the accuracies of these technologies in ambient settings is not.

Reducing size and cost without compromising accuracy and detection capabilities can be difficult. Non-Dispersive Infrared (NDIR) sensing technology in particular, has proven to be stable and robust against interference from other gases and is durable during handling $^{14}$. NDIR CO$_2$ sensors are principally used for heating, ventilation, and air conditioning (HVAC) purposes$^{14}$. Research has shown that in addition to contributing to climate change, CO$_2$ can
negatively affect human health. CO$_2$ inside buildings can reach concentration levels up to several thousand parts per million, which preliminary studies have indicated can negatively influence human decision making and function $^{16}$. HVAC CO$_2$ NDIR sensors are often implemented in indoor settings where CO$_2$ concentrations are frequently elevated above 400 ppm, however there is increasing interest in using these sensors in ambient conditions.

Use of NDIR sensors for other applications such as personal monitoring, environmental research, and developing sensor networks has been increasing, but approached with caution. This caution is primarily due to the variability observed in the accuracy of NDIR CO$_2$ sensors. Research on CO$_2$ NDIR sensors, such as a study conducted at Iowa State University on 15 different HVAC-grade NDIR sensors, supports concern regarding accuracy. For each sensor model, three individual sensors were tested. The test conducted consisted of a controlled chamber held at 40% relative humidity, 73°F, and 14.7 psi. The test began at a concentration of 400 ppm with an increment of 350 ppm until 1800 ppm was reached. The concentration was controlled by a CO$_2$ and N$_2$ mixture, adjusted using mass flow controllers. Out of the 15 different models tested, none of the sensors met the manufacturer’s accuracy statement for all three replicates $^{17}$. Table 1.1 demonstrates the results of this study, which did not provide model names for the sensors analyzed. Discrepancies from manufacturer’s accuracy are influenced by temperature, humidity, pressure, and frequency and duration of use $^{17}$. A comprehensive understanding of the influence of these environmental factors is therefore essential for mobile deployment of NDIR CO$_2$ sensors in an ambient environment.

**Table 1.1.** Study Summary of 15 Different NDIR CO$_2$ Sensors Tested for Meeting Manufacturer’s Accuracy Statement $^{17}$

<table>
<thead>
<tr>
<th>Sensor Model</th>
<th>All 3 sensors meet the manufacturer’s accuracy statement</th>
<th>Two sensors meet the manufacturer’s accuracy statement</th>
<th>One sensor meets the manufacturer’s accuracy statement</th>
<th>None of the sensors meet the manufacturer’s accuracy statement</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1</td>
<td>X</td>
<td></td>
<td></td>
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<td>S4</td>
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<tr>
<td>S15</td>
<td>X</td>
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</tbody>
</table>
1.2 Problem Statement

Previous studies have indicated that NDIR sensors have the potential to provide accurate and reliable CO\textsubscript{2} measurements in ambient conditions. At the University of Vermont Rubenstein School there is a desire to implement the K30 NDIR sensor on unmanned aerial vehicles (UAVs) for ambient GHG monitoring. This would allow for the deployment of numerous sensors, increasing the spatial resolution of measurements and developing a sensing network. There is insufficient research documenting how accurate these sensors are under different ambient conditions. To maximize the potential gains that small, low-cost sensors can provide, further research and understanding is needed. The aim of this research is to quantify two low-cost portable CO\textsubscript{2} sensors in terms of sensor accuracy, sensitivity, response time, and capabilities for long-term monitoring. These factors are essential for expanding sensor usefulness in monitoring emissions.

1.3 Introduction to Instrumentation

1.3.1 NDIR Sensing Technology

The working principle for NDIR sensing technology is the Beer-Lambert Law seen in equation 1. This theory is based on light absorbance, which occurs due to the vibrations of molecular bonds. If the frequency of a specific bond’s vibration matches the frequency of IR light, absorption will occur \textsuperscript{18}. Equation 1 indicates that the concentration of the gas of interest, c, is directly proportional to the absorbance of infrared (IR) light, A, at a certain wavelength that corresponds to the molecule’s absorbance spectrum \textsuperscript{19}. 
Beer-Lambert Law

\[ A = \log \left( \frac{I_o}{I} \right) = \varepsilon cl \]  

(1)

Where:

\( A \) = absorbance (absorbance units, A.U.)
\( I_o \) = incoming “reference” IR radiation intensity (W/m²)
\( I \) = IR radiation intensity after passing through CO₂ gas sample (W/m²)
\( \varepsilon \) = molar absorption coefficient (L/mol·cm)
\( c \) = concentration of CO₂ (mol/L)
\( l \) = beam path length (cm)

This theory is implemented in NDIR CO₂ sensors by directing an IR light source of known intensity, \( I_o \), through a volume with a sample of the gas inside. The CO₂ gas can be sampled actively by pumping, or passively. CO₂ will absorb IR light at 4.26 microns (µm) as well as 2.7 and 15 µm. The NDIR sensors use the 4.26 µm absorption band and allow the other wavelengths of IR light to pass through. The light passing through will then reach a filter that absorbs each wavelength of the IR source light except for the 4.26 µm. This is a narrow band with narrow filters referring to a 90±20 nm half bandwidth and standard filters referring to a 180±20 nm half bandwidth, making CO₂ NDIR very selective. A detector behind this filter will determine how much of the initial IR light was not absorbed by the CO₂ molecules or filter and compare it to the intensity of the initial light source, \( I_o \). This relationship, shown in [equation 1](#), provides indication of the concentration of CO₂ present. Figure 1.1 provides a schematic of the different components of a typical NDIR CO₂ sensor. Figure 1.2 shows the infrared transmission spectrum of CO₂. The y-axis shows the intensity of transmitted IR light for a given wavelength in microns (µm) in the presence of CO₂ molecules. Figure 1.2 shows that at 4.26 µm the intensity of transmitted radiation drops to zero. This indicates that CO₂ will absorb all IR light at this wavelength. The sensors used in this project use this wavelength. It is relatively narrow in width and highly selective to CO₂. Another drop is seen just above 14 µm, but is not the standard wavelength used in NDIR CO₂ sensors seen throughout the literature and by the current commercially available NDIR sensing technologies.
**Figure 1.1** Schematic of NDIR CO$_2$ Sensor. Ref. Sig. Vr is reference signal and Absorption Sig. Vs is signal due to gas absorption.

**Figure 1.2.** Intensity of Transmitted IR Light Source with CO$_2$ Molecules by IR Wavelength (absorption at 2.7 µm not shown).

### 1.3.2 Instrumentation Used

The two sensors analyzed were the K30 FR 1% (K30) and K33 ELG 10,000 ppm (K33) produced by SenseAir (Delsbo, Sweden). These sensors are sold commercially and recommended for HVAC purposes. The K30 costs $95.00 and the K33 is $250.00 and both are considered to be low-cost. The K30 model sensor used is unique as it is advertised as a fast response (FR) sensor with a rate of measurement of 2Hz or once every 0.5 seconds and response
time of 2 seconds at 0.5 L/min tube gas flow. The K33 model is unique in that it also contains temperature and relative humidity sensing, using a Sensirion AG (Staefa, Switzerland) SHT11 Temperature / RH sensor that is installed on the board. Both sensors have a CO₂ measurement range of 0-10,000 ppm and an accuracy of ± 30 ppm or ± 3 % of the measured value as Table 1.2 shows these specifications. Both sensors have dimensions of 51 × 57 × 14 mm (L x W x H), a weight of about 17 g, and have advertised lifetimes of 15 years. It should be noted that the K30 and K33 both have an automatic baseline correction (ABC) algorithm feature that takes the lowest detected CO₂ concentration read over a series of 7.5 days and calibrates its readings according to this concentration being set equal to 400 ppm. For the analysis conducted in this thesis, the ABC feature was turned off because only some tests were conducted under ambient CO₂ concentration levels.

In addition to the K30 and K33 NDIR CO₂ sensors, the larger field-portable Li-COR 8100A (Lincoln, Nebraska) instrument makes CO₂ concentration measurements using NDIR technology. The Li-COR 8100A was developed for agricultural soil gas flux measurements using chambers. Different Li-COR brand CO₂ sensing technologies have been used as a benchmark in the literature discussing low-cost NDIR sensors. Li-COR brand CO₂ monitors have been used to assess NDIR CO₂ sensors potential for measuring soil CO₂ efflux and point concentration and to develop a portable CO₂ apparatus. The Li-COR8100A was used as a benchmark in this study and was available through the University of Vermont Rubenstein school for use in this study. The Li-COR 8100A has a higher resolution and better accuracy than the low-cost SenseAir sensors, as Table 1.2 indicates. The K30 and K33 have an accuracy of ± 3 % of the reading while the Li-COR has an accuracy of ± 1.5 % of the measured reading, twice as accurate. Prior to gaining access to the Li-COR 8100A, an AutoLogic 5-Gas Analyzer (Chicago, Illinois) was used for comparison. This instrument measures hydrocarbons (HC), oxides of nitrogen (NOₓ), carbon monoxide (CO), oxygen (O₂), and CO₂ and is typically used for monitoring vehicle tailpipe emissions in the UVM TAQ Lab. The disadvantage of the AutoLogic 5-Gas instrument is that it only has a resolution of 0.01%, 100 ppm, which is limiting in terms of analyzing the accuracy of the K30 and K33 sensors. All instruments used can be seen in Figure 1.3.
<table>
<thead>
<tr>
<th>Model</th>
<th>Measurement Range</th>
<th>Rate of Measurement</th>
<th>Accuracy</th>
<th>Resolution</th>
<th>Weight</th>
<th>Dimension</th>
</tr>
</thead>
<tbody>
<tr>
<td>SenseAir K30 FR 1%</td>
<td>0-10,000 ppm</td>
<td>2Hz (once every 0.5 sec)</td>
<td>+/- 30 ppm, +/- 3% of measured value</td>
<td>1 ppm</td>
<td>17 g</td>
<td>51 × 57 × 14 mm</td>
</tr>
<tr>
<td>SenseAir K33 ELG</td>
<td>0-10,000 ppm</td>
<td>Max 1/15 Hz (or 15-sec sampling intervals)</td>
<td>+/- 30 ppm, +/- 3% of measured value</td>
<td>1 ppm</td>
<td>17 g</td>
<td>51 × 57 × 14 mm</td>
</tr>
<tr>
<td>AutoLogic 5-Gas</td>
<td>0-20 %</td>
<td>1 Hz</td>
<td>+/- 0.3% abs. or +/- 3% rel.</td>
<td>.01 ppm (100 ppm)</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>Li-COR 8100A</td>
<td>0-20,000 ppm</td>
<td>1 Hz</td>
<td>1.5% of reading</td>
<td>.01 ppm</td>
<td>5.3 kg (11.8 lb.)</td>
<td>29 cm x 38.1 cm x 16.5 cm</td>
</tr>
</tbody>
</table>

**Table 1.2. Instrument Specifications**
Figure 1.3. All Instruments Used (not to scale). (A) Li-COR8100A (B) Autologic 5-Gas Analyzer (C) K30 FR (D) K33 ELG

Throughout the conducted experiments, temperature and relative humidity were independently monitored inside and outside of the testing chamber using two Hobo (Bourne, Massachusetts) U23 Pro v2 Temperature/Relative Humidity Data Loggers, referred to as Hobo 1 or Hobo 2 throughout the analysis. Hobo 1 and 2 are the same model. Hobo 1 was kept inside during experiments and Hobo 2 remained outside of the chamber during experiments. The manufacturer specified accuracy is ±0.21°C from 0°C to 50°C and ±2.5% from 10% to 90% RH. Both Hobo loggers were placed inside the 6-L testing chamber for 24 hours to determine how close the loggers read to one another. These data can be found in Section 2.4.
2.0 Methods

2.1 Gas Mixing Apparatus

The gas mixing apparatus (Figure 2.1) began with two compressed gas cylinders (AirGas East, Williston VT), one containing nitrogen (N\textsubscript{2}) and the second cylinder containing either a 5-Gas Calibration mix or a mixture of CO\textsubscript{2} with balance nitrogen. The 5-Gas Calibration mix, blend code 35 vehicle emission EPA blend, contains 12.20\% of CO\textsubscript{2}, or 122,000 ppm, and was used for the first set of experiments up until March 18, 2019. The CO\textsubscript{2}/N\textsubscript{2} mix is 1.011\% CO\textsubscript{2} balanced with nitrogen and was used for all experiments after March 19, 2019. From the cylinders, the gases were fed through stainless steel tubing to two rotameters. The rotameters provided fine control over gas flow in addition to the regulators attached to the cylinders. The rotameters used were Aalborg Instruments rotameters (Orangeburg, New York) with FM 34-039 glass tubes and read from 0 to 150. Calibration of the rotameters was conducted previously by Caitlin Patterson (Figure 2.2) as reported in her thesis appendix and was checked prior to use here.  

![Figure 2.1. Gas configuration for sensor testing](image)

Figure 2.1. Gas configuration for sensor testing
Following the rotameters, the gases were fed into a stainless steel canteen for mixing. The mixture exits the canteen and enters a 6-liter polycarbonate chamber. The tubing is fitted with Swagelok compression fittings and a cable gland to feed required wires into the chamber. The K30, K33, and Hobo 1 were inside the chamber. For humidity tests, the flow was first directed through Perma Pure Nafion membrane tubing that was connected to a temperature-controlled water bath (Fisher Sci 3016H). This tubing allows water molecules to cross the membrane into the gas phase creating humidity. The water bath’s temperature was controlled to adjust the humidity. At the outlet of the Nafion tubing, the gas was first fed through an additional plastic 1-
L chamber that could collect any condensate and house a digital T/RH sensor with readout (the Hobo loggers do not have readouts). After this container, the gas was directed into the 6-L testing chamber. This additional apparatus was only used for humidity tests. A T-shaped (“tee”) fitting at the outlet of the testing chamber directed part of the flow to the 5-Gas Analyzer or Li-COR 8100A and the rest to waste. The 5-Gas Analyzer was used for experiments prior to March 18th, and the Li-COR 8100A was used for all further experiments.

The stainless steel ¼-inch O.D. inlet tubing to the 6-liter polycarbonate testing chamber was wrapped in heat tape and insulation (marked with heat waves in Figure 2.2). Figure 2.3 shows the rotameters and mixing chamber and Figure 2.4 shows the testing chamber and inlet tubing wrapped in heat tape. Chamber residence times were determined using the known 6-L volume and the entering flow rate as determined by TSI Model 4140 Mass Flow Meter in units of L/min. The TSI Flow Meter range is 0.01-20 standard L/min and has an accuracy for air and O₂ of ±2% of reading or 0.005 std L/min, depending on which is greater.

Figure 2.3. Rotameter Placement and Gas Mixing Apparatus
Figure 2.4. Top view of 6-Liter Testing Chamber (chamber lid removed for photo). The Inlet (1) and Outlet (3) Tubing bulkhead fittings and Cable Gland (6) are visible. The Hobo1 (2) and SenseAir CO₂ sensors are inside the chamber while Raspberry Pi (RPi3) (7) and Hobo 2 (5) are outside. The tubing to the 5-Gas/Li-COR benchmarks (4) are also visible.

2.2 Sensor Configuration

The K30 sensor requires a minimum of 5V and the K33 sensor requires a minimum of 6V power supply. A 9.6V battery was split and connected to two eBoot LM2596 DC-to-DC Buck Power Supply Step Down Modules that were used to power the K33 sensor and RPi3. These converters can reduce 3.0-40V inputs to 1.5-35V outputs and are easily adjusted by a potentiometer on the board. One converter was attached to a micro-USB plug and was set to 5.1V output to power the RPi3. The other converter provided power to the K33 after being set to give an output voltage of 6.1V. The K30 was powered by the RPi3 via a USB connection. To communicate with the sensors and store data, a Raspberry Pi 3 Model B (RPi3) was used. Python code used to communicate with the sensors was adapted from CO2meter.com documentation for the K30 sensor and using CO2meter.com Application Notes 104 and 105 (AN 104 and AN105). The code and detailed directions for use can be found in Appendix C. Both sensors used UART
communication protocols. Figure 2.5 shows the preliminary sensor data and power configuration. The battery, RPi3, and converters were located outside the testing chamber.

Figure 2.5. Preliminary Sensor Data and Power Configuration

This setup was used until March 23rd, when an issue with a voltage converter and associated “hot” ground wire was encountered. Tests conducted after March 23rd used two battery packs, a 6V battery to power the K33 and a 5V battery to provide power to the RPi3 and the K30. The battery pack for the K33 consisted of four AA batteries in parallel, which were provided in the K33 Sensor Development Kit. This battery pack has an on and off switch and provides 6V to the K33. The battery used for the RPi3 and the K30 was the RAVPower Turbo+ Series RP-PB043 Portable Charger. This battery provides a 5V output and is rated as 20100mAh (milli Amp hours) or 74.3 Wh (Watt hours). 20100mAh/74.3Wh. The voltage regulators were no longer used in this new set-up as shown in Figure 2.6.
Figure 2.6. Secondary Sensor Data and Power Configuration

Throughout the course of testing, an HDMI connection was used to view the RPi3 screen using the Raspian NOOBs software and desktop. Details on this procedure are described in Appendix C (all other code is found here too).

2.3 Testing Methodology

Several different test types were conducted on the sensors. Table 2.1 summarizes the tests conducted as well as where to find the data within the report. It should be noted that the majority of these tests were conducted at ambient or above ambient CO$_2$ concentrations. Raw outputs for all tests can be found in Appendix A.
<table>
<thead>
<tr>
<th>Test Date</th>
<th>Benchmark Instrument</th>
<th>Type of Test/Purpose</th>
<th>Thesis Section</th>
<th>Concentration Range Tested (ppm)</th>
<th>Duration of Test</th>
<th>Flowrate (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>3/12/19</td>
<td>5-Gas</td>
<td>Accuracy/preliminary test</td>
<td>3.1, Appendix A</td>
<td>4,000–7,000</td>
<td>40 min</td>
<td>2.700–2.800</td>
</tr>
<tr>
<td>3/13/19</td>
<td>5-Gas</td>
<td>Accuracy</td>
<td>3.1, Appendix A</td>
<td>6,000–10,000</td>
<td>15 min</td>
<td>2.38</td>
</tr>
<tr>
<td>3/13/19</td>
<td>5-Gas</td>
<td>Accuracy</td>
<td>3.1, Appendix A</td>
<td>2,000–7,000</td>
<td>15 min</td>
<td>2.23</td>
</tr>
<tr>
<td>3/13/19</td>
<td>5-Gas</td>
<td>Accuracy</td>
<td>3.1, Appendix A</td>
<td>1,000–6,000</td>
<td>15 min</td>
<td>2.15</td>
</tr>
<tr>
<td>3/14/19</td>
<td>5-Gas</td>
<td>N₂ Drift</td>
<td>3.2, Appendix A</td>
<td>0</td>
<td>1 hr</td>
<td>2.26</td>
</tr>
<tr>
<td>3/17/19</td>
<td>5-Gas</td>
<td>Accuracy</td>
<td>3.1, Appendix A</td>
<td>2,000–5,000</td>
<td>15 min</td>
<td>2.79</td>
</tr>
<tr>
<td>3/17/19</td>
<td>5-Gas</td>
<td>Accuracy</td>
<td>3.1, Appendix A</td>
<td>1,500–5,000</td>
<td>15 min</td>
<td>2.15</td>
</tr>
<tr>
<td>3/23/19</td>
<td>Li-COR</td>
<td>Li-COR curve</td>
<td>Appendix A</td>
<td>400–10,000</td>
<td></td>
<td>4.30</td>
</tr>
<tr>
<td>3/26/19</td>
<td>Li-COR</td>
<td>Preliminary step-input</td>
<td>Appendix A</td>
<td>400–750</td>
<td>40 min</td>
<td></td>
</tr>
<tr>
<td>3/31/19</td>
<td>Li-COR</td>
<td>Step-input test/accuracy</td>
<td>3.1, Appendix A</td>
<td>400–2,000</td>
<td>1.5 hr</td>
<td>10.19 starting flow</td>
</tr>
<tr>
<td>4/6/19</td>
<td>Li-COR</td>
<td>Humidity</td>
<td>3.3, Appendix A</td>
<td>450</td>
<td>1.5 hr</td>
<td>9.40</td>
</tr>
<tr>
<td>4/8/19</td>
<td>Li-COR</td>
<td>Drift</td>
<td>3.2, Appendix A</td>
<td>1,000</td>
<td>1.25 hr</td>
<td>3.93</td>
</tr>
<tr>
<td>4/9/19</td>
<td>Li-COR</td>
<td>Humidity</td>
<td>3.3, Appendix A</td>
<td>400–500</td>
<td>2.3 hr</td>
<td>3.57</td>
</tr>
<tr>
<td>4/9/19</td>
<td>Li-COR</td>
<td>Humidity</td>
<td>3.3, Appendix A</td>
<td>2,000–2,600</td>
<td>1 hr</td>
<td>3.59</td>
</tr>
<tr>
<td>4/10/19</td>
<td>Li-COR</td>
<td>Drift</td>
<td>3.2, Appendix A</td>
<td>600</td>
<td>1.25 hr</td>
<td>4.82</td>
</tr>
<tr>
<td>4/13/19</td>
<td>None</td>
<td>Response Time</td>
<td>Appendix A</td>
<td>Range</td>
<td>20 min each</td>
<td>0.5</td>
</tr>
<tr>
<td>4/15/19</td>
<td>None</td>
<td>Response Time</td>
<td>Appendix A</td>
<td>Range</td>
<td>20 min each</td>
<td>0.5</td>
</tr>
<tr>
<td>4/19/19</td>
<td>Li-COR</td>
<td>Response Time</td>
<td>3.5, Appendix A</td>
<td>400–10,000</td>
<td>20 min each</td>
<td>1.900</td>
</tr>
<tr>
<td>4/20/19</td>
<td>Li-COR</td>
<td>Temperature</td>
<td>3.4, Appendix A</td>
<td>500–600</td>
<td>2.5 hr</td>
<td>7.100</td>
</tr>
</tbody>
</table>
2.4 Accuracy Tests

Determining sensor accuracy was performed using the same lab testing apparatus (Figures 3-5). Initially, the 5-Gas Analyzer was used. An initial test for 40 minutes was conducted, followed by a series of five different tests at known cylinder, rotameter, and flow parameters. These parameters varied test to test and can be seen in Table 2.2. These initial tests showed that the 5-Gas Analyzer software was not properly calibrated, and difficulty in diluting the 5-Gas mixture to low concentrations was encountered.

Table 2.2. Preliminary Accuracy Test Settings with 5-Gas Analyzer

<table>
<thead>
<tr>
<th>Trial Number</th>
<th>(N_2) Cylinder (psi)</th>
<th>(N_2) Rotameter</th>
<th>5-Gas Cylinder (psi)</th>
<th>Cal. Gas Rotameter</th>
<th>Flow Rate Into Chamber (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>2.5</td>
<td>11</td>
<td>7</td>
<td>0 (bouncing below)</td>
<td>2.38</td>
</tr>
<tr>
<td>2</td>
<td>2.5</td>
<td>10</td>
<td>4</td>
<td>0</td>
<td>2.23</td>
</tr>
<tr>
<td>3</td>
<td>2.5</td>
<td>15</td>
<td>3</td>
<td>0</td>
<td>2.15</td>
</tr>
<tr>
<td>4</td>
<td>3</td>
<td>20</td>
<td>2</td>
<td>0</td>
<td>2.79</td>
</tr>
<tr>
<td>5</td>
<td>3.5</td>
<td>12</td>
<td>2</td>
<td>0</td>
<td>2.15</td>
</tr>
</tbody>
</table>

To overcome the initial test problems, subsequent accuracy tests were conducted using the CO\(_2\) cylinder and the Li-COR 8100A benchmark instrument. A known concentration of CO\(_2\) was introduced to the sealed testing environment. This concentration was estimated using a dilution ratio based upon the \(N_2\) and the CO\(_2\) rotameter readings. This ratio multiplied by the known concentration of CO\(_2\) in the tank (1.011\%), provided the expected CO\(_2\) concentration in the chamber. The actual concentration in the chamber was assumed to be the Li-COR 8100A reading. In one continuous test of about 1.25 hours, a total of 7 different CO\(_2\) concentrations, ranging from ambient CO\(_2\) concentrations at 400 ppm to elevated concentrations of 2500 ppm were monitored for approximately 15 minutes at each concentration. Cylinder and rotameter readings...
settings found in Table 2.3 were held constant for these 15 minutes, resulting in plateaus in the CO₂ concentration. The concentration was increased to the next level by lowering the N₂ rotameter setting and cylinder pressure as well as increasing the CO₂ rotameter setting. The starting flow rate for this experiment was 10 L/min. Data were recorded at 1Hz for the Li-COR and 0.5 Hz for the K33 and K30. Data collected during transitions between different CO₂ concentrations were omitted from data analysis.

Table 2.3. Cylinder and Rotameter Settings for Step Input Tests

<table>
<thead>
<tr>
<th>Step #</th>
<th>N₂ Cylinder (psi)</th>
<th>N₂ Rotameter</th>
<th>CO₂ Cylinder (psi)</th>
<th>CO₂ Rotameter</th>
<th>Approximate Concentration According to Li-COR (ppm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>23.5</td>
<td>93</td>
<td>8.9</td>
<td>Near 0*</td>
<td>400</td>
</tr>
<tr>
<td>2</td>
<td>22</td>
<td>82</td>
<td>8.9</td>
<td>Near 0</td>
<td>500</td>
</tr>
<tr>
<td>3</td>
<td>18</td>
<td>79</td>
<td>8.9</td>
<td>Near 0</td>
<td>600</td>
</tr>
<tr>
<td>4</td>
<td>14</td>
<td>61</td>
<td>8.9</td>
<td>Near 0</td>
<td>700</td>
</tr>
<tr>
<td>5</td>
<td>14</td>
<td>61</td>
<td>8.9</td>
<td>2</td>
<td>900</td>
</tr>
<tr>
<td>6</td>
<td>10</td>
<td>48</td>
<td>8.9</td>
<td>2</td>
<td>1100</td>
</tr>
<tr>
<td>7</td>
<td>7</td>
<td>35</td>
<td>8.9</td>
<td>5</td>
<td>1800</td>
</tr>
</tbody>
</table>

* Near 0 means the rotameter was set to its lowest value based on the center position of the float. The float position was not changed for steps 1-4.

For the accuracy tests conducted with the 5-Gas Analyzer and Li-COR, percent deviation (PD) of the sensors from the benchmark’s readings were calculated. Using the K30 and K33 values and the known concentration (assumed to be the Li-COR/5-Gas benchmark value) the percent deviation was determined using equation 2 to represent the amount the sensor deviated from the known concentration measured by the benchmark instrument. In addition to the percent deviation, the average CO₂ concentration was computed for each of the three instruments measuring CO₂. The mean and standard deviation of these trials was then calculated for each instrument, K30, K33, 5-Gas/Li-COR, and plotted for comparison. Also, a CO₂ versus time plot was analyzed for each sensor as well as the Li-COR measurement.

\[
Percent\ Deviation\ (PD) = \frac{CO_2(\text{observed}) - CO_2(\text{LiCOR})}{CO_2(\text{LiCOR})} \times 100\%
\]  

(2)
In addition to determining the CO$_2$ concentration accuracy in terms of percent deviation, the K33 temperature and relative humidity measurements were verified as well. The Hobo 1 device served as the benchmark to check the K33 reported temperature and relative humidity trends and accuracy. The Hobo 2 device was not used to check the K33 readings, but rather monitored ambient conditions outside the testing chamber. The two Hobo sensors were tested against one another and Figure 2.7 shows the temperature and relative humidity for both loggers plotted over a 21 hour period. Table 2.4 provides the average of these values and the standard deviation which show very good agreement between the two Hobo loggers.

![Hobo Logger Agreement Test](image)

**Figure 2.7.** Hobo Logger Agreement Test

**Table 2.4.** Average and Standard Deviations of Hobo Loggers Under Identical Conditions

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Hobo #1</th>
<th>Hobo #2</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average Temperature ($^\circ$F)</td>
<td>69.418</td>
<td>69.599</td>
</tr>
<tr>
<td>Standard Deviation Temperature</td>
<td>0.892</td>
<td>0.893</td>
</tr>
<tr>
<td>Average Humidity (%)</td>
<td>31.987</td>
<td>31.992</td>
</tr>
<tr>
<td>Standard Deviation Humidity</td>
<td>0.821</td>
<td>0.825</td>
</tr>
</tbody>
</table>
2.5 Sensitivity Tests

The K30 and K33 sensors’ sensitivity was tested based on environmental conditions and drift. The sensors’ sensitivity to relative humidity and temperature was analyzed. The noise when exposed to 0 ppm, 600 ppm, and 1000 ppm \( \text{CO}_2 \) was also studied. Drift and noise were quantified by the standard deviation of the sensor once a steady concentration was observed. Determining the sensors’ sensitivity to temperature was completed by testing the sensors under four different heated conditions including ambient room temperature. Heat tape wrapped around the inlet tubing to the testing chamber was used to increase the temperature. The heat tape reads in percentage as opposed to temperature degrees, and ranges from 5% to 100%. The true temperature was monitored using Hobo 1, and a Type T thermocouple located on the inlet tubing about 30 cm upstream of the chamber inlet was used to monitor the temperature during heat tape adjustment to determine constant conditions. The test was completed with the same cylinder and rotameter parameters for each temperature increment as Table 2.4 shows.

Table 2.5. 4/20/19 Temperature Test Cylinder and Rotamer Settings

<table>
<thead>
<tr>
<th>( \text{N}_2 ) Cylinder (psi)</th>
<th>( \text{N}_2 ) Rotamer</th>
<th>( \text{CO}_2 ) Cylinder (psi)</th>
<th>( \text{CO}_2 ) Rotamer</th>
<th>( Q ) (L/min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>12</td>
<td>50</td>
<td>6</td>
<td>Near 0</td>
<td>7.114</td>
</tr>
</tbody>
</table>

The initial ambient temperature step served as the baseline. The subsequent tests were then used to determine the influence of heat on the sensors’ readings. The same \( \text{N}_2 \) cylinder and rotameter and \( \text{CO}_2 \) cylinder and rotameter settings were used for all tests with a flow rate of 7.114 L/min. This test was conducted at approximately 500 ppm \( \text{CO}_2 \).

2.6 Response Rate Tests

The K30 and K33 response times were analyzed by determining the amount of time the sensor took to reach its final indication. The experimental set-up for these tests differed as active sampling was used. This was conducted by using a Tube Cap Adapter and small pump purchased from CO2meter.com. The pump performed at a rate of 0.5 L/min and was placed at the outlet of
the sensor’s adapter to pull the gas through the tubing. Excess gas flowed past the sensors to waste. Figure 2.8 shows the direct connection of 2.0 mm diameter Tygon tubing to the K30 sensor and the pump. This same connection was made for the K33. The tubing had to have a “tee” so that the K3x innards would not be physically damaged from high flow, the bypass the “tee” provides is critical to sensor “health”. The test was run for about 20 minutes. For the first 10 minutes, the inlet tubing attached to the Tube Cap Adapter (Figure 2.8) was not attached. The pump was on and pulling ambient air through the sensor cap. During this time the CO2 cylinder was on and flowing through the inlet tubing, but unattached to the Tube Cap Adapter. At ten minutes, the inlet tubing (top photo in Figure 2.8) was attached directly to the Tube Cap Adapter with the 10,000 ppm CO2 cylinder mixture, with no extra nitrogen dilution. The time of attachment was recorded. This time was used for the beginning time stamp for response time calculation. After plotting the CO2 concentration over time and analyzing the individual data points, it was determined at what time the sensor reached its full reading. The difference between the inlet tubing attachment timestamp and the time the sensor met its full reading was used to calculate the sensor response time. The volume of the K3x sensor cell when the Tube Cap Adapter is in place is unknown and this information was not retrieved from the manufacturer.

Figure 2.8. Tube and Pump Apparatus Used for Response Time Tests
These tests were conducted three times for both sensors and three times for the Li-COR8100A. The flow for these tests (K3x and Li-COR) all ranged from 1.946 to 1.986 L/min, higher than the 0.5 L/min rate of the pump. It was then observed how long it takes the sensor to respond to this step increase and to reach a stabilized measurement. It should be noted that prior to connection the Tube Cap Adapter the CO2 cylinder was open, and gas was flowing directly through the Tube Cap Adapter inlet tubing, therefore, attaching the Tube Cap Adapter inlet tubing connection should represent an instantaneous increase in CO2.

2.7 Data Analysis

The K30 and K33 data were plotted as raw time series, instrument comparison 1:1 scatter plots, and mean scatter plots against the 5-Gas and Li-COR CO2 measurements for the appropriate tests, and can be located using the summary table Table 2.1. The R² and Root Mean Square Error (RMSE) values were determined to serve as an indication of closeness to the benchmark instrument as seen in Harmon et al. analysis of low-cost soil CO2 efflux and point concentration sensing systems22. The R² value was determined using Microsoft Excel and RMSE was determined using equation 3. Due to difficulties of aligning data exactly by second, for the calculations of RMSE, the averages of values sampled from the same 10-second time interval were determined. The average 10-second CO2 concentrations for the K33, K30, and Li-COR were determined as \(y_i\) and then used to calculate the value of \(\sum_{i=1}^{n} (\hat{y}_i - y_i)^2\) and the corresponding RMSE values.

\[
RMSE_{error} = \sqrt{\frac{\sum_{i=1}^{n} (\hat{y}_i - y_i)^2}{n}} \quad (3)
\]

Where: 
- \(n\) = total number of values (number of 10 second intervals analyzed, the same for each instrument)
- \(\hat{y}_i\) = known concentration (Li-COR CO2, ppm)
- \(y_i\) = tested concentration (K30/K33 CO2, ppm)

In addition to analyzing the individual capabilities of the sensors against benchmark instruments, the sensors were compared to one another. This was done throughout all
experiments by comparing the percent deviations, CO$_2$ concentration means, and visual indications shown in the time series plots.
3.0 Results

3.1 Accuracy

Accuracy tests indicate consistent trends and relationships between the K30 and K33 and benchmark instruments. Due to lack of calibration, the 5-Gas Analyzer did not serve as an indicator of true CO₂ concentration, but the tests conducted can show that the K30 and K33 trends are consistent with the 5-Gas Analyzer trends in terms of increasing and decreasing CO₂ concentration. Figure 3.1 shows a summary of five 15-minute tests, referred to as trials in the figure, conducted on 3/13/19 and 3/17/19 and the trends observed based on average concentration and standard error of readings from each instrument. Complete data on tests conducted with the 5-Gas Analyzer as a benchmark as described in summary table, Table 2.1, can be found in Appendix A.

![K30 and K33 Average Concentration by Trial](image)

**Figure 3.1.** 3/13/19 and 3/17/19 15-Minute Accuracy Tests. Error bars represent one standard error of the mean.

The Li-COR8100A served as a more reliable benchmark instrument and showed that the K30 and K33 sensors have a consistent deviation from benchmark readings. The 3/31/19 step input test indicated that, at seven different concentrations, the K30 and K33 follow the same trends as the Li-COR. Figure 3.2 shows the raw output and plateaus and Figure 3.3 shows the average
values at each concentration step plateau plotted against the Li-COR average concentration at the plateau. It should be noted that the last plateau was still increasing. The results indicate that this condition was not held long enough to fully test the CO₂ setting and achieve constant concentration. Both the K30 and K33 followed the expected trends and closely followed the expected 1:1 linear relationship (Figure 3.3). The offset between this linear relationship and the actual values was consistent throughout the test. The average, standard deviation, percent difference, and RMSE using the 10-second averaging method (equation 3), calculated for the K30 and K33 sensors for each concentration step of this test can be seen in Table 3.1. The standard deviation for the K30, K33, and Li-COR are all plotted in Figure 3.3 as error bars in the x and y directions but are not visible.

Figure 3.2. 3/31/19 Step Input Test Raw CO₂ Concentration Data Plateaus
Figure 3.3. 3/31/19 Step Input Average Concentration scatterplot with 1:1 line and one standard deviation x and y error bars (all smaller than symbol size).

Table 3.1. 3/31/19 Step Input Test Statistical Data for Each Plateau

<table>
<thead>
<tr>
<th>Step #</th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>K33</td>
<td>K30</td>
<td>K33</td>
<td>K30</td>
<td>K33</td>
<td>K30</td>
<td>K33</td>
<td>K30</td>
</tr>
<tr>
<td>Average (ppm)</td>
<td>497</td>
<td>473</td>
<td>524</td>
<td>498</td>
<td>524</td>
<td>497</td>
<td>715</td>
<td>689</td>
</tr>
<tr>
<td>Standard Deviation (ppm)</td>
<td>1.8</td>
<td>1.0</td>
<td>1.2</td>
<td>1.0</td>
<td>1.6</td>
<td>1.4</td>
<td>1.7</td>
<td>1.6</td>
</tr>
<tr>
<td>RMSE (ppm)</td>
<td>78.5</td>
<td>53.9</td>
<td>78.7</td>
<td>52.3</td>
<td>78.6</td>
<td>52.1</td>
<td>76.0</td>
<td>49.6</td>
</tr>
<tr>
<td>Percent Difference (%)</td>
<td>18.6</td>
<td>12.8</td>
<td>17.6</td>
<td>11.7</td>
<td>17.7</td>
<td>11.7</td>
<td>11.9</td>
<td>7.7</td>
</tr>
</tbody>
</table>

The drift test also provided indications of accuracy. The 4/8/19 1000 ppm drift test data averaged over 10 seconds for both the sensors and the Li-COR are plotted in Figure 3.4. Both the K30 and K33 sensors follow similar trends to the expected 1:1 linear relationship, but by inspection of Figure 3.4 appear to be offset by roughly 70 ppm for the K30 and 90 ppm for the K3. The $R^2$ value for the K33 is very close to 1 and the $R^2$ value for the K30 is 0.902, which indicates similar
trends. The RMSE of both the K30 and K33 for this test, compared to LiCOR, are 70 and 82 ppm, respectively. These values are close to the visual offset from the 1:1 linear relationship and are also in a similar range to that found in the 3/31/19 step input test previously discussed (see Figure 3.3).

![Graph showing 4/19 1000 ppm Drift Test 10 Second Average K33/K30 Against Li-COR]

**Figure 3.4.** 4/19 1000 ppm Drift Test 10 Second Average K33/K30 Against Li-COR

### 3.2 Drift

The sensors had drift less than 5 ppm (or less than 1% of the reading), as indicated by the calculated standard deviations for the drift test conducted at about 700 ppm on 4/10/19. Figure 3.5 shows the raw output of this data and Table 3.2 summarizes the drift as the standard deviation over the test period after the 2000 second mark as Figure 3.5 indicates. The raw output is observed to have an initial high concentration, which can be attributed to stabilization of CO₂ concentration in the testing chamber. Due to this initial stabilization, all data analysis was conducted using data after the 2000 second mark. The Li-COR had less drift compared to the K33 and K30 sensors, however this is only by 0.68 ppm. The relative standard deviation (RSD) normalizes the deviations of the sensing methods and the K33 is observed to have an RSD of 0.45% and the K30 has an RSD of 0.36%. The difference between the RSD of the K33 and K30 is only 0.09%. The K30 and K33 sensors are reading about 87 to 89 ppm higher than the Li-COR. This difference in reading is represented by the percent deviations seen in Table 3.2. Over
time this difference appears consistent with the K30 and K33 sensors following the same trends in CO$_2$ concentration.

**Figure 3.5.** 4/10/19 Drift Test at 700 ppm. The red line represents the time when the data analysis period was started. The decreasing signal may be attributed to an initial decrease in concentration during the stabilization period or perhaps a small air leak somewhere in the set-up. The set-up was tested for leaks using water and soap to observe bubbles and none were detected.

<table>
<thead>
<tr>
<th></th>
<th>K33</th>
<th>K30</th>
<th>Li-COR</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (ppm)</td>
<td>722</td>
<td>720</td>
<td>633.1</td>
</tr>
<tr>
<td>Standard Deviation (ppm)</td>
<td>3.30</td>
<td>2.62</td>
<td>1.28</td>
</tr>
<tr>
<td>Relative Standard Deviation (%)</td>
<td>0.45</td>
<td>0.36</td>
<td>0.20</td>
</tr>
<tr>
<td>Percent Deviation (%)</td>
<td>14</td>
<td>13</td>
<td>NA</td>
</tr>
</tbody>
</table>

*NA = Not applicable

At 1000 ppm, similar trends in drift are observed. The K30 and K33 sensors show drift less than 1% of the concentration reading, even with observable peaks in the K30 reading. These peaks can be seen in **Figure 3.6.** The initial stabilization was not included in calculations, which began at time 17:16:48. **Table 3.3** shows the summary statistics. The standard deviation was slightly higher than the 700 ppm test with the K30 and K33 standard deviation for the 1000 ppm test being 8.28 and 4.33 ppm respectively, however RSD values were comparable to the 700 ppm test. The RSD for the K33 and K30 for the 1000 ppm test were 0.81 and 0.43%, respectively, compared to the 700 ppm test RSD values for the K33 and K30 of 0.45 and 0.36%, respectively. This larger difference in RSD values for the 1000 ppm test can be seen visually in **Figure 3.6** as the K33 appeared to “lag” behind the K30 in terms of stabilization of CO$_2$ readings. The K33 rate of measurement was slower and can be seen to take longer to reach a stable signal. This
indicates a longer test should have been conducted. For this test, the RSD value for the K30, 0.43%, was lower than the RSD of the Li-COR, 0.63%. The percent difference of the K33 and K30 was lower than in the 700 ppm drift test, as the overall magnitude of the 1000 ppm test was larger.

![4/8/19 Raw 1000 ppm Drift CO₂ Concentration by Time](image)

**Figure 3.6.** 4/8/19 1000 ppm Drift Test Output. The two orange peaks may be attributed to loose connections. These contribute to the standard deviation. The red line represents the time when data analysis period was started.

**Table 3.3.** 4/8/19 1000 ppm Drift Test Summary Statistics

<table>
<thead>
<tr>
<th></th>
<th><strong>K33</strong></th>
<th><strong>K30</strong></th>
<th><strong>Li-COR</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (ppm)</td>
<td>1018</td>
<td>1006</td>
<td>935.5</td>
</tr>
<tr>
<td>Standard Deviation (ppm)</td>
<td>8.28</td>
<td>4.33</td>
<td>5.85</td>
</tr>
<tr>
<td>Relative Standard Deviation (%)</td>
<td>0.81</td>
<td>0.43</td>
<td>0.63</td>
</tr>
<tr>
<td>Percent Deviation (%)</td>
<td>8.81</td>
<td>7.52</td>
<td>NA</td>
</tr>
</tbody>
</table>

Drift at 0 ppm CO₂ (CO₂ tank closed) was also very small. **Table 3.4** shows the average and standard deviation of analysis with 0 ppm CO₂. **Figure 3.7** shows this consistency. Averages and standard deviations were calculated after 300 seconds. It should be noted that the data for the 0 ppm drift test using N₂ resulted in irregular output from the K30. Once 0 ppm was reached, the readings increased to 65536 ppm. This value is equivalent to 4 raised to the eighth power, and suggests an output error as this is equal 16 bits in the binary system. For data analysis, it was assumed that this output corresponded to a negative reading. The K30 sensor reading was then
corrected by subtracting the K30 value from 65536 and then subtracting this difference from 0 to obtain an approximation of the negative concentration value. **Equation 4** demonstrates how this was corrected. The standard deviations of the K33 and K30 for this 0 ppm drift test were very similar at 2.1 and 1.9 ppm, respectively. Compared to the 1000 ppm and 700 ppm drift tests, the 0 ppm test has the lowest deviation and the highest RSD. With decreasing concentration, the standard deviation of the sensors decreases. The RSD does not have an observable consistent trend between the different drift test concentrations.

\[
\text{Corrected } K30 \text{ CO}_2 = 0 - (65536 - K30 \text{ output})
\]  

(4)

Figure 3.7. 3/14/19 N\textsubscript{2} Drift Test Raw Output

Table 3.4. 3/14/19 N\textsubscript{2} Drift Statistical Data

<table>
<thead>
<tr>
<th></th>
<th>K33</th>
<th>K30</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average (ppm)</td>
<td>13</td>
<td>-13</td>
</tr>
<tr>
<td>Standard Deviation (ppm)</td>
<td>2.1</td>
<td>1.9</td>
</tr>
<tr>
<td>RSD (%)</td>
<td>15.9</td>
<td>-14.5</td>
</tr>
</tbody>
</table>

3.3 Relative Humidity

Humidity tests were conducted on two separate days, 4/6/19 and 4/9/16. On 4/6/19, three humidity conditions were tested, including dry conditions. On 4/9/19, four different humidity conditions were tested. For both tests, the humidity started at dry conditions and was increased.
over time. The exception to this is the last humidity condition of the 4/9/19 test, which was conducted later in the day after the first three conditions were tested. It should be noted that the cylinder pressure and rotameter settings were not adjusted between the first three conditions and the fourth condition. It should be noted that the CO₂ concentration in the testing chamber differed between these two humidity testing days, as Figure 3.8 shows that the 4/6/19 test was lower at about 440 – 480 ppm and the 4/9/19 test was at about 2500 – 2650 ppm. The mean relative humidity and standard deviation for each relative humidity can be found in Table 3.5. RH conditions 2 through 9 apply to the 4/6/19 and 4/9/19 tests. The temperature for the 4/6/19 test ranged from 21.4 - 25.1 °C and for the 4/9/19 test it ranged from 19.9 – 23.4 °C. These ranges were due to the time of day the tests were conducted as well as the increase in temperature of the water bath to achieve higher humidity in the test chamber.

The box plots in Figure 3.8 show the output from the two different test dates. On the left, the 4/6/19 test shows a decreasing trend in CO₂ concentration. On the right, the 4/9/19 test shows an increasing trend in CO₂ concentration with increasing humidity. For both tests, the error bars generally overlap between the different relative humidity conditions. Thus, it is difficult to concluding from these data whether there is a direct relationship between relative humidity and measured K3x CO₂ concentration. The observed decreasing trend may be the same decreasing trend observed throughout previous experiments. In the drift tests, it was observed that the CO₂ took time to stabilize and up until that final concentration stabilization, the CO₂ reading decreased. Because the differences in the relative humidity steps of the first 4/6/19 test were small, it could be that the humidity was not high enough to influence the CO₂ and the decrease in CO₂ is due to sensor drift tendencies. The observed increase in CO₂ on 4/9/19 may be attributed to the humidity influence, however percent increases of average CO₂ concentration for Step 1 to 2, Step 2 to 3, and Step 3 to 4 were 2.02%, 1.43%, and 0.53%, respectively for the K33 sensor. For the K30 sensor percent increases of average CO₂ concentration for Step 1 to 2, Step 2 to 3, and Step 3 to 4 were 2.65%, 0.25%, and -0.10%, respectively. The observed percent increase of CO₂ concentration appeared to decrease with increasing humidity. In total, the CO₂ concentration for the K33 and K30 respectively, increased from 2471 and 2446 during dry conditions to 2627 and 2578 at the last condition (average 79.7% relative humidity).
It should be noted that sudden changes in average CO₂ concentration between the initial dry conditions and the introduction of humidity can be attributed to attaching the tubing inlet (originally attached directly to the testing chamber) to the humidified air line after passing through the Nafion membrane. This change can be seen more clearly in the raw time plots in Appendix A Figure A.13 and A.21. Data collected in this span was omitted from analysis. It should also be noted that although the K33 collects temperature and relative humidity data, the sensor does not use this data in the computation of CO₂ concentration, but rather provides the data to user for correction as needed. How the humidity trends found in this study compare to the literature is discussed further in the results section.

**Figure 3.8.** 4/6/19 and 4/9/19 Humidity Tests CO₂ by Average Humidity of Individual Steps. Note the different y-axis scales.

The humidity readings of the K33 and Hobo 1 throughout tests conducted can also be compared. All raw humidity over time plots can be found in Appendix A, but a summary of test by test averages and standard deviations can be seen in Table 3.5 below. The “Test #” associated with the test description is used in Figure 3.9 to graphically show how the humidity readings compare from test to test for the K33 and Hobo 1, both located inside the testing chamber. The K33 consistently reported lower relative humidity than the Hobo 1 for all tests analyzed, with the magnitude of the percent difference of relative humidity ranging from 8.5 - 89.6 %. For RH conditions 7 and 8 a larger standard deviation was observed. This is likely because these tests were specifically testing relative humidity at high percentages. Due to the nature of the set-up
and water bath it was difficult to achieve a constant high humidity value, thus the standard deviations for these conditions were larger except for condition 9. It is possible that condition 9 showed lower variability because it was in the upper end of the sensor and logger’s range.

Table 3.5. Summary of K33 and Hobo 1 Relative Humidity Readings (%)

<table>
<thead>
<tr>
<th>RH Condition #</th>
<th>Date – Test</th>
<th>K33 Average (%)</th>
<th>K33 Standard Deviation (%)</th>
<th>Hobo 1 Average (%)</th>
<th>Hobo 1 Standard Deviation (%)</th>
<th>K33 Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>RH 1</td>
<td>3/31/19 Step input</td>
<td>0.6</td>
<td>0.2</td>
<td>6.1</td>
<td>0.2</td>
<td>89.6</td>
</tr>
<tr>
<td>RH 2</td>
<td>4/6/19 Humidity Dry (Step 1)</td>
<td>1.3</td>
<td>0.0</td>
<td>7.2</td>
<td>0.3</td>
<td>82.2</td>
</tr>
<tr>
<td>RH 3</td>
<td>4/6/19 Humidity Step 2</td>
<td>15.8</td>
<td>0.0</td>
<td>34.7</td>
<td>0.2</td>
<td>54.5</td>
</tr>
<tr>
<td>RH 4</td>
<td>4/6/19 Humidity Step 3</td>
<td>17.5</td>
<td>0.0</td>
<td>34.5</td>
<td>0.1</td>
<td>49.2</td>
</tr>
<tr>
<td>RH 5</td>
<td>4/8/19 1000 ppm Drift</td>
<td>2.0</td>
<td>3.3</td>
<td>6.3</td>
<td>3.1</td>
<td>68.8</td>
</tr>
<tr>
<td>RH 6</td>
<td>4/9/19 Humidity Dry</td>
<td>2.6</td>
<td>1.2</td>
<td>6.8</td>
<td>1.0</td>
<td>61.8</td>
</tr>
<tr>
<td>RH 7</td>
<td>4/9/19 Humidity Step 1</td>
<td>50.2</td>
<td>10.7</td>
<td>56.7</td>
<td>12.5</td>
<td>11.5</td>
</tr>
<tr>
<td>RH 8</td>
<td>4/9/19 Humidity Step 2</td>
<td>51.8</td>
<td>4.0</td>
<td>63.3</td>
<td>5.0</td>
<td>18.2</td>
</tr>
<tr>
<td>RH 9</td>
<td>4/9/19 Humidity Step 3</td>
<td>79.7</td>
<td>0.2</td>
<td>87.1</td>
<td>0.0</td>
<td>8.5</td>
</tr>
<tr>
<td>RH 10</td>
<td>4/10/2019 700 ppm Drift</td>
<td>2.4</td>
<td>1.6</td>
<td>6.5</td>
<td>0.8</td>
<td>63.2</td>
</tr>
</tbody>
</table>
Figure 3.9. K33 Relative Humidity Compared to Hobo 1 Summary Graph of means with one standard deviation error bars.

3.4 Temperature

Temperature tests were conducted 4/20/19. Data analysis indicated that the chamber temperature did not increase as expected. This may have been due to the high flow rate of 7.114 L/min and the gas not having a residence time long enough in order for it to equilibrate with the heating tape system. The 4/20/19 test was conducted at ambient room temperature until 2:21:05 PM when the heat tape was turned on to 15%, which stabilized around 60°C as indicated by the thermocouple in the inlet tubing ~30 cm upstream of the test chamber inlet fittings. At 2:45:25 PM, the heat tape was turned up to 25% which was read as 107°C. Finally, at 3:48:29 PM, the heat tape was turned up to 40% which was read as 150°C. Figure 3.10 shows the temperature readings according to the Hobo 1 and K33 located inside the test chamber. No further analysis was conducted on the chamber temperature data due to project time constraints. In the future, temperature tests should use a lower flow rate and insulation around the test chamber as well as
the inlet tubing. It also may be advisable to purchase a heat jacket to wrap the chamber in to ensure observable temperature increases in the test chamber.

**Figure 3.10.** 4/20/19 Temperature Test. Raw temperature data recorded inside the test chamber as heat tape settings were increased over time.

Over multiple tests, the K33 temperature outputs showed consistent deviations compared to the Hobo 1. The temperature reading of the K33 was consistently higher than the Hobo 1 by 11 to 15% as Table 3.6 and Figure 3.11 indicate. This percent difference was calculated according to equation 5, sharing the same principles as the previously outlined equation 2 in the methods section.

\[
Percent\ Difference\ (PD) = \frac{K33\ (\text{temp.}) - \text{Hobo 1 (temp.)}}{\text{Hobo 1 (temp.)}} \times 100\%
\] (5)
Table 3.6. Summary of K33 and Hobo 1 Temperature Readings (°C)

<table>
<thead>
<tr>
<th>Temperature Condition #</th>
<th>Date – Test</th>
<th>K33 Average (°C)</th>
<th>K33 Standard Deviation (°C)</th>
<th>Hobo 1 Average (°C)</th>
<th>Hobo 1 Standard Deviation (°C)</th>
<th>K33 Percent Difference (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Temp. 1</td>
<td>3/31/19 Step input 4/6/19</td>
<td>24.0</td>
<td>0.1</td>
<td>21.6</td>
<td>0.1</td>
<td>11.0</td>
</tr>
<tr>
<td>Temp. 2</td>
<td>4/6/19 Humidity Dry (Step 1)</td>
<td>24.8</td>
<td>0.4</td>
<td>22.0</td>
<td>0.3</td>
<td>13.0</td>
</tr>
<tr>
<td>Temp. 3</td>
<td>4/6/19 Humidity Step 2</td>
<td>29.0</td>
<td>0.1</td>
<td>25.0</td>
<td>0.0</td>
<td>15.8</td>
</tr>
<tr>
<td>Temp. 4</td>
<td>4/6/19 Humidity Step 3</td>
<td>28.9</td>
<td>0.0</td>
<td>25.1</td>
<td>0.0</td>
<td>15.0</td>
</tr>
<tr>
<td>Temp. 5</td>
<td>4/8/19 1000 ppm Drift</td>
<td>23.1</td>
<td>0.4</td>
<td>20.6</td>
<td>0.1</td>
<td>12.1</td>
</tr>
<tr>
<td>Temp. 6</td>
<td>4/9/19 Humidity Dry 4/9/19</td>
<td>23.2</td>
<td>0.5</td>
<td>20.8</td>
<td>0.6</td>
<td>11.5</td>
</tr>
<tr>
<td>Temp. 7</td>
<td>4/9/19 Humidity Step 1</td>
<td>25.4</td>
<td>0.6</td>
<td>22.8</td>
<td>0.4</td>
<td>11.4</td>
</tr>
<tr>
<td>Temp. 8</td>
<td>4/9/19 Humidity Step 2</td>
<td>26.5</td>
<td>0.1</td>
<td>23.0</td>
<td>0.3</td>
<td>15.2</td>
</tr>
<tr>
<td>Temp. 9</td>
<td>4/9/19 Humidity Step 3</td>
<td>24.0</td>
<td>0.1</td>
<td>21.0</td>
<td>0.0</td>
<td>14.3</td>
</tr>
<tr>
<td>Temp. 10</td>
<td>4/10/2019 700 ppm Drift</td>
<td>21.7</td>
<td>0.2</td>
<td>19.0</td>
<td>6.5</td>
<td>14.2</td>
</tr>
</tbody>
</table>

Figure 3.11. K33 Temperature (from Sensirion SHT11) Compared to Hobo 1 Summary Graph
3.5 Response Time

The response time of the K30 sensor was the fastest of the instruments tested (Figures 3.12-3.14). The K33 was twice as slow as the K30. The Li-COR 8100A also had a slower response time than the K30. This is most likely due to the fast response nature of the K30, sampling every 0.5 seconds. It can also be observed that the Li-COR CO₂ reading spiked above the expected 10,000 ppm reading prior to stabilizing around the expected value (Figure 3.14). The computed response time for the Li-COR was longer than expected due to the incorporation of this initial spike. Figure 3.15 shows the pressure readings of the Li-COR. The three timestamps in this figure showing an increase in pressure correspond to the timestamps showing a CO₂ flux above 10,000 ppm and are thought to contribute to this abnormality as well as the transient nature of the benchmark instrument. Figures 3.11 to 3.13 show the raw output and Table 3.5 summarizes the response time in seconds. These tests were conducted at ambient room conditions with an average temperature of 23.9°C and an average humidity of 51.7% as logged by Hobo 1.

![Graph of CO₂ vs Time for 4/19/19 K30 Response Time Tests](image)

**Figure 3.12.** 4/19/19 K30 (sampling rate 0.5Hz) Response Time Tests
Figure 3.13. 4/19/19 K33 (sampling rate 2 Hz) Response Time Tests

Figure 3.14. 4/19/19 Li-COR (sampling rate 1Hz) Response Time Tests
Table 3.7. Response Time Summary Table

<table>
<thead>
<tr>
<th>Model Tested</th>
<th>Test 1</th>
<th>Test 2</th>
<th>Test 3</th>
<th>Average</th>
<th>Standard Deviation</th>
</tr>
</thead>
<tbody>
<tr>
<td>K30</td>
<td>12</td>
<td>10</td>
<td>12</td>
<td>11</td>
<td>1.2</td>
</tr>
<tr>
<td>K33</td>
<td>22</td>
<td>26</td>
<td>18</td>
<td>22</td>
<td>4.0</td>
</tr>
<tr>
<td>Li-COR 8100A</td>
<td>20</td>
<td>18</td>
<td>18</td>
<td>19</td>
<td>1.2</td>
</tr>
</tbody>
</table>

Figure 3.15. 4/19/19 Li-COR Response Time Test Pressure Output
4.0 Conclusion

From the data analysis and results presented it can be concluded that the K30 and K33 sensors are not accurate compared to using the Li-COR8100A as a benchmark, but do show similar trends in CO₂ concentration decreases and increases over time. The K30 and K33 sensor CO₂ concentrations were offset high from benchmark readings by a range of 70 ppm to 100 ppm. The trends observed in this study have been reported previously throughout the literature. In a similar study conducted on a series of NDIR CO₂ sensors in order to build a portable sensing module, the K30 sensor was found to be about 100 ppm higher than the benchmark instrument, a Li-COR6400, as Figure 4.1 shows with the light grey plot\textsuperscript{14}. The Figure 4.1 black plot represents the K30 sensor reading when a correction algorithm based on temperature, length of use, atmospheric pressure, and water vapor partial pressure was applied.

![Figure 4.1](image.png)

**Figure 4.1.** Output from K30 Correction Analysis for Portable Measurement Device. Figure reproduced from Ref 14\textsuperscript{14}

The K33 readings were consistently higher than those of the K30 up to 28 ppm. In the drift test conducted at a constant gas concentration over longer periods of time from 1 hour to 1.5 hours however, the K33 average concentration was within 12 ppm of the K30 average concentration (see Tables 3.2 and 3.3). This suggests it takes the K33 longer to stabilize and respond; due to the slow sampling rate of the K33, it should not be used for applications with transient or highly varying CO₂ concentrations. For applications requiring fast response and quick concentration fluxes, the K30 would be a more reliable option. The RMSE found for the K33 ranged from 73
ppm to 101 ppm. This means that throughout the tests conducted, the average error and K33 offset is within this range. Comparing this result to the literature, an analysis of the K33 ELG to the K33 BLG, showed that the K33 ELG had a RMSE of 179 ppm and very good correlation with the benchmark instrument, a Li-COR6262, with an $R^2$ value of 0.99 at a CO2 concentration similar/different from the tests conducted here (Figure 4.2)\textsuperscript{25} The K33 BLG did not have as high of an $R^2$ value at 0.94 and the RMSE was reported at 424 ppm \textsuperscript{25}. In Figure 4.2, the benchmark instrument is displayed as the yellow line and the K33 values are seen in black. The $R^2$ value for the K33 found in the 4/8/19 drift tests was 0.987 and the RMSE found was 82 ppm (see section 3.1 and Figure 3.4). These values align well with the discussed literature.

![Figure 4.2. Analysis of K33 ELG Used in Soil Flux Monitoring Systems. Figure reproduced from Ref 25.](image)

The SenseAir sensors were observed to have two different trends in CO$_2$ concentration between the two humidity tests conducted. The 4/6/19 test saw a decrease in CO$_2$ concentration while the 4/9/19 test saw an increase. A study on HVAC grade NDIR sensors found trends that show an increase in CO$_2$ concentration for some sensors due to humidity. Figure 4.3 is adapted from this study and shows the percent difference of CO$_2$ concentrations measured at different humidity values compared to concentrations measured at 40% humidity. The specific models of the sensors were not provided in the study.
Figure 4.3. CO₂ Concentration Percent Deviation Due to Different Humidity Conditions. Figure reproduced from Ref 17.

Temperature should be investigated further with a testing procedure that involves a lower flow rate and insulation around the actual chamber. The observed drift of the sensors in the 3/13/19, 4/6/19, and 4/10/19 drift tests was low with the concentration fluctuating 2 - 8 ppm over 0.5 to 1.25 hours and was comparable to benchmark instruments standard deviation of 1 – 5 ppm over 0.5 to 1.25 hours (see section 3.2). Further testing will help fully understand the K30 and K33 sensor capabilities. The values found for each sensor’s CO₂ concentration offset from the benchmark values vary slightly compared to those found in the literature, indicating rather good manufacturer reproducibility, which is a necessity for low-cost sensor development. A study of multiple sensors will provide further insight in how to best correct for the offset between the NDIR low-cost sensors and benchmark technologies. It is likely that not all sensors manufactured have the same offset. Further investigation of sensor calibration procedures should also be conducted prior to developing any correction algorithm. This includes the manufacturer’s automatic background correction (ABC) algorithm mentioned in the instrumentation introduction that is only applicable to ambient air monitoring near 400ppm CO₂. With a future goal of deploying a CO₂ NDIR sensor in the field in an ambient environment, the K30 FR will provide the greatest capabilities for responding to rapid concentration changes.
5.0 References


Appendix A. Raw Outputs

**Figure A.1.** 3/12/19 Test 1 With 5-Gas Raw Output Over Time

**Figure A.2.** 3/13/19 Accuracy Test With 5-Gas Trial 1
Figure A.3. 3/13/19 Accuracy Test With 5-Gas Trial 2

Figure A.4. 3/13/19 Accuracy Test With 5-Gas Trial 3

Figure A.5. 3/17/19 Accuracy Test With 5-Gas Trial 4
Figure A.6. 3/17/19 Accuracy Test With 5-Gas Trial 5

Figure A.7. 3/23/19 Li-COR First Run Dilution Check Output From Ambient Concentration to 10,000 ppm
Figure A.8. 3/23/19 Li-COR First Run Temperature and Humidity Conditions Inside (Hobo 1) and Outside of Chamber (Hobo 2)

Table A.1. 3/23/19 Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>19.92</td>
<td>15.27</td>
<td>19.46</td>
<td>28.61</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.23</td>
<td>10.09</td>
<td>0.14</td>
<td>0.52</td>
</tr>
</tbody>
</table>

Figure A.9. 3/26/19 Step-Input Accuracy Test. The K30 and K33 sensor logs were cutoff due to a battery dying. A follow up test was conducted on 3/31/19 to obtain more comprehensive data.
Figure A.10. 3/26/19 Preliminary Step Input Test Temperature and Humidity Conditions Inside of Chamber

Table A.2. 3/26/19 Preliminary Step Input Test Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 $T$ (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 $T$ (°C)</th>
<th>Hobo 1 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>20.78</td>
<td>0.78</td>
<td>18.7</td>
<td>5.94</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.09</td>
<td>0.24</td>
<td>0.04</td>
<td>0.32</td>
</tr>
</tbody>
</table>

Figure A.11. 3/31/19 Step Input Test Raw Output of 7 Concentrations
Figure A.12. 3/31/19 Step Input Test Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.3. 3/26/19 Step Input Test Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>23.99</td>
<td>0.63</td>
<td>21.61</td>
<td>6.05</td>
<td>21.78</td>
<td>31.20</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.05</td>
<td>0.22</td>
<td>0.09</td>
<td>0.45</td>
<td>0.16</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Figure A.13. 4/6/19 Humidity Test Dry Initial Conditions Raw Output
Figure A.14. 4/6/19 Humidity Test Dry Initial Conditions Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.4. 4/6/19 Humidity Test Dry Initial Conditions Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>24.81</td>
<td>1.29</td>
<td>21.95</td>
<td>7.24</td>
<td>21.67</td>
<td>37.28</td>
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<tr>
<td>Standard Deviation</td>
<td>0.40</td>
<td>4.11E-15</td>
<td>0.29</td>
<td>0.27</td>
<td>0.08</td>
<td>0.11</td>
</tr>
</tbody>
</table>

Figure A.15. 4/6/19 Humidity Test Step 2 Conditions Raw Output
Figure A.16. 4/6/19 Humidity Step 2 Conditions Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.5. 4/6/19 Humidity Step 2 Conditions Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>28.99</td>
<td>15.8</td>
<td>25.03</td>
<td>23.75</td>
<td>23.14</td>
<td>34.70</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.06</td>
<td>1.2E-13</td>
<td>0.04</td>
<td>0.04</td>
<td>0.05</td>
<td>0.17</td>
</tr>
</tbody>
</table>

Figure A.17. 4/6/19 Humidity Test Step 3 Conditions Raw Output
Figure A.18. 4/6/19 Humidity Test Step 3 Conditions Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.6. 4/6/19 Humidity Test Step 3 Conditions Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>28.9</td>
<td>17.5</td>
<td>25.13</td>
<td>25.45</td>
<td>23.09</td>
<td>34.46</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.01</td>
<td>0.01</td>
<td>0.09</td>
<td>0.01</td>
<td>0.08</td>
<td></td>
</tr>
</tbody>
</table>

Figure A.19. 4/8/19 1000 ppm Drift Test Raw Output
Figure A.20. 4/8/19 1000 ppm Drift Test Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.7. 4/8/19 1000 ppm Drift Test Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>23.06</td>
<td>1.96</td>
<td>20.57</td>
<td>6.29</td>
<td>20.87</td>
<td>41.9</td>
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<tr>
<td>Standard Deviation</td>
<td>0.41</td>
<td>3.25</td>
<td>0.12</td>
<td>3.14</td>
<td>0.15</td>
<td>3.14</td>
</tr>
</tbody>
</table>

Figure A.21. 4/9/19 Humidity Test Raw Output. The dip in concentration at about 13:45:00 can be attributed to disconnecting the inlet tube directly from the chamber and connecting it to the water bath and humidity set-up.
Figure A.22. 4/9/19 Raw Output Humidity Test Dry Conditions

Figure A.23. 4/9/19 Humidity Test Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.8. 4/9/19 Humidity Test Temperature and Humidity Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>23.2</td>
<td>2.6</td>
<td>20.8</td>
<td>6.8</td>
<td>21.0</td>
<td>35.2</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.5</td>
<td>1.2</td>
<td>0.6</td>
<td>1.0</td>
<td>0.4</td>
<td>0.1</td>
</tr>
</tbody>
</table>
Figure A.24. 4/9/19 Raw Output Humidity Test Step 1. The initial drop is due to disconnection of direct tube connection to testing chamber. Tube was disconnected and connected to humidity water bath tubing.

![Figure A.24](image)

Table A.9. 4/9/19 Humidity Test Step 1 Humidity and Temperature Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>25.4</td>
<td>50.2</td>
<td>22.8</td>
<td>56.7</td>
<td>22.1</td>
<td>34.9</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.6</td>
<td>10.7</td>
<td>0.4</td>
<td>12.5</td>
<td>0.2</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure A.25. 4/9/19 Humidity Test Step 1 Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

![Figure A.25](image)
Figure A.26. 4/9/19 Raw Output Humidity Test Step 2

![Graph showing CO₂ concentration over time for K33, K30, and Li-COR sensors.]

Figure A.27. 4/9/19 Humidity Test Step 2 Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)

Table A.10. 4/9/19 Humidity Test Step 2 Humidity and Temperature Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>26.5</td>
<td>51.8</td>
<td>23.0</td>
<td>63.3</td>
<td>22.0</td>
<td>35.6</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.1</td>
<td>4.0</td>
<td>0.3</td>
<td>5.1</td>
<td>0.2</td>
<td>0.6</td>
</tr>
</tbody>
</table>
Figure A.28. 4/9/19 Raw Output Humidity Test Step 3. The dip is due to stabilization of CO₂ concentration as this test was conducted later in the day than the other tests and the concentration mixture needed to be adjusted again.

Table A.11. 4/9/19 Humidity Test Step 3 Humidity and Temperature Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>24.0</td>
<td>79.7</td>
<td>21.0</td>
<td>87.1</td>
<td>21.0</td>
<td>39.2</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.1</td>
<td>0.2</td>
<td>0.0</td>
<td>0.0</td>
<td>0.0</td>
<td>0.1</td>
</tr>
</tbody>
</table>

Figure A.29. 4/9/19 Humidity Test Step 3 Temperature and Humidity Conditions Inside (Hobo 1 and K33) and Outside of Chamber (Hobo 2)
Figure A.30. 4/10/19 Raw Output 700 ppm Drift Test

Table A.12. 4/9/19 700 ppm Drift Test Humidity and Temperature Averages

<table>
<thead>
<tr>
<th></th>
<th>K33 T (°C)</th>
<th>K33 RH (%)</th>
<th>Hobo 1 T (°C)</th>
<th>Hobo 1 RH (%)</th>
<th>Hobo 2 T (°C)</th>
<th>Hobo 2 RH (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Average</td>
<td>21.7</td>
<td>2.4</td>
<td>19.0</td>
<td>6.52</td>
<td>19.45</td>
<td>30.8</td>
</tr>
<tr>
<td>Standard Deviation</td>
<td>0.2</td>
<td>1.6</td>
<td>0.04</td>
<td>0.80</td>
<td>0.04</td>
<td>0.3</td>
</tr>
</tbody>
</table>
Appendix B. Response Time Tests

This section includes a series of response rate tests conducted prior to finalizing response rate testing procedures. This test consisted of the same tubing, pump, and tube cap adapter outline in the methods section, but the inlet tubing to the tube cap adapter was attached to the sensor for the entirety of the test. The step increase or decreases seen are due to adjustments made to the N₂ cylinder, rotameter, or CO₂ cylinder. The CO₂ concentration did not respond as expected when the N₂ rotameter and cylinder were decreased and instead it is suspected that back pressure from N₂ cylinder resulted in an increase in the outlet pressure of N₂ and therefore a decrease in CO₂ concentration. The tube length also was suspected to be a problem in providing accurate results. The raw data from these tests is plotted as time series in this appendix, but were not used for calculation of response time.

Figure C.1. 4/13/19 Raw Output K30 Response Time
Figure C.2. 4/15/19 Raw Output K30 Response Time

Figure C.3. 4/13/19 Raw Output K33 Response Time Tests
Figure C.4. 4/15/19 Raw Output K33 Response Time Tests
Appendix C. Code and Sensor Instructions

C.1 Python Code

This code is found in <filename> and must be uploaded to the RPi3 computer in the documents folder. The Python 3.4 was used to edit this code, but it can also be edited within Geany of the RPi3 desktop (more details on Geany below).

```python
#Annaliese Keimel  Written: February 2019  Last edited: 4/26/19
#Adapted from CO2meter.com using AN104 and AN105
#rpi serial connections
#Python app to run a K-30 & K-33 Sensor
import serial
import time
import datetime

filename = "co2_log.csv"  #designates file name log is saved to,
change this to save to new filename/location, the default
location is the RPi3 documents folder from which code was
launched

csv = open(filename, 'w')
csv.write("Timestamp,CO2K33,CO2K30,Temp(Celsius),RH(%)  \n")
csv.close

ser = serial.Serial("/dev/ttyUSB0",baudrate = 9600,timeout = 0.5)
#sensor connected to USB0 port as described further in C.2
instructions
ser2 = serial.Serial("/dev/ttyUSB1",baudrate = 9600,timeout = 0.5)
#sensor connected to USB0 port as described further in C.2
instructions
print "  AN-137: Raspberry Pi3 to K-30 Via UART\n"
ser.flushInput()
ser2.flushInput()
time.sleep(1)

print "Timestamp,CO2K33,CO2K30,Temp(Celsius),RH(%)"
for i in range(1,201):  #change this number to increase sampling
time, meaning the total duration that this code will loop to
collect data
ser.flushInput()
ser2.flushInput()
```

C.2 Sensor Hardware Setup

C.3 Testing Procedures
ser.write("\xFE\x44\x00\x02\x9F\x25") #pulls CO2 from K33

time.sleep(0.125) #change this number to adjust sampling rate of
the sensors in seconds

#The time.sleep for each ser#.write adds up. In example the code
written has 0.125 four time within the loop. This means in total
the loop and readings will run at as 0.5 second rate. If each
time.sleep was 0.5 seconds, the for loop and readings would be
reported and executed every 2 seconds.

resp = ser.read(7)
high = ord(resp[3])
low = ord(resp[4])
co2K33 = (high*256) + low

ser2.write("\xFE\x44\x00\x02\x9F\x25") #pulls CO2 from K30

time.sleep(0.125) #change this number to adjust sampling rate, units are in seconds

resp4 = ser2.read(7)
high4 = ord(resp4[3])
low4 = ord(resp4[4])
co2K30 = (high4*256) + low4

ser.write("\xFE\x44\x00\x14\x02\x97\xE5") #pulls relative
humidity from K33

time.sleep(0.125) #change this number to adjust sampling rate, units are in seconds

resp3 = ser.read(7)
high3 = ord(resp3[3])
low3 = ord(resp3[4])
rh = ((high3*256) + low3)*.01

ser.write("\xFE\x44\x00\x12\x02\x94\x45") #pulls temperature from K33

time.sleep(0.125) #change this number to adjust sampling rate, units are in seconds

resp2 = ser.read(7)
high2 = ord(resp2[3])
low2 = ord(resp2[4])
temp = ((high2*256) + low2)*.01

entry = str(datetime.datetime.now()) #command that adds a
timestamp to the final printed data row

entry = entry + "," + str(co2K33) + "," + str(co2K30) + "," +
str(temp) + "," + str(rh) + 

"n" #row of data represented as entry, which contains original entry written in line 85 (timestamp) and
CO2 reading with RH and Temperature

print(entry)
csv = open(filename, 'a')
csv.write(entry)
csv.close()
```python
time.sleep(.1)
csv = open(filename, 'r')
print(csv.read())
csv.close()
```
C.2 Sensor Hardware Setup

Parts and cables needed:

- HDMI to VGA converter
- VGA display cable
- PC monitor (analog): if digital PC monitor is available HDMI to VGA converter is not needed and RPi3 can be connected through HDMI (digital)
- USB Mouse
- USB Keyboard

Software:

- Python 3.4
- NOOBS for Raspberry Pi

Optional:

- VNC Server (on Raspberry Pi with NOOBS software package)
- VNC Viewer 6.18.907 (downloaded to computer you wish to view RPi3 desktop on)

1. Before turning on RPi3*

   **First:** Plug K30 (power and communication standard USB) in the top left USB port (Figure C.1). This port corresponds to “ttyUSB0” in line 20 of code

   **Second:** Plug K33 (communication and ground standard USB) in the top right USB port (Figure C.1). This port corresponds to “ttyUSB1” in line 23 of code

*Note – if RPi3 is already on, as indicated by LED light shown in Figure C.1., before plugging in sensors to USB ports, USB0 corresponds to whichever sensor is plugged in first. USB1 corresponds to the second sensor plugged in. If RPi3 is off prior to plugging in, USB0 corresponds automatically to whichever sensor is plugged into the top left corner and USB1 to whichever is plugged into top right (Figure C.2.).

In order to program, monitor operation, edit python code (change file names and change code run length), plug in USB mouse and keypad on bottom USB ports (mouse and keyboard must be plugged into RPi3, not the monitor screen). To view RPi3 desktop, use HDMI on RPi3 port to connect to a HDMI to VGA convertor and then connect to a VGA chord, which can then be connected to the PC monitor (analog). VNC Server and Viewer can also be used to view RPi3 desktop remotely. RPi3 and host computer need to be on the same wireless network for this application to work, which can not be achieved using UVM Guest Wifi.
Figure C.1. Photo of LED Power Light Indicator on RPi3

Figure C.2. Raspberry Pi Communications, Power, and Display Ports. RPi3 Power is connected to the RavPower Battery Pack as described in instrumentation section of thesis. This powers the RPi3. HDMI goes to HDMI to VGA converter, which is then connected to a VGA cable that can be connected to the PC monitor (analog). This allows viewing of the RPi3 desktop interface. USB2 is connected to the mouse. USB3 is next to USB2 and underneath USB1 in the bottom right (not shown). USB3 is connected to the keyboard.
2. Using the RPi3 desktop interface provided from Raspberry Pi NOOBS software (already downloaded on SD card) go to the top corner and open the drop down menu. Select programming from menu and open “Geany.” Geany is an application, which allows you to run various codes including Python scripts.

![Image](image-url)

**Figure C.3.** RPi3 Desktop: Where to Find Geany Application. The red arrow in the left photo shows where to find the “programming” selection in the main menu. The red arrow in the right photo shows was the Geany application selection looks like. This is what you click to open Geany.

3. There are 3 Python code files written for this project (see list below). Programs are located in document folder on RPi3 folder path is as follows: pi\Documents. Codes run sensors as follows:

- k30\&k33realtime.py – K30 & K33 together
- k30timestamp.py – K30 only
- K33.py – K33 only

4. In order to change file name change **line 10** of the code
5. In order to change how long the program runs change **line 34** of the code
6. After making edits go to the top panel, select “build” drop-down option and choose “compile” (**Figure C.4.**)
7. After selecting “compile”, to run script select “build” from the top panel and choose “execute” (**Figure C.4.**). A window will pop-up and display the sensor readings real time.
8. Output file will be saved in RPi3’s documents folder found in the path: pi\Documents
9. Script window can be close by simply hitting the close button in the top right corner of the pop-up window described in step 7.
C.3 Testing Procedures

C.3.1 Pre-Test Set-Up

1. Turn on Li-COR 8100A (or chosen benchmark instrument)
2. Turn on sensors
3. Connect the sensors to UVM Guest Wifi
   a. Make a UVM Guest account using UVM credentials
   b. Use the following link to create account:
      http://www.uvm.edu/it/wireless/?Page=guestnet/guestnet.html
   c. Link provides sign-in password which will be used when you connect via RPi3
   d. **Figure C.5.** shows where to click to view the wireless networks in the area,
      shown by the red arrow on the right labeled “Wifi Connection”
   e. This drop down will show UVM Guest where you can then sign in using UVM credentials

![Figure C.5. How To Connect RPi3 to Wifi](image)

4. Wait until the time on the RPi3 desktop (top right corner) agrees with the time on the PC
   a. RPi3 needs to be connected to Wifi to read correct time as the RPi3 internal clock
      only reads correct when connected to wifi. This is important for post data
      analysis. Once connected to wifi it takes several minutes for the RPi3 clock to
      read the correct time.
5. Open Geany and adjust any time parameters needed
a. You can set the “for” loop to something like 15,000 and the program will stop when you close out the script window. Data sent to the csv file will be saved still.

6. Start the *py script through Geany program
7. Turn on Nitrogen and CO₂ Cylinders to appropriate gas mixtures desired
8. Monitor the CO₂ concentration using the Li-COR8100A and RPi3 desktop screens
9. Adjust the CO₂ and N₂ rotameters until desired concentration range is achieved
   a. It may take a while for the CO₂ reading to stabilize, generally it will decrease/increase for 10 – 20 minutes. However, once the change begins to slow down, the end concentration should be within that indicated range
10. Once cylinder and rotameter settings are determined open up the 6-L chamber and take flow rate readings using the TSI model 4100 digital meter at the inlet of the chamber. You will need the large black tubing (1.3 mm diameter) attached to the flow meter to fit around the inlet chamber’s fitting.
   a. Take 3 flow rate readings and record (L/min)
11. Once flow is recorded and settings are determined start a continuous measurement on the Li-COR or other benchmark instrument.
   a. Additional requirements prior to turning on Li-COR measurement, include insuring that the IRGA measurement feature says “ready” on the software (see LED is green on instrument plate or Li-COR software on PC).
   b. This Li-COR warm-up should take about 10 minutes. Run the sensors for this ten minutes as well to allow them to warm up.
12. Exit out of the RPi3 module in Geany pop-up and restart the script for the actual test and desired recording time period
13. Ensure that the .csv file has the desired file name in the *.py file code prior to restarting and running the script as the program will over write any previous files saved as this name.
14. Run the test. You can watch the data real time on the Li-COR software on the PC or the Geany pop-up screen discussed in section C.2.
C.3.2 Post Test Instructions

1. Check the cylinder and rotameter readings to ensure they didn’t change. If they did, record.
2. Turn off compressed gas tank cylinders at top valve
3. Turn off Li-COR8100A continuous measurement
   a. Go to file manager in Li-COR software
   b. Scroll in the top box of the software until file name is found (this is not alphabetical order)
   c. Transfer file to PC
   d. Copy file to flash drive using file explorer
4. Turn off RPi3 sensor recording module
   a. Go into RPi3 documents folder
   b. Find the .csv file with corresponding name to test just run
   c. Plug in flash drive to RPi3 using USB 2 or 3 as shown in Figure C.2, and move .csv file there OR email file to self

C.3.4 Step-Input Accuracy Test

1. Once settings stabilize, run each concentration setting for 10 minutes
2. After ten minutes increase concentration by decreasing N₂ rotameter (flow rate can not be checked during this test because if the chamber is open, the CO₂ mixture will be heavily influenced by ambient air)
   a. I found that slightly adjusting rotameter (i.e. 1.5 psi from 23.5 to 22 psi) will allow you to increase by 100 ppm (i.e. for the mentioned N₂ cylinder decrease, the CO₂ concentration increased from about 450 ppm to 550 ppm)
   b. At higher CO₂ concentrations adjust the CO₂ rotameter as well.
3. At higher concentrations it may be beneficial to run the plateau for 20 minutes. In reproducing tests it would be recommended to carry out each concentration for 20 minutes.
4. At each concentration step record the N₂ cylinder, CO₂ cylinder, N₂ rotameter, and CO₂ rotameter.
5. Shut down test as described above in C.3.2

C.3.4 Response Time Test

1. Attach the tube cap adapter to the K3X sensor to be tested
   a. There are two screws to attach. Prior to screwing in, twist in the opposite direction until a click occurs and the screw falls into the threads. Screw carefully into place as the screw threads are plastic.
2. Attach the outlet tubing to the tube cap adapter (see Figure 2.8 in thesis)
3. The outlet tubing should be attached to the pump inlet \((Q = 0.5 \text{ L/min})\) and at the pump outlet attach tubing to go to waste
4. On the inlet tubing to the normal testing chamber there should be a “T” with a cap that can be unscrewed. Attach tubing to this “T”, which will serve as inlet tubing for the tube cap adapter. Details are seen in Figure C.6.

![Figure C.6. “T” Apparatus for the Response Time Tests](image)

5. Turn on RPi3 program for the sensor tested and run the script from Geany
6. Turn on pump, by using the on/off switch of the pump battery power supply, attached to the outlet tubing of the tube cap adapter (you will be pulling ambient air through the tube cap adapter)
7. Open CO\(_2\) cylinder, but **DO NOT** attach inlet tubing to tube cap adapter
8. Measure flow of the inlet tubing from the cylinder and record three measurements
9. After ten minutes attach the inlet tubing to the tube cap adapter and record the time stamp seen on the RPi3 log of when tubing was attached.
10. Continue measurements for 10 minutes with the inlet tubing attached.
11. Shut down test as described above in C.3.2.

C.3.5 Humidity Test

1. Turn on water bath and set temperature to desired temperature (Humidity test on 4/6/19 can serve as a indicator of bath settings and the achieved humidity percentage. Take note that this is heavily dependent on having similar cylinder and flow rate settings).
2. Start test as described in C.3.1, procedures above
   a. Note: Cylinder settings need to be low enough or sufficient high humidity will be difficult to achieve. (i.e. for tests reported in thesis 87% was achieved with N$_2$ – 4 psi, CO$_2$ – 6 psi, and water bath at 55°C)
3. For test with dry conditions, the tubing can be directly connected to the testing chamber and will not be fed through the humidity set-up.
4. Run dry conditions for 20 minutes
5. After 20 minutes, detach tubing from testing chamber inlet, and attach to water bath set-up. Attach water bath outlet tubing to the testing chamber inlet.
6. Run test at humidity setting for 20 minutes and increase for the desired amount of subsequent humidity steps.
7. Increase temperature of water bath to increase humidity.
8. Shut down test a described above in C.3.2.

C.3.6 Drift Test

1. Set-up test as described above in C.3.1.
2. Once CO$_2$ concentration stabilizes begin recording data
3. Previous tests ran for 45 min – 1 hr, it is recommended future tests be run for 2 hours or longer (i.e. days, taking care to ensure there is sufficient calibration gas supply).
4. During test it is recommended to periodically check the cylinder and rotameter settings and record any changes observed. Concentration may not be stable throughout due to pressure changes. If a decrease in CO$_2$ concentration is observed on the Li-COR or sensor outputs this may be the cause and serve as an indication to check settings.