Portable Calorimeter for Fire Experiments
FDR Report

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Executive Summary

An oxygen consumption calorimeter works by measuring the heat release rate of a burning substance. This value is calculated by measuring the oxygen and byproducts in smoke from a fire. In order to get these values two types of sensors were used. A non-dispersive infrared sensor (NDIR) that measured CO and CO_2 and a zirconium O_2 sensor were used to find their respective gas concentrations. The design to calculate the heat release rate is focused on maximizing sensor accuracy and portability while simplifying the manufacturing by using off the shelf components. The goal included making the system simple to recreate and package in a portable system.

Multiple designs were considered to ensure that the system would be portable. The final design is focused on working around the Crestline 7911 NDIR sensor and AO2 Citacel sensor. The other key components include the microcontroller, pump, power supply, air filter, and mounting platform, which were designed around these two sensors. These components are packaged together in a briefcase that will house the components and protect them during transportation and usage. This flexibility for transportation allows the system to be used in different locations.

The oxygen consumption calorimeter also has several specific design specifications that it will meet. These fall under three categories: safety, usability, and data acquisition. Safety considerations involve ensuring that the system is not exposed to excessive heat, well insulated, does not deflect or fracture, etc. To ensure the usability of the device, the engineering team will record issues and the appropriate solutions for hardware and software issues to establish a working guideline for future users. Another key specification category is data acquisition. It is important for the system accurately acquire data and that the system is calibrated properly.

This document will serve as the scope of work and as a design report for the mechanical engineering team working on the Portable Calorimeter for Fire Experiments project. The objective of this document is to define the problem and detail the steps that were taken to design the portable oxygen consumption calorimeter.

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Appendices

1. Introduction

The purpose of this project is to build a portable oxygen consumption calorimeter that can be used on any smoke collection system to analyze the oxygen consumption in order to calculate the heat release rate of the substance being burned. This project is sponsored by Professor Richard Emberley and will be mainly used in the Cal Poly Combustion Lab. The team working on this project consists of Kayla Collins, Joel Keddie, Christopher Chen, and Kara Hewson. This document will cover the design process from the background research to the implementation of the solution.

The following sections are the background, objectives, concept design, project management, final design, manufacturing plan, design verification plan, and conclusion. The background section consists of the research conducted in order to narrow down the scope, understand current products used for fire experiments, know related patents, and understand the analysis to be performed. The objectives section describes the problem statement, the needs and wants of the customer, boundary diagram, the QFD, and stretch goal. This is to fully demonstrate understanding of the scope of the project and the requirements that must be met. Then, the concept design discusses the original design decisions, concept CAD model, concept prototype, preliminary analysis, and current risks. This section demonstrated the teams progress towards the solution. The final design section displays the final CAD model, final built system, electrical diagram of the system, pseudo code and final code, and explanations on how the design will meet all its specifications and justifies the design decisions. The manufacturing section outlines how components are manufactured and assembled. This allowed the team to estimate the time needed to manufacture and assemble the device. Then, the design verification plan discusses all the tests that were performed and explains all the future tests that will be performed to validate the design. All the tests that were unable to be performed have detailed test procedures so that the team’s sponsor, Dr. Emberley, can perform them when he has access to the Combustion Lab. The project management section discusses the steps that will be taken to accomplish this project including a table of key deliverables and the team’s Gantt chart. The table of key deliverables and Gantt chart ensured that tasks were accomplished in a timely matter and ensured the team stayed on the right track. Lastly, the conclusion summarizes the scope of the project, results, and steps moving forward.

2. Background

In order to understand the project goals, background research was conducted to fully understand the scope of the project. A meeting was conducted with the entire team and Dr. Richard Emberley to discuss the scope of the project. The team then investigated similar existing products, patents, standards, journal articles, case studies, and reports to give the team a basic foundational knowledge and ultimately guide the design of the product.

2.1 Overview and Types of Calorimeters

Calorimetry is the measurement of heat transfer either in or out of a system (Redfern). In the case of fire testing, there are multiple types of calorimeters that are used. The two most common calorimeters are cone calorimeters and bomb calorimeters. Cone calorimeters use used by putting a small sample in the cone of the calorimeter and putting it under a constant heat flux. This induces a fire in the sample from which it is possible to collect soot and measure the gases that are released during combustion. These gases can be used to determine the heat transfer rate of the combustion reaction (Redfern). Bomb calorimeters are a constant volume device. The calorimeters take small samples to be burned. Because of the constant volume property, the sample that is burned releases its energy in heat and not as work (Lyon). A thermometer is used to measure the change in temperature in the water; and with the bomb factor rating of the calorimeter the heating release rate can be determined. Both calorimeters can find the heat transfer rate of a sample; however, their limitation is that the samples they can test are too small for practical fire testing.

Figure 1: Cone Calorimeter (Redfern)

Figure 2: Bomb Calorimeter (Orbit Technologies)

Another type of calorimeter, which is less commonly known, is the oxygen consumption calorimeter. This is what the team will be focusing on designing for this project. The oxygen consumption calorimeter was developed in that late 1970's and was refined over the years by several people. Notable researchers were Dr. William Parker and the late Dr Clayton Huggett (Beyler). This type of calorimeter was designed to be able to measure the rate of heat release of a system through oxygen consumption (Beyler). The instrument can measure the amount of oxygen combusted by taking in the by-products of the combustion. By measuring the percentage of the other molecular groups in the smoke using Non-Dispersive Infrared Ray (NDIR) sensors it is possible to get the amount of oxygen consumed in the fire (Seitz). Because the amount of energy that oxygen releases when it combusts with fuels stays constant under most conditions, the calculated heat release rate is constant based on the fuel. This information has had a large impact on public safety. The data obtained from oxygen consumption calorimeters allowed researches to have a more accurate method of determining the heat released in a fire (Beyler). The oxygen consumption calorimeter became widely used for fire testing, research, and was used to help create standardized fire test methods.

The oxygen consumption calorimeter is made up of several components that must be integrated together with software for it work properly. There are several types of sensors that are involved in its construction. These sensors include the NDIR sensor that will monitor both CO_2 and CO and an O_2 analyzer. These sensors output their data to a Data Acquisition System (DAQ) that will collect and store the data. A micro controller that has been coded to calculate the heat transfer rate will take the data from the DAQ and plot it as a function of time. The graph is then output to a computer so those using the device can see how the heat transfer rate fluctuates over time (Dlugogorski).

2.2 Patents

Though oxygen consumption calorimetry is an established method of calculating the heat release rate of various materials, there aren't many products that are quite like the device this project requires. There are other types of calorimeters such as bomb calorimeters, cone calorimeters, and fire calorimeters (similar to the device being asked for, but not portable). There are also products that achieve the same goal as the device being asked for but are only for certain materials (like polymers) or for a very specific scale (extremely small or extremely large). Table 1 below summarizes differences between some of these products. The first patent listed is the device that most closely addresses the needs proposed by this project, however it is only meant for extremely small samples to be combusted within the device. From this product, the way in which the sensors are connected can be studied and applied to the device that will be built for this project. Additionally, cone calorimeters can give good insight into the product that will be made because it utilizes the same method for data collection. See Appendix A for the full list and breakdown of each patent.

Table 1: Summary of Related Patents

Patent Product	Strengths	Weaknesses	Cite
Heat Release Rate for Milligram Samples	Measures heat release rate by oxygen consumption, without measuring mass loss	• Only for very small samples (~ 10 milligrams) • Sample burned within a chamber	A1
Method for Measuring Heat Release of Polymeric Compounds	Similar method to product #1	Only for polymers	A2
Coal Calorimetry System	Utilizes an online interface	Specifically, for combustion of coal	A3
Bomb Type Calorimeter	• Very compact and portable • Accurately measures heat release rate	Not compatible with fume hood combustion experiments	A4
Cone Calorimeter	Utilizes same sensors that will be needed for our product	Not compact/portable	A5

2.3 Sensors

There are two types of sensors that are essential for oxygen consumption calorimeter analysis, an oxygen sensor and a carbon dioxide sensor. The oxygen sensor measures the percentage of oxygen gas in the inlet smoke using a variety of methods, including electrochemical, infrared, and laser technology. The most common oxygen sensor uses a zirconia ceramic coated bulb that converts the amount of oxygen in the exhaust of the fire to a voltage output. The voltage can then be sent to the data acquisition device, where it is compared to the percentage of oxygen in the surroundings (Izu). For the zirconia sensor, the output voltage is not linear, meaning that it works best around standard temperature and pressure. The most sensitive probe at low oxygen concentrations is an oxygen optode, which uses an optical tip focused on a piece of chemical film. The sensor analyzes the fluorescent properties of the film in the presence of oxygen and works best at low concentrations of oxygen (Johnson). A laser reader would be more accurate, as it uses a spectrometer to analyze the amount of oxygen, but the oxygen reader is a large economic investment (Hangauer). However, after a discussion with Dr. Emberley, the industry standard for an oxygen sensor appears to be an electrical sensor, which can read oxygen levels throughout the stochiometric spectrum and is affordable.

The carbon dioxide sensor uses a Non-Dispersive Infrared Ray (NDIR) which measures the amount of CO_2 in the sample using an infrared gas sensor. The sensor uses a wavelength spectrometer with the NDIR to measure the amount of CO_2 molecules in the system. This is done using the known absorptivity of the CO_2 and spectroscopy to filter the other molecules that are present in the smoke (Hangauer).

2.4 Calculating Heat Release Rate

Heat release rate evaluation is a major consideration in any fire risk assessment procedure (Parker). The oxygen consumption calorimetry is based on Thornton's rule that states that the heat release is approximately proportional to oxygen consumption for complete combustion of most liquids and gasses. Hugget proved in 1980 that Thornton's rule also applies to solids (Brobez).

The equations for measuring the rate of heat release by oxygen consumption are already developed and are accurate to most applications within ±5%. A few key notes are that all of combustion products are collected and removed through an exhaust duct and the composition of the gases are measured once adequate mixing has occurred downstream (Janssens).

There are a few main assumptions that are made in the analysis to get the rate of heat release, $\dot{q}$ **.** The amount of energy released by complete combustion per unit mass of oxygen consumed is taken as a constant of 13.1 MJ*kg^{-1} of O_2 (Huggett). All gases are considered to behave as ideal gases, e.g., one mole of any gas is assumed to occupy a constant volume at the same pressure and temperature. Incoming air consists of O_2, CO_2, H_2O, and N_2. Lastly, O_2, CO_2. And CO are measured on a dry basis, i.e., water vapor is removed from the sample before gas measurements are made (Janssens).

The governing equation for the rate of heat release is given by:

$$[1] \quad \dot{q} = \left[E\phi - (E_{CO} - E)\frac{1-\phi}{2}\frac{X_{CO}^{A}}{X_{O_2}^{A}}\right]\frac{\dot{m}_e}{1+\phi(\alpha-1)}\frac{M_{O_2}}{M_o}\left(1 - X_{H_2O}^{O}\right)X_{O_2}^{A^o} \quad \text{(Janssens)}$$

where,

$\dot{q}$ = Rate of heat release (kW)
ϕ = Oxygen depletion factor
E_{CO} = Net heat release per unit of O_2 consumed for combustion of CO to CO_2 (≈ 17.6 MJ/kg of O_2)
X_{CO}^{A} = Mole fraction of CO in the analyzer
$X_{O_2}^{A}$ = Mole fraction of O_2 in the analyzer
$\dot{m}_e$ = Mass flow rate in the duct (kg/s)
α = Ratio of two aforementioned molar quantities (= 1.105)
M_{O_2} = Molecular weight of oxygen (≈ 32 kg/kmol)
M_o = Molecular weight of the incoming air (kg/kmol)
$X_{H_2O}^{O}$ = Mole fraction of H_2O in the incoming air
$X_{O_2}^{A^o}$ = Measured^2 oxygen molar fraction in the incoming air

The quantities in this equation are either constants or can be calculated.

3. Objectives

This section will discuss the problem statement, wants and needs of the customer, boundary diagram, Quality Function Deployment, risk assessment, and stretch goal. This section can be used to ensure that the final product achieves the function desired by the client.

3.1 Problem Statement

Dr. Emberley and the students of the fire engineering lab need a portable oxygen consumption calorimeter to measure the heat rate of a burning substance both inside and outside of the fire engineering lab. Currently, oxygen consumption calorimeters are immobile due to their size and very expensive. The samples must be brought into the lab and cannot be conducted out in the field. Dr. Richard Emberley wants to open the market by bringing costs down and by allowing the oxygen consumption calorimeter to be able to be brought out to the field. A stretch goal of the project is to improve the existing fume hood in the lab by constructing a hood with a shape that will allow as much smoke as possible to be collected from samples being burned.

3.2 Needs and Wants

The needs and wants of the customers include a working prototype, a graphical user interface, compatibility with other apparatuses, functionality, thorough documentation, cost under $3000, portability, easy to use, low maintenance, safe, durable, precise, and accurate.

3.3 Boundary Diagram

The boundary diagram in Figure 3 shows which components of the project are within the control of the project team. The dashed line shows the scope of project, including the carbon dioxide sensor and oxygen sensor, as well as the pump and data acquisition device for the system. The diagram also shows that the project does not include developing an enclosure to contain the combustion.

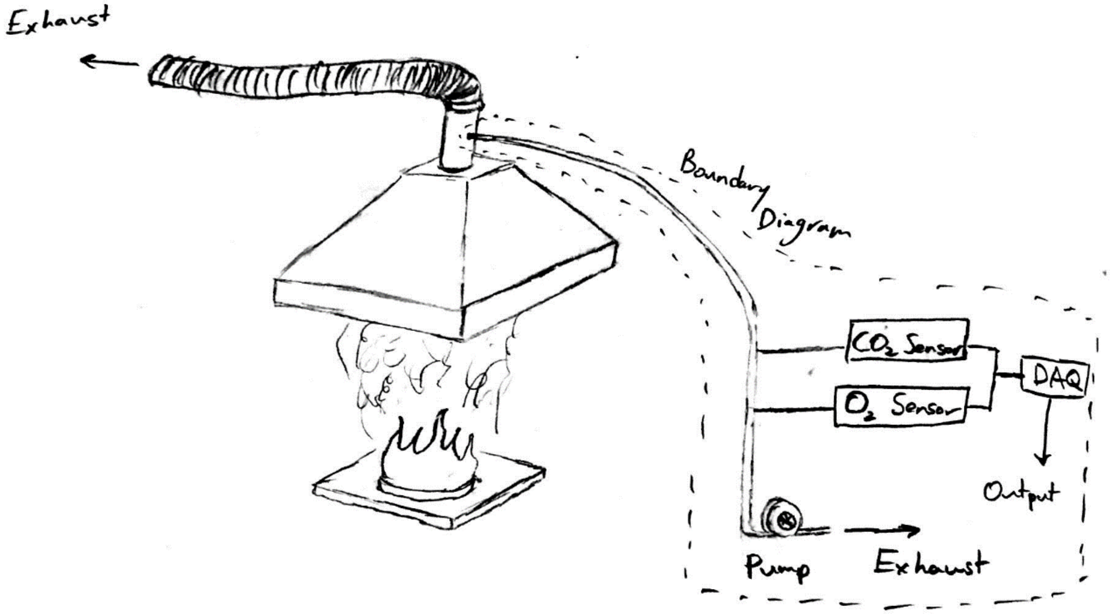


Figure 3: Project Scope Boundary Diagram

3.4 Quality Function Deployment (QFD)

Quality Function Deployment (QFD) is a way to define a problem based on a House of Quality diagram, which is shown in Appendix B. This helps guarantee that the correct problem is being solved and that the specifications are correct. The House of Quality contains a Who, How, Now, What, and How Much sections and the interactions between them. The Who section lists the customers who will benefit from this product: Dr. Richard Emberley, students, and researchers. The What section is a list of the customer wants and needs. The wants and needs of these customers are weighted so that it becomes clear which requirements are most important to the customer. Then, the competitors are listed to better understand the competitive advantage and product improvement the team can make. The How section contains a list of engineering specifications that are measurable and verifiable. The customers need and wants are then related to these engineering specifications based on how strong of a relation they have. The How Much section lists the numbers and units of the engineering specifications.

Table 2 shows our engineering specifications (how), our targets (how much), tolerance of our acceptable variation from the target, risk of how challenging it will be to meet each specification, and compliance of how the team will meet each specification. In the compliance section T refers to Test, A refers to Analysis, I refer to Inspection, and S refers to Similarity.

Table 2: Engineering Specifications Table

Spec. #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Smoke Extraction System	flowrate between 0.5 liters/min and 1.5 liters/min	Max	M	T
2	Dimensions	24 in long by 24 in wide by 12 in tall	Max	L	I
3	Heat Release Values	Less than 5% difference	Max	H	I
4	User Testing Survey	4 out of 5	Min	L	T
5	Thermal Analysis	Calculated results match experimental +/- 5%	Max	M	T, I
6	Software Testing	Delay of 10 seconds	Max	H	T, I, S
7	Testing with other lab devices or apparatuses	Compatible with other devices in the lab	Pass	M	T
8	Travel Testing	Able to withstand impacts and bumps (from travel)	Pass	M	T
9	Structural Integrity Factor	Deflection of 3inches under 50lbs load	Max	L	A, I
10	Weight	20 lbs	Max	L	I
11	Electrical Wiring Safety	No shorts, wires are properly insulated	Pass	L	I, T
12	Heat Exposure	Tubing is safe to touch, and components are under allowable temperatures	Pass	M	I, T

The engineering specifications and how they will be measured are:

1. Flowrate of the extracted smoke will be measured with a flowmeter to ensure the correct flowrate for the CO/CO2 sensor.
2. Dimensions, which will be measured using a tape measurer.
3. The accuracy of the calorimeter will be compared with known heat release values. Specific materials with known heat release values will be burned, the heat release value will be calculated with the team’s device, and then this value will be compared with the known values. This will allow for calibration of the calorimeter and demonstrates what sort of accuracy the calorimeter can achieve.
4. User testing surveys, which will have 2-4 users testing certain aspects of the portable calorimeter to then give feedback on improvements they can make with the user interface, software, operation of the calorimeter, and more.
5. The test for thermal analysis will simply be calculations at specific points (connection to the fume hood and inlet to the sensors) and will be compared with the measured values from thermocouples at those positions.

6. Software testing will be verified whether the code does what it is supposed to do or not such as having real-time display, working emergency stop, etc.
7. Testing with other lab devices or apparatuses will be verified whether the calorimeter works with the other equipment in the lab.
8. Weather condition/travel testing of the calorimeter will be tested by comparing the heat release values in various weather conditions such as high humidity, 90°F or above, and 30°F or below, to the calibrated state and then seeing how much it deviates.
9. Structural integrity will be hand calculated to ensure the device can handle impact and vibrational loads.
10. The device's weight will be measured on a scale.
11. The electrical system will be visually inspected and tested with a multimeter to ensure everything is connected correctly.
12. The temperature of the sensor will be measured with thermocouples to ensure that it is within its acceptable limits.

3.5 Risk Assessment

The software testing is the highest risk specification. First, the team does not have any experience coding in C++. Hence, setting up the drivers for the sensors, collecting the data, and then displaying the code on a Graphical User Interface (GUI) will be challenging, especially when integrating all this together. The second most challenging risk specification is to compare with known heat release rate values in order to calibrate the device. This will be difficult as the values need to be accurate and will take a lot of time to calculate.

3.6 Stretch Goal

If time permits, Dr. Richard Emberley would like a new fume hood for the oxygen consumption calorimeter in the Combustion Lab at Cal Poly, which is shown in Figure 4. The current design does not collect all the CO_2, O_2, and CO molecules off the burning substance. The fume hood is flat on the top, which causes the smoke to bounce off the hood instead of going through the hole in the top of the fume hood. The team will incorporate this goal into the project if time permits.

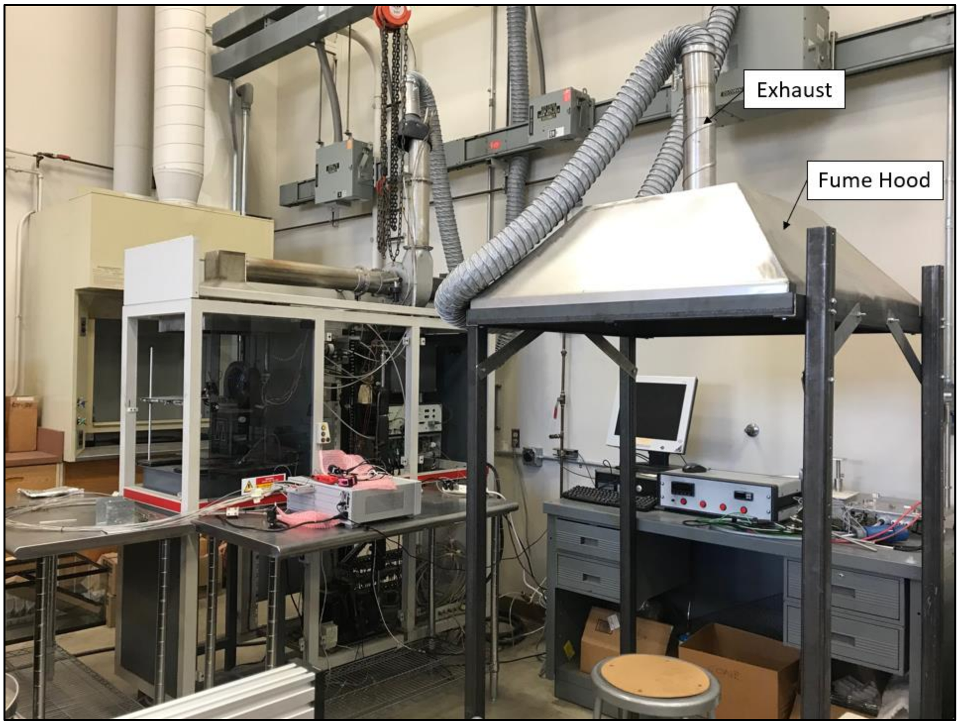


Figure 4: Oxygen Consumption Calorimeter in the Combustion Lab

As of CDR, the team has decided to prioritize the calorimeter and therefore will not be pursuing the stretch goal asked for by Dr. Emberley. Designing and fabricating the fume hood would require computational fluid dynamics to figure out the ideal shape. Additionally, none of the group members on the project have structural welding experience, especially with organic shapes that are more challenging to fixture. In the interest of time and quality, they will leave this project for another team.

4. Concept Design

The final concept design was chosen using decision-making tools such as decision matrices. The nature of the project means that the driving factors behind the design are the available sensors and pumps, as well as the need for the calorimeter to be portable. The concept development process is outlined below.

4.1 Decision Process

The first part of the decision process consisted of developing ideas through brainstorming. Three different ideation sessions were held for the functions: user friendly, portable, and air extraction. The ideas generated from these sessions are attached in Appendix D.

For the ‘user friendly’ function, some ideas consisted of: clear code commenting, instructional videos and pictures, list of components and how they interface with one another, a search/help button integrated onto the GUI, datasheets easily accessible, buttons, a nice font, soft colors, and more. Then different ways the oxygen consumption calorimeter could be portable were thought of - including giving it handles, the ability to roll, having the option of being connected to a power supply or an outlet, developing an app that is compatible with a phone, laptop, or tablet, and lots more. The air extraction ideation included using a fan, a pump, increasing the flow of the duct system, and more, which can be found in Appendix D.

After this ideation phase, each component was researched – oxygen sensor, carbon dioxide and carbon monoxide sensor, pumps, and coding languages for developing a GUI - and for each component, a decision matrix was created, which is attached in Appendix E.

An integrated sensor that measures oxygen, carbon dioxide, and carbon monoxide was chosen. However, this option is very expensive so if adequate funding is not achieved, an individual sensor for each molecule will be used. The integrated sensor is further discussed in Section 4.4 Sensor Comparison.

The most inexpensive option for their pump was chosen, since it is also the smallest and lightest, making it extremely portable. If greater funding becomes available, a stronger pump may be considered depending on the required flowrate for the sensors. The second pump will be tested to get a sense of how powerful the most inexpensive pump option is.

We planned on using C++ to be the programming language used in this project because it is most compatible with the Arduino that has been chosen. The Arduino has a lot of public libraries and resources available to assist with the code development process.

4.2 Selected Concept

The final product will consist of a pump that extracts the smoke from the fume hood through the inlet on the hose, a sensor that taps into the hose to read the amount of oxygen, carbon dioxide, and carbon monoxide in the line, an Arduino to collect the data from the sensors, a power supply to power the Arduino and sensor, and an outlet where the smoke can go back into the exhaust pipe connected to the fume hood. A computer will be hooked up to the Arduino, which will display the data being collected. An isometric view of the system is shown in Figure 5.

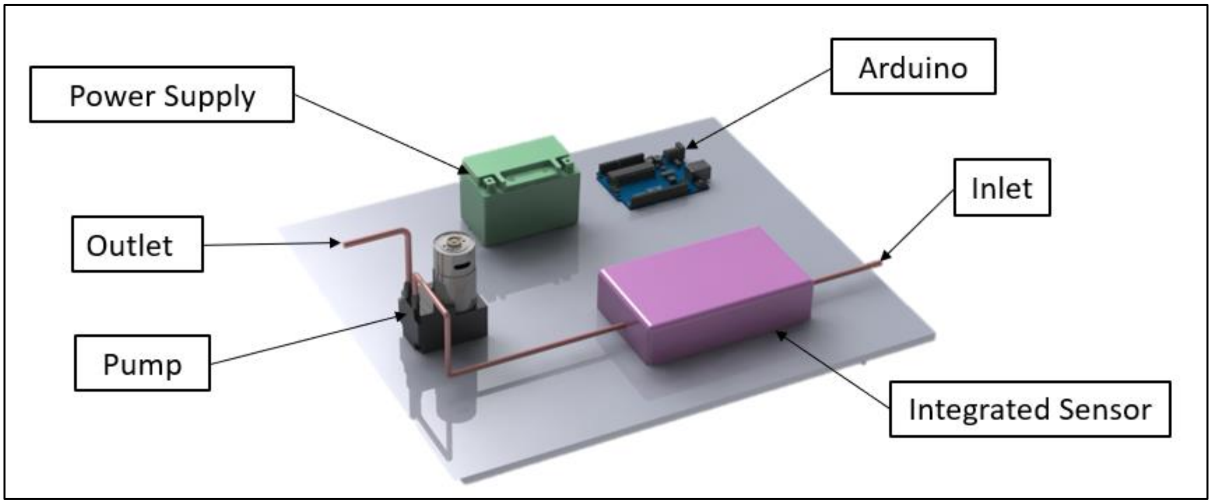


Figure 5: Isometric view of the portable oxygen calorimeter CAD concept.

A concept prototype was developed in order to get a better understanding of the size of the system and to conduct preliminary testing on the pump. The size of the system is estimated to be about 1 ft by 1.5 ft and will also have some type of handle in order to enhance its portability. The concept prototype is shown in Figure 6.

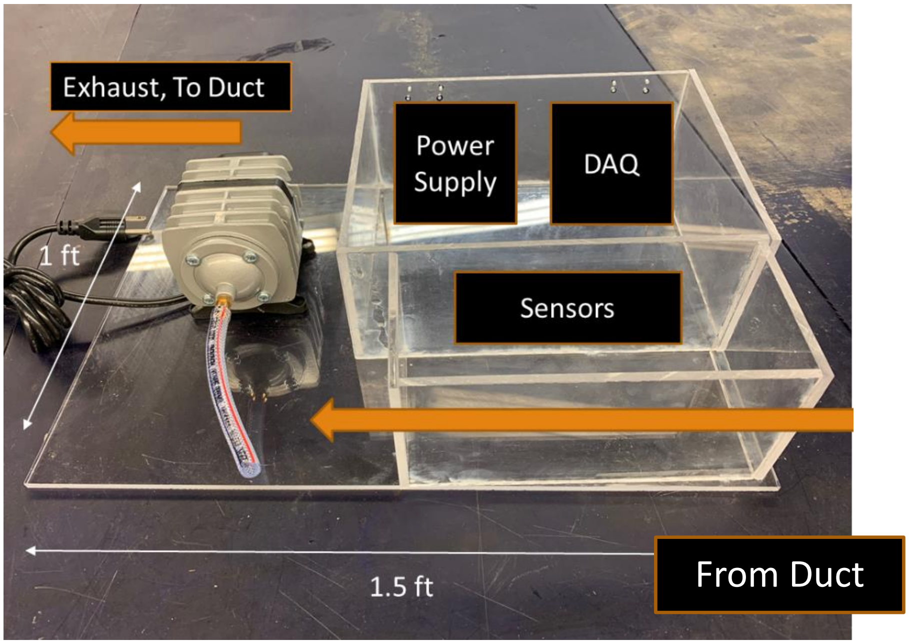


Figure 6: Concept Prototype

4.3 Pump Analysis

For the calorimeter to work, it was necessary for the smoke to be extracted from the fume duct in order for it to be analyzed by the sensors. Many options were considered to perform this function, as shown in Appendix D, but ultimately a pump was chosen as the most practical option.

Once it was decided that a pump would be used, the team needed to decide which pump would be best for the system. There were several pumps taken into consideration of various sizes and price points. The characteristics of each of these pumps is shown below in Table 3. The characteristics of each pump that were considered were cost, volume, weight, and flowrate. The cost is important because the team would like to remain within their allocated budget. Volume and weight show the relative size of the pump which will affect the portability of the system. Additionally, maximum flowrate of each pump matters because the system needs to be able to in draw enough air for the sensors, but not so much that the sensors can’t analyze the incoming air.

Table 3: Pump Comparison

	#1: EcoPlus 3566GPH	#2: EcoPlus 793GPH	#3:12V Vacuum Pump	#4: DYMAX 8	#5: B85T PTFE
Cost	$118	$38	$17	$721	$1378
Volume	562 in^3	123 in^3	42 in^3	215 in^3	442 in^3
Weight	13.2 lbs	2.5 lbs	0.68 lbs	7.3 lbs	12 lbs
Flowrate	59.4 gal/min	26.4 gal/min	18.5 gal/min	2.1 gal/min	5.3 gal/min

After placing these pumps into a decision matrix, which can be found in Appendix E, the top choice ended up being the 12V vacuum pump (#3) due to it being the smallest, lightest, and cheapest. This pump is shown in Figure 7. At the start of the project, the ideal flowrate for the system was unknown because it was dependent on the requirements of the sensors and resistance caused by air filters. As of CDR, the necessary flowrate dictated by the CO/CO2 sensor was determined to be 0.132 - 0.396 gal/min, with a lower flowrate allowing for more accurate readings. However, with the addition of an air filter creating resistance to flow, the pump would need a high enough flowrate to overcome this. Two pumps were the purchased for testing purposes since they both had low costs but did not provide pump curves for proper analysis. These pumps were the 12V Vacuum Pump and the EcoPlus 793GPH (#2). The EcoPlus 793GPH pump is less ideal since it is slightly larger and would require a larger briefcase for packaging but can provide a higher flowrate. If it is determined that a lower flowrate is needed than either of these pumps can provide, a flow regulator will be added into the system.

Figure 7: 12V Vacuum Pump

(Amazon)

Figure 8: EcoPlus 793GPH

(Amazon)

4.4 Sensor Comparison

For this project it was imperative that the group compared the available types of sensors on the market. There are multiple sensors that could function for the calorimeter, but not all of them are compatible with each other or the system that the team is planning on using.

For both CO_2 and CO monitoring, the plan is to use a NDIR type sensor. There are the industry grade sensors which are used for research and commercial application and there are smaller sensors that are used for home improvement or small experiments. There is a large disparity in the accuracy of the sensor and quality of the data. The specification comparison can be found in Table 4 below.

Table 4. Comparisons Between Sensors

Specifications:	Integrated	Response Time (s)	Data Refresh Rate (per/s)	Operating Voltage (V)	Range (ppm or rel %)	Power (W)
Crestline 7911	CO2/CO	<5	2	8-42	10%	1.5
Andros 6511	CO2/CO	<30	1	12	20%	1.8
MH-Z16	CO2	<30	1	4.5-5.5	5000	.46
MH-Z14	CO2	<90	1	3.3	2000	.46
ExplorIR	CO2	<30	2	3.3-5.5	100%	.003
EuroGas	CO2/CO	15-40	.5	9-24	5000	.81
Gascard NG	CO2/CO	10	1	7-30	5000	.6
Alphasense	CO	<25	1	3.3-5.5	1000	.003

One of the key differences between sensors is that there are integrated sensors and individual sensors. Most of the industry grade CO2 and CO sensors are integrated sensors and can measure both gases. This is the type of sensor that has been heavily recommended by Dr. Emberley. These types of sensors such as the Crestline model and the Andros model are precise with their measurements.

The O2 sensor will be an AO2 CiTicel sensor, which covers the correct range and is inexpensive as an individual sensor. The decision matrix in Appendix E covers the alternative sensors for detecting oxygen in the system, but the AO2 sensor is the cheapest that fulfills all the requirements.

4.5 Current Risks

Utilizing the Design Hazard Checklist provided, the possible risks of the projects were assessed. One potential risk identified of the system is that it could fall or be dropped which could cause injury to the user (or could harm the system itself, a secondary concern). Use of the product also involves extracting smoke, which could be dangerous if inhaled or could be very hot and cause injury to a user or the system. The plan to mitigate these risks are to make the product as light as possible, with minimal sharp edges, and add a soot filter early in the sampling line. Analysis will be performed in order to figure out how hot the system could potentially get and add safety measures accordingly. Additionally, the product will include an emergency stop to the shut off the pump as an added precaution, mainly protecting the sensor from damage. A less obvious risk associated with the project is not satisfying the customer by producing a product that doesn’t work as intended. Many tests have been planned to ensure that the product will function as intended. These tests are described in detail in section 7. If the project fails to function as intended, it would be up to the team to detail the system’s issues and needs so that a future project team to finish this for Dr. Emberley. Some of the risks visible in our design are shown in the Risk Assessment document in Appendix R. The risks and the plans to minimize them can be found in the Design Hazard Checklist in Appendix F.

5. Final Design

This section discusses the final design of the calorimeter. It also considers the safety, maintenance, repair considerations; discusses why specific parts and materials were chosen; and summarizes the cost analysis associated with the final design.

5.1 Final Selected Design

The final selected design for our portable oxygen consumption calorimeter focuses on maximizing portability and sensor accuracy. The device will be composed of several key components; these include a pump, air filter, and gas analyzing sensors for O_2 and CO/CO_2. All the sensor components will be mounted on top of an acrylic board as seen in Figure 9 below. The tubing will be secured in place with routing clamps as needed and the process for mounting these is discussed in the manufacturing section. The device will be mounted inside an aluminum briefcase, which can be seen in the isometric view of the final built assembly in Figure 10.

The device also has handles to make it easier to pick up the device, feet to keep the device level, and thumb screws that allow the user to lock the mounting plate into the briefcase. These components can also be seen in Figure 9.

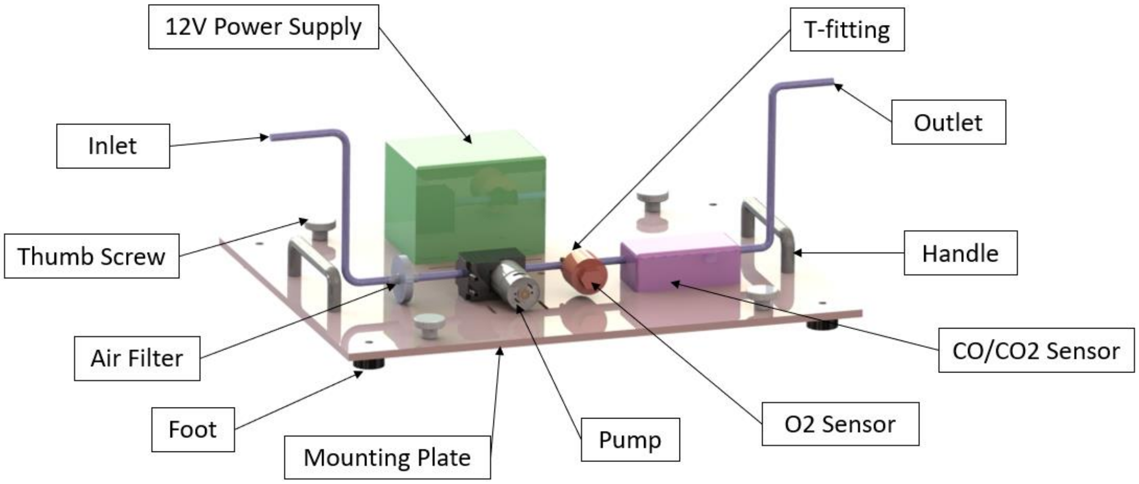


Figure 9. Isometric View of Portable Oxygen Consumption Calorimeter

Figure 10. Isometric View of the Final Assembly

The CO/CO2 sensor has a breakout board with a microcontroller that uses an RS232 to USB connector to send the data collected from the sensor to a computer. A picture of the device connected to a computer is shown in Figure 11.

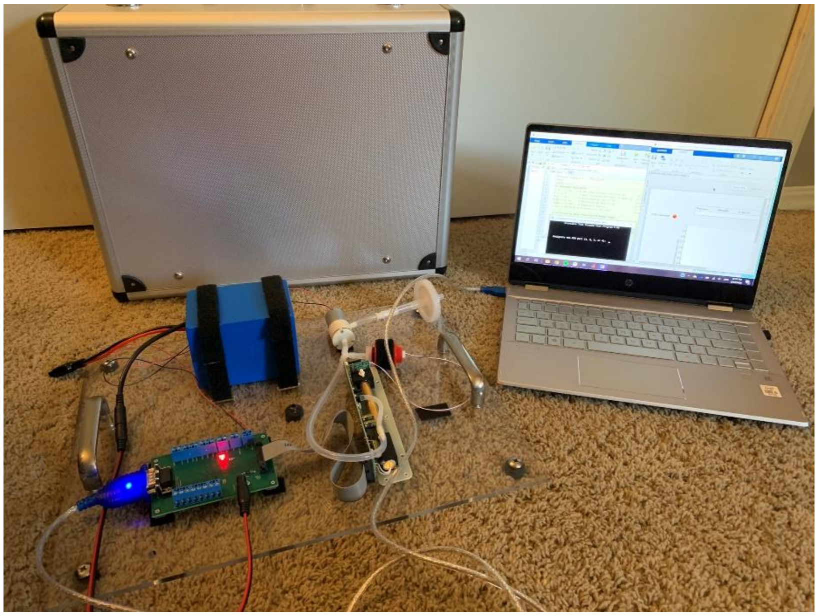


Figure 11. Device Connected to a Computer

The system's function is to take in smoke and gas from a fume hood that it is hooked up to. The pump pulls gas through the system at a flowrate between 0.5 and 1 L/m. The smoke is pulled through a 0.3-micron filter and pumped to the two sensor components. The oxygen sensor measures the concentration of oxygen in the smoke extraction line. The CO_2/CO NDIR sensor measures their respective gas concentrations. After the smoke's gas concentrations are measured, the exhaust smoke is pumped back into the fume hood as shown in Figure 12. The outlet line is above the inlet line in the bulkhead fittings to avoid analyzing the same smoke twice.

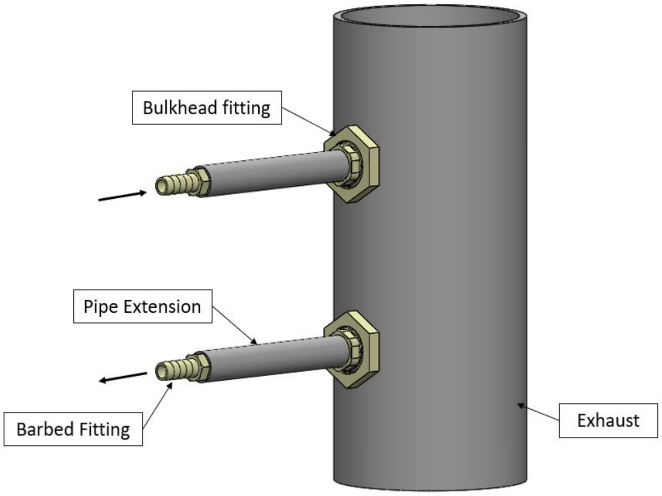
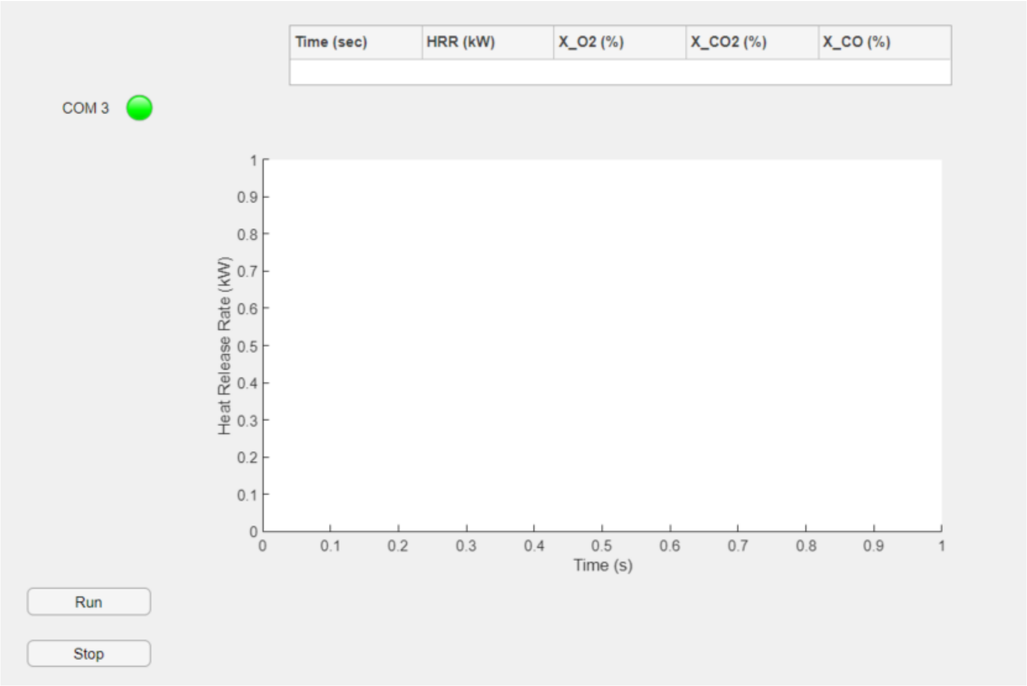


Figure 12. Exhaust Connection

A 12 V power supply powers the pump and CO/CO2 sensor. This power supply can last up to 14 hours, allowing a user to run multiple tests out in the field before having to recharge. The oxygen sensor gets its power from the breakout board from the CO/CO2 sensor. The CO/CO2 sensor connects to a computer to transmit its data. The diagram for how the sensors and computer will be wired together is attached in Appendix I.

The data collected from the sensors is then processed by a computer that's connected to the sensors. This data is collected in real-time and is processed through a MATLAB script to calculate the heat release rate of the burning substance. The GUI for the device was made in MATLAB's App Designer. The features include: plotting heat release rate against time is displayed in real-time, displaying the current values of the concentrations and heat release values in a table, turning on/off a light indicator to notify the user that a device is recognized/ not recognized in a COM port, and pressing a run/stop button to start/stop collecting data. When a user presses the stop button, the data for the time, heat release rate, and concentrations of the three gases is saved to an excel sheet. A picture of the GUI is shown in Figure 13. The pseudocode for how the sensor will calculate the heat release can be seen in Appendix J as well as the actual MATLAB code can be seen in Appendix O.



Time (sec)	HRR (kW)	X_O2 (%)	X_CO2 (%)	X_CO (%)

Figure 13. GUI Display for Portable Oxygen Consumption Calorimeter

The MATLAB GUI displays the data and the CO/CO2 sensor's software, which is called the Crestline software. The Crestline software reads the concentration data coming from the CO/CO2 and O2 sensors and exports the recorded data as a text file. This text file is read by the MATLAB program. The Crestline software must be running in order for the MATLAB program to be able to read the text file and plot data. The team tried to integrate the two programs together, but they were unable to get the MATLAB to send commands to the Crestline software. The specifics on how to operate the portable oxygen consumption calorimeter is outlined in the Operator's Manual as seen in Appendix Q. This manual outlines the process for connecting the tubing and wires correctly as well as how to set-up and run the software. The Operator's Manual also details how to run the software to do the calibration testing for the sensors.

5.2 Material and Part Selection Justification

5.2.1 Briefcase

One of the key functions of this system is for it to be portable. To make sure that the device was portable, the group decided to put the calorimeter in a travel sized briefcase. However, one of the issues with picking any travel sized briefcase is that it would have to be durable during transportation. The decision to choose the material for the briefcase was based on material cost and relative toughens. The three most common briefcase external shell materials on the market are aluminum, polycarbonate, and leather. The relevant material data can be found below in Table 5.

Table 5. Comparison of Briefcase Materials

Material	Weight (lbs)	Young's Modulus (GPa)	Fracture Toughness (MPa/m^2)	Cost (USD)
Aluminum	8.2	68	33	38.99
Leather	7.72	.3	4	114.99
PC+PBT(20% GF)	4.49	5.1	4.85	99.00

Although Aluminum is the heaviest material, it has the highest elastic modulus and fracture toughness. It is important that the case must not deform under heavy pressures as it could possibly damage the components inside. Aluminum is rigid enough to support the components in the case and is stiff enough to resist most bumping that may happen during travel.

5.2.2 Mounting Platform

The mounting platform for attaching all of the major components to is made of acrylic. Acrylic provides a stiff base that is resistant to the environment. Compared to the other platform materials that were considered such as steel, aluminum, and wood; acrylic outperformed all of the other materials in terms of cost and weight. In terms of water resistance, only acrylic and aluminum are water resistant and acrylic is much cheaper than aluminum.

Table 6. Comparisons for a 2' x 4' x 0.25" Platform

Material	Cost ($)	Weight (lb)
Acrylic	29.78	12.27
Steel – Hot Rolled	77.52	45.04
Aluminum – 6061	131.96	14.24
Sande Plywood	44.98	22.15

5.2.3 CO_2, CO, O_2 Sensor Selection

The NDIR CO_2 Crestline sensor was chosen because it is one of the few integrated NDIR sensors on the market. The requirements that were set for the sensor can be found in Table 7. In addition, Crestline, the manufacturer of the NDIR sensor recommended two types of oxygen sensor. The comparison for these sensors can be seen below in Table 8. The chosen sensor was the AO2 Citacel. This sensor had a faster response time than the 2FO and could measure a greater oxygen concentration range. Because these sensors can be linked to each other, it makes data acquisition through a microcontroller much easier. The device compiles the data from all three sensors and outputs them together in one text file. The product literature can be found in Appendix K.

Table 7. NDIR Comparison to Prerequisite Values

	Resp. Time	CO_2 Conc.	CO Conc.	Voltage	Power	Tolerance	Integrated
Required	< 10s	0-16%	0-10%	<24 V	< 20 W	+/- 5%	✓
Model 7911	< 5s	0-20%	0-15%	8-42 VDC	< 1.5 W	+/- 3%	✓

Table 8. Comparison between Oxygen Sensors

Sensor	Cost ($)	Resp. Time	Measurement Range (O_2)	Temp Range
2FO	103	< 10 s	0-30%	-20 to +45 (C)
AO2	89.90	< 5 s	0-100%	-20 to +50 (C)

5.2.4 Air Filter

The air filter that was chosen for this project is the Whatman 6723-5000 HEPA-VENT Filter. They are able to filter out particles as small as 0.3 microns at 99.97% efficiency. Other filters that are used in more industrial practices require the system to have compressed air, however the HEPA-VENT filter works with ambient air. Without an air filter, the soot and detritus would get into the sensor and reduce the flowrate of the system which leads to issues with the data measurement. Having this HEPA filter would prevent all of these problems. In addition, they are quite cheap at approximately $12 USD. This allows them to be replaced quite easily when they are filled with particulate. A detailed test procedure was created in order to determine the lifespan on the filters as shown in Appendix P since the team could not perform the test.

5.2.5 Air Line

The chosen air line for smoke extraction is the High – Temperature Soft Rubber Tubing for Air and Water from McMaster-Carr. The tube was chosen because it is compatible with the barbed tube fittings that are going to be used to connect the tube to our system. In addition, the temperature of this rubber allows it to handle liquids or gases up to 390F. This temperature range will be high enough for any of the application that will be conducted in the Combustion Lab. Tubing with inner diameter of ¼” will span from the inlet port of the exhaust duct to the air filter which has ¼” barbs on each side. A very short amount of ¼” tube will connect to a barbed adapter fitting that goes from ¼” to 1/8”. Tubing with inner diameter of 1/8” will then connect to the pump which has 1/8” inlet and outlet. From the pump, 1/8” ID tube will connect to a T-fitting with 1/8” barbs in order to connect to the CO/CO2 sensor as well as the O2 sensor. Lastly, a short length of 1/8” tubing will connect the outlet of the CO/CO2 sensor to another barbed adapter fitting so that ¼” tubing may span from the adapter back to the exhaust duct.

5.2.6 Pump

The chosen pump for the project is the 12V Vacuum Pump made by Gikfun. This pump was chosen because it delivers an appropriate flowrate for the sensor to take its measurements. Additionally, it is modestly priced and small in size and weight, making it easy to package and incorporate into the system. For additional details refer to Section 4.3.

5.2.7 Battery

The Bioenno Power 12V, 9Ah LFP LiFePO4 Lithium Iron Phosphate Battery was chosen to meet the power requirements of our sensors and pump. The battery also has its own charger and be charging and powering the system simultaneously. Another reason this power supply was chosen was because it can last up to 14 hours, allowing a user to run multiple tests out in the field before having to recharge.

5.3 Safety, Maintenance, and Repair Considerations

The safety of the user and the device is of upmost importance. The team reviewed the safety of the design by creating a Failure Modes and Effects Analysis, which is attached in Appendix M. This process investigates how the design will fail, considers how these failures might affect the customer, and focuses the team to work on the most critical potential issues. Since most of the points of failure are software related, actions to mitigate and reduce failure modes will be achieved once the programming phase occurs. This phase will start in mid-February when the sensors are in.

Other safety precautions taken for the user are -- device was designed to be less than 30 lbs, sharp edges are to be rounded, no exposed conductors, and handles are installed to make carrying the device easier. Also, the software is to be user friendly and have lots of helpful comments to make debugging quicker and easier. The GUI has an emergency stop to be able to turn off the system quickly if something goes wrong.

In order to mitigate damage to the device, it is enclosed and secured in an aluminum briefcase as well as the wires are properly insulated and connected so they do not short the device. The tubing that goes to the exhaust duct will be detachable so that can be stored rolled up within the briefcase. If the suitcase lid was closed while the hoses are still attached, the hoses will be fine since they are very flexible. Other protective measures include a well written manual on how to operate the device and safely replace components for maintenance.

The components that will require maintenance or replacement depends heavily on how quickly soot builds up. The air filter will need to be changed the most often. The tubing on either side must be pulled off, a new filter must be inserted, and then the tubing must be reattached. Tubing, on the inlet of the air filter may need to be replaced once a year – depending on usage – which is a simple take it out and replace with a new one. The rest of the components should last a lot longer, but their part number and vendor are contained in the budget table in Appendix L. There are test procedures to determine the life of the filters in Appendix P.

5.4 Cost Analysis Summary

After sourcing components and compiling their prices, the total cost of the system came out to around $1300. The bulk of the system's costs come from the two sensors (~$450), the power supply (~$120), and the SPAN gases for calibration (~$220). For quality components that are durable and will last for many years of use, these prices are justified. Additionally, the SPAN gases are needed for calibration purposes and are a one-time cost. All necessary components besides the SPAN gases have been purchased by the team so this is the only thing the sponsor will need to purchase later.

The smoke extraction/tubing network has a total cost of about $100. This means that the briefcase sub-assembly carries most of the cost of the entire system. All bolts and connectors for the system are based on standard sizes, however some of the locking mechanism components such as the thumb screws and coupling nuts bring the price up. The sum of the prices of all these connectors are also about $100.

Since this project has been allocated a budget of $3000, the team feels confident that even if changes must be made to the prototype before building the final assembly, they will have the funds necessary to purchase extra or replacement parts. A summary of these costs can be found in Table 7. For a more detailed cost analysis, refer to Appendix L.

Table 7. Summary of Costs

Component	Cost
Briefcase	$38.99
Acrylic for Mounting Plate (final and prototype)	$69.99
Oxygen Sensor	$89.90
CO/CO2 Sensor	$347.00
Power Supply	$133.32
Pumps (two types for testing)	$46.00
Prototyping Materials	$45.00
Air Filter	$129.00
Tubing and Fittings	$35.91
SPAN gases (for calibration)	$226.28
Misc. Hardware and Fasteners	$70.00
Estimated Shipping and Taxes	$122.98
Total	$1354.37

6. Manufacturing

This design for the Portable Oxygen Consumption Calorimeter was created to keep the manufactured or modified parts to a minimum. Most of the key components are sensors that will need to be purchased from third party sources. However, the mounting platform for the briefcase and fitting to the fume hood duct will need to be manufactured. The mounting platform and fume hood duct fitting for this project will need to be fully designed and fabricated. The drawings for the exhaust and the mounting platform as well as their respective assembly drawings are attached in Appendix H. In addition, the GUI and data output will need to be programmed. Pseudocode has been written to show what the program is intended to do and the final code that was written is attached in Appendix O.

6.1 Material Procurement

Due to the nature of this project, key components such as the sensors were purchased from a third-party manufacturer. The NDIR CO_2 and CO sensor were purchased from Crestline Inc. The other electrical components such as the oxygen sensor, wires, and power supply were purchased from the online retailer Amazon. The acrylic, push to connect fittings, barbed fitting, and machine nuts and bolts will be purchased from a Home Depot or ACE hardware depending on part availability. A detailed breakdown of the parts purchased is described further in the Indented BOM attached in Appendix G.

6.2 Mounting Platform

This is the platform that the sensor components, power supply, pump, and air filter are mounted to. The components that mount to the pink mounting platform is shown in Figure 14.

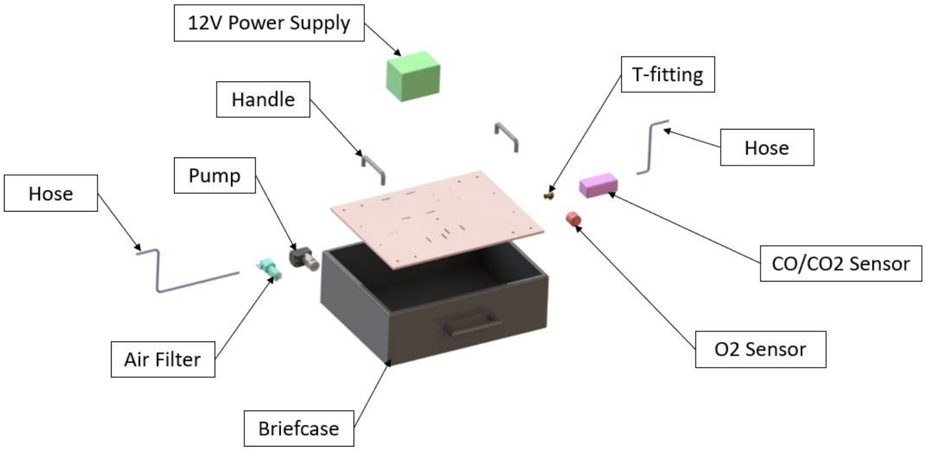


Figure 14. Mounting Platform and the Components

Step 1: The stock acrylic was cut down to 18” in length and 14” in width with a laser cutter.

Step 2: ¼” holes were laser cut into the corner of the platform, and rubber feet were threaded onto the platform.

Step 3: ¼” holes were laser cut 1” into the short side of the platform spaced 4” vertically from each other and 3.71” from the top. This was mirrored on the other side of the acrylic platform. Handles were attached to the platform with bolts and nuts using these holes.

Figure 15. Handles, Bolts, Pump/O_2 Sensors Mounted

Step 4: Two 1/8” holes were laser cut 1.25” from the top of the platform and 10.19” from the left side with 1.882” distance separating them vertically.

Step 5: Laser cut 1” x 1/8” slots around battery, pump, and oxygen sensor (see part drawing for locations). These components that were strapped to the mounting platform by using these slots and Velcro straps. These components were strapped to the mounting platform by using these slots and Velcro straps. This makes them easy to remove for maintenance purposes.

Step 6: ¼” holes were laser cut into the mounting platform. Thumbscrews were mounted through the platform onto the coupling nuts.

Step 7: ¼” holes were drilled into the bottom of the briefcase. A round headed bolts were inserted and connected with a coupling nut and thumbscrew as seen in Figure 16. Round headed bolts were inserted and connected with a coupling nut and thumbscrew as seen in Figure 16.

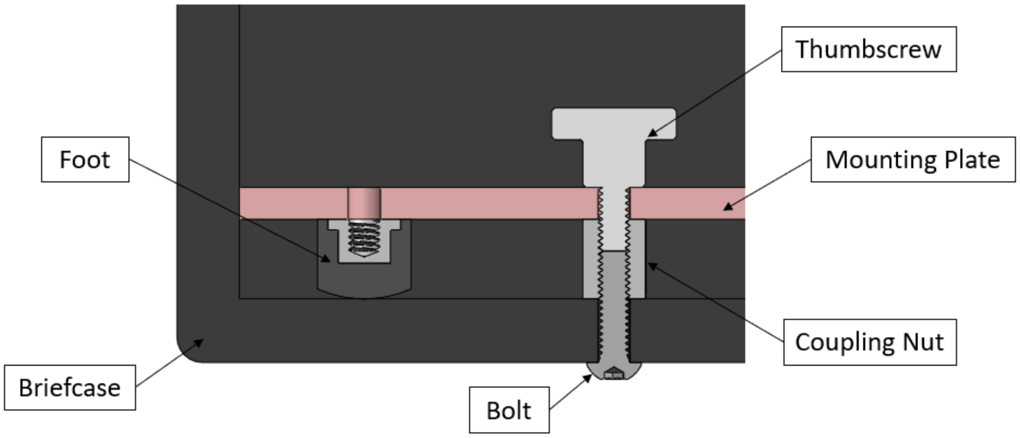


Figure 16. Visual of Round Headed Bolt and Coupling Nut (Right)

Figure 17. Round Headed Bolt and Coupling Nut Mounted

6.3 Tubing Network

High-Flex PVC has been selected for the tubing to route the smoke through the mounting platform between components. The inner diameter of the tubes will be ¼".

Step 1: The tube was hooked up to the system components (pump, air filter, sensors) through their barbed fittings.

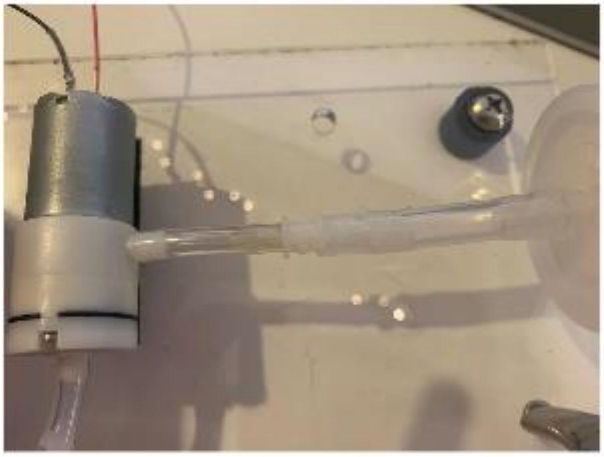


Figure 18. Pump and Filter Fitting

Figure 19. Fully Attached System

Going forward with the tubing network, there is still some work to be done. Since the fume hood duct fitting in Section 6.4 has been delayed due to current events, the last tubing connection from the sensor to the hood has yet to be connected. The barbed fitting has already been attached to the sensor, so the tube can be easily just pushed onto the sensor and the home hood connection.

6.4 Fumehood Duct Fittings

For the duct fitting, two airline bulkhead fittings will be attached to the duct above the fume hood. These bulkhead fittings will have steel tubes with barbed fittings at the end. These barbed fittings will then connect to the tubing network mentioned above. An exploded view of these components is shown in Figure 15. Due to current events, this component has yet to be manufactured. Manufacturing will be done either by Dr. Emberley or by team members at a later date.

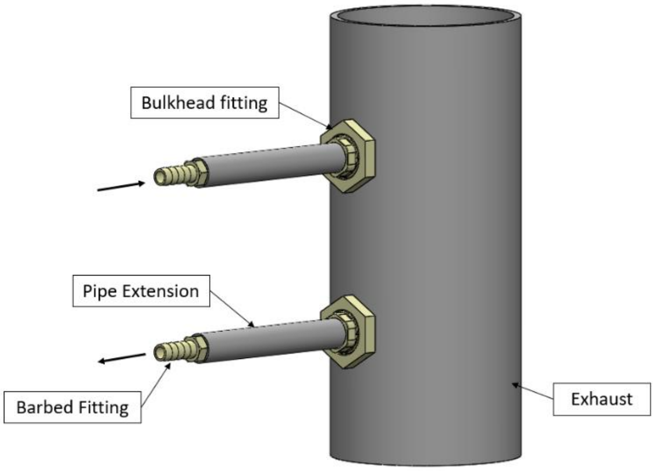


Figure 20. View of Exhaust Connection

Step 1: A ¼" hole will be drilled into the duct 5” above the fume hood. A second ¼" hole will be drilled 2” above the first hole.

Step 2: Bulkhead fittings will be threaded onto the ¼" holes.

Step 3: A 5” steel tube will be attached onto the threaded end of both bulkhead fittings.

Step 4: A barbed fitting will be attached to the end of the 5” steel pipe.

Step 5: The tubing network inlet and outlet pipes will then be inserted onto the barbed fittings. The inlet tube should be hooked up to the bottom barbed fitting.

6.5 Wiring the System

Step 1: Connect the O_2 sensor to the integrated sensor with a Molex connector.

Step 2: Connect battery to pump and CO/CO2 sensor when ready to use device. The red LED will light up on the breakout board (Figure 21 on the right) if there is power to the device.

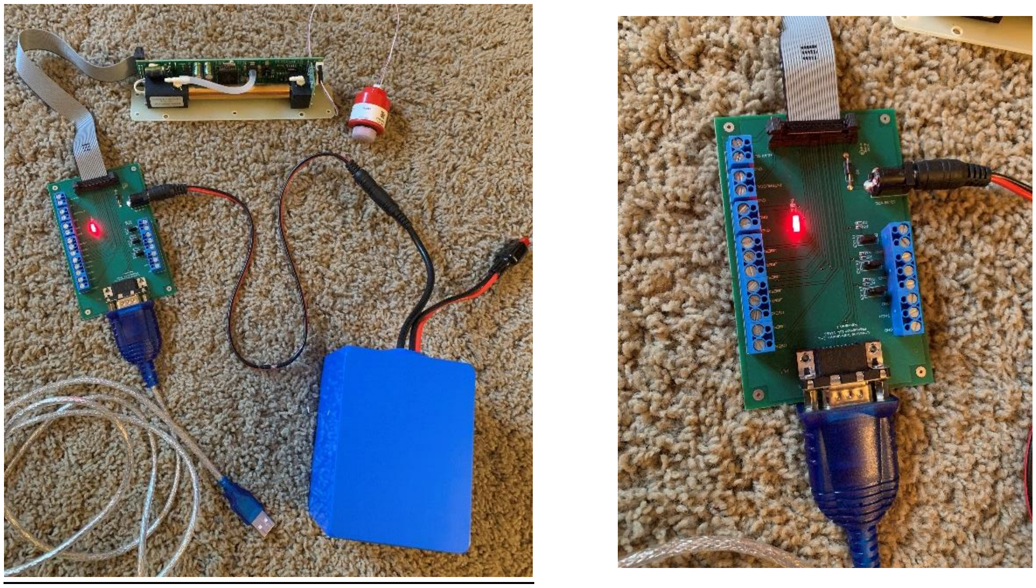


Figure 21. CO/CO2 and O2 Sensor Connected to Battery

Step 3: Connect RS-232 to USB cable with the RS-232 connector into the breakout board and the USB connector into computer. (See Fig 22). There will be a blue light inside the cable if the device is connected properly.

Figure 22. USB connection to the computer (pictured on the left) and the RS-232 Connection to the breakout board (pictured on the right)

6.6 Assembly

For this device to work, all three of the previous systems need to be attached together. Once the mounting platform is built into the briefcase the inner tubing networks can be connected and secured to the platform. Once the fittings for the tube network are bolted down onto the board, the tube network will be linked up with the fume hood duct fittings. The inlet tube will be attached to the lower duct fitting and the outlet tube will be attached to the upper duct fitting. However, with problems due to COVID-19, the assembly of the fume hood duct fittings will be completed by Professor Emberley before conducting testing. Our final assembled device is seen in Figure 23.

Figure 23. Isometric View of the Final Assembly

6.7 Coding

The programming in this project consisted of two parts: learning and understanding the Crestline sensor software as well as creating a GUI for users to their desired data. The steps for installing and sending commands to the Crestline Sensor software to get the sensor to collect data is described in the Operator's Manual which can be found in Appendix Q. The GUI was created using MATLAB and the process for creating it are outlined below. The final code for the GUI and heat release calculations is attached in Appendix O.

Step 1: Create a MATLAB script to calculate the heat release rate as outline in the Pseudo Code in Appendix J. This script reads the text file that the Crestline sensor outputs.

Step 2: Use MATLAB’s App Designer to create the features of the GUI as seen in Figure 24.

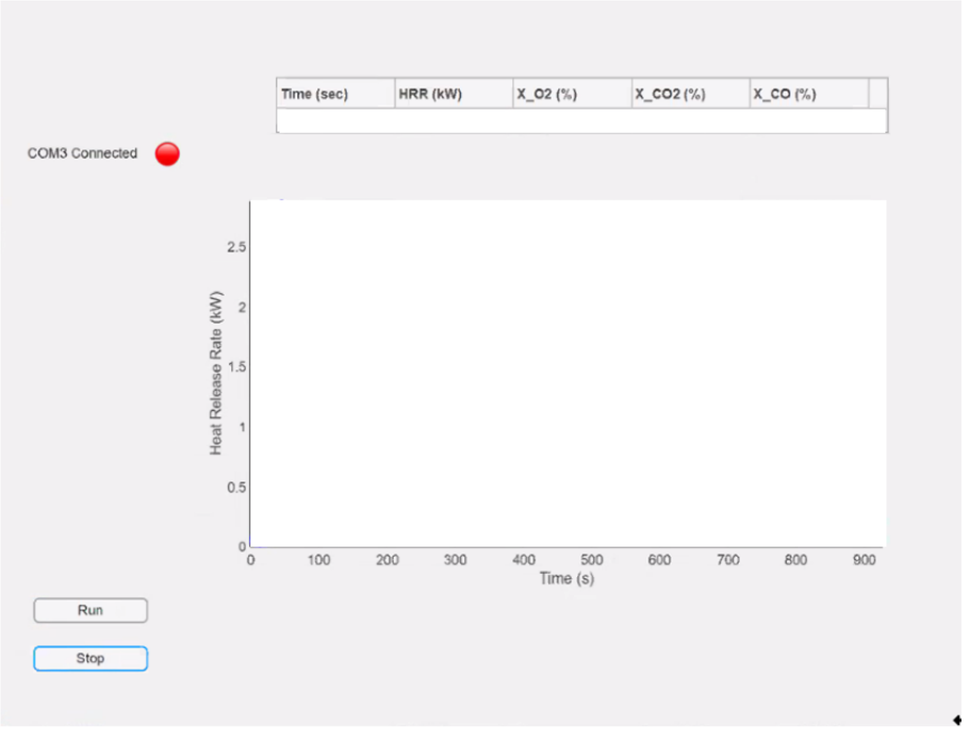


Figure 24. Features of the GUI

Step 3: Set up a while loop for the run button so that it can plot the collected data while the user has the code running.

Step 4: Inside the while loop, call the MATLAB script and then plot the heat release rate against time during each pass through.

Step 5: Create a function to update the table with the current concentration values, heat release rate, and time. This function is called in the while loop to update the table through each pass.

Step 6: Create a global variable that can stop the running of the while loop when the stop button is pressed.

Step 7: Store the collected data (heat release rate, time, and concentrations) to an excel file called *testdata.xls* for the user to use after the stop button is pressed. The text file from the sensor can also be accessed in the Crestline folder, which is specified in the Operator’s Manual in Appendix Q.

Step 8: The start button can then be pressed again, which clears the graph and starts the cycle over again.

6.8 Challenges and Future Production:

The biggest challenge that occurred was creating a plan that would be dealing with the manufacturing processes after COVID-19. There were several manufacturing delays and the team was also spread out across several states. This significantly hampered production time as only one member was able to be working on the device. Future production, however, should be simpler to carry out. A majority of the complex manufacturing is done by the laser cutter and the other manufacturing consists of drilling.

One change for future production would be to drill holes and add zipties for better cable management. There aren’t too many wires that get in the way of the components. However, it would be better to keep the wires contained under the acrylic plate, or at least tied to the plate to avoid tangling.

7. Design Verification

There are three categories for the testing of the specifications described in the Specifications Table in Section 3.4, safety, usability, and data. Also, the results from the testing procedures in Appendix P are included in Appendix N and are discussed in the results section (Section 7.4).

7.1 Safety:

The smoke extraction cannot leak as this would be a safety hazard for people in the lab. Also, the sensors only work properly for a certain flowrate (0.5 L/min to 1.5 L/min), necessitating a proper test of the smoke extraction system. For the test, a flowmeter will be attached to the tubing of the system as well as a visual inspection of the components to make sure that there are no leaks (the smoke will be visible before the filter due to the soot from the combustion).

Electrical wiring safety is important when working with this system. While there are no high voltages, the battery has enough energy to provide a shock to a person if there are exposed wires. Wires must be properly insulated and there cannot be any shorts in the system, as this is a safety hazard. The test for exposed wires can be performed visually as well as with a voltmeter.

Heat is present in any system with smoke and combustion, which is a hazard to the components of the calorimeter as well as the user. To minimize this, we will ensure that all tubing and components are safe to the touch. The equipment used for the temperature reading will be thermocouples throughout the system.

Thermal analysis of expected temperatures will also be used to compare the actual temperatures for selected areas of interest (connection to the fume hood and inlet to the sensors) and they should be within 5% of the calculated values to ensure the system is safe for the user. The test for thermal analysis will simply be calculations at specific points and will be compared with the measured values from thermocouples at those positions.

The case of the calorimeter must protect the components from damage from an unexpected load or weight. The structural integrity factor quantifies this with minimal deflection by the expected load range (50-100 lbs). This is the expected force that the calorimeter device will feel under normal loading conditions. The structural integrity factor will be tested on the briefcase and acrylic plate by using a tape measure as well as weights to quantify the deflection of the calorimeter under load for a known load.

Travel is a key part of portability that must be specified, especially if the calorimeter is moved to a new location. The transportation may be in a car or on a cart, where there may be vibrations or bumps. Testing to ensure that all components are secure and safe in the briefcase will be done by simulating an expected travel scenario. This would involve placing the calorimeter in a vehicle and ensuring that all the components are secure after 30 minutes of travel.

7.2 Usability:

To consider the calorimeter portable, the user must be able to move the device to the desired location. Dimensions of 24 inches long by 24 inches tall by 12 inches wide with a tolerance of +/-5 inches were chosen. This allows the system to include all the required components, while limiting the size. The test for verifying the correct dimensions for the portable calorimeter will use a tape measure to record the length, width, and height of the calorimeter. Comparing the actual values to the parameters will determine if the specification is met or not.

Portability also includes the weight of the device, which we have chosen to be less than 30 pounds. The test for this device involves placing the calorimeter on a scale and comparing the results to the chosen specification.

The calorimeter needs to be usable without extended training or familiarity, it must be usable and intuitive from the beginning. To test the usability of the entire system, especially the software user interface, a survey will be conducted after the user interacts with the calorimeter. The results will be tabulated and analyzed to ensure that four out of five users have a positive experience.

The calorimeter must be compatible with other devices in the lab, including the fume hood, computers, and electronics in the Combustions Lab. Testing for this will be an inspection of the system to ensure that all properties of the calorimeter work properly.

7.3 Data Acquisition:

The heat release rate values are the most important outputs of this system as they are the primary data measured with the calorimeter. Ensuring the calorimeter has an accurate calibration is necessary to determine the accuracy of the entire device. The test for heat release rate uses the outputs from the oxygen and NDIR sensors compared to the known heat release rate of the sample undergoing combustion in the fume hood. The sensor will collect the numerical data of the heat release rate to perform data analysis and uncertainty propagation calculation.

Software testing will ensure that the runtime for the code is minimized to lower the response time of the entire system. A lower response time gives data that is closer to real time, removing as much lag as possible from the system. Software that takes a long time to run negatively affects the time response and to test this, a stopwatch will be used to measure the time it takes for the software to compile and run. This response time should be less than one minute, and the software may be refined to run much faster than this specification.

The main equipment necessary for these tests will be a flowmeter, a sample with a known heat release rate, and thermocouples for measuring the temperature of the system. The flowmeter may need to be integrated into the calorimeter if testing reveals that the pump does not produce a constant flowrate, as the sensors only operate in a specified flow range. All equipment can be found in the Combustions Lab or borrowed from faculty. When each component is received, it will undergo individual testing and the entire system will be tested as soon as it is assembled.

All specifications and testing requirements, as well as preliminary dates for testing, can be found in the Design Verification Plan in Appendix N.

7.4 Results:

The design was verified using the guidelines in Appendix N (Design Verification Plan). However, there was a significant disruption in the testing procedures due to COVID-19. The Combustion Lab at Cal Poly was not accessible, and no data collection of the combustion products could be completed off campus.

The tests that could be completed were the dimensions, weight of the device, software testing, the structural integrity factor, and the heat release values (to an extent). The dimensions, structural integrity factor, and weight of the device were pass/fail according the specifications in the DVP. In Figure 25, the software testing of the Crestline software was performed in the Electrical Engineering Lab at Cal Poly. The power supply is attached to the Crestline calorimeter sensor and the sensor is attached to the computer. This initial testing allowed the team to learn the commands and the setup needed for collecting data from the sensor. This helped in understanding how the sensor stores the data so that it could be used when writing the MATLAB code that processes this data to calculate the heat release rate.

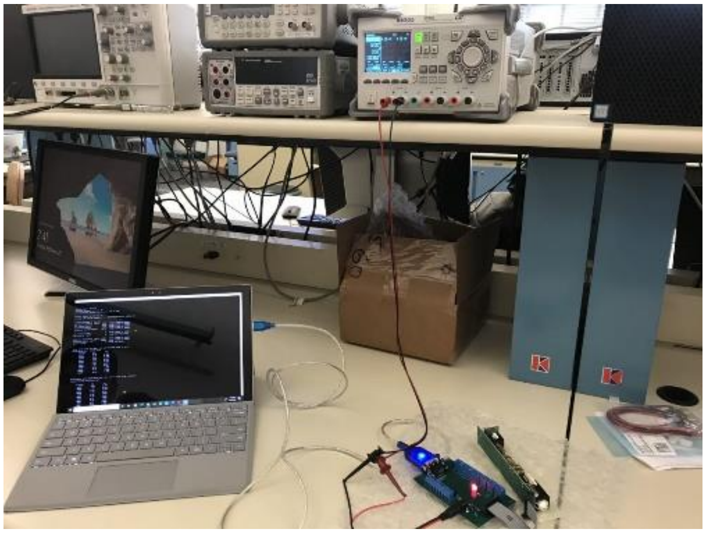
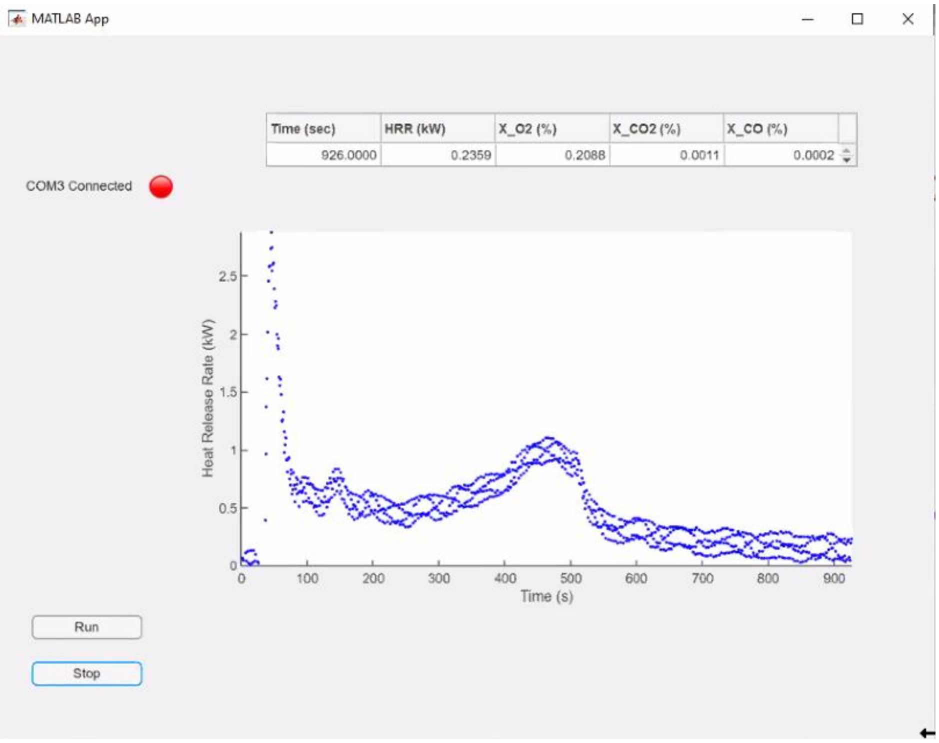


Figure 25. Initial CO/CO2 Sensor Testing in an Electrical Engineering Lab at Cal Poly.

The heat release values were partially completed using data from a previous combustion experiment. However, the goal of comparing the values from a previous combustion experiment to an actual experiment run in the Cal Poly labs was not completed due to complications from COVID-19. Figure 26 shows the MATLAB software after running the Excel data, where the Heat Release Rate versus time was plotted. The results had less than a 2% difference between the MATLAB calculated HRR and experimental HRR. However, uncertainty results could not be calculated for the heat release due to the inability to perform any experiments in the lab. The team also ran the MATLAB code while the sensor was collecting data to ensure that the two programs work together.



Time (sec)	HRR (kW)	X_O2 (%)	X_CO2 (%)	X_CO (%)
926.0000	0.2359	0.2088	0.0011	0.0002

COM3 Connected

Figure 26. Plot of Heat Release Over Time from Data Given by Dr. Emberley.

7.5 Future Tests

Tests that were not completed due to COVID-19 were the test of the smoke extraction system, user testing survey, thermal analysis of the system, compatibility with other lab devices, travel testing, electrical wiring safety, and heat exposure testing. The main reason these tests could not be completed was because of the Cal Poly Combustion Lab being closed, which was a large challenge in the verification of the design. However, the team outlined the testing procedures in Appendix P for Professor Emberley to complete the testing in the Fall Quarter of 2020.

8. Project Management

This section outlines the team's design process and deadlines and detail the special techniques that were used to solve the problem.

8.1 The Design Process and Deadlines

The design process for the first ten weeks consisted of sponsor interviews, preliminary research and component review. Sponsor interviews and preliminary research was conducted concurrently to help the engineering team determine the scale of the project. The next step was to create a scope of work document and send it to the project's sponsor. Once the engineering team could move forward, they conducted component review on the parts that will be necessary for creating a functioning prototype. After the research on the individual sensors was complete, the team moved onto understanding the design limitations of the integrated system. When the components were chosen for the final design, the team could proceed with designing the physical containment package of the device. The packaging of the portable calorimeter is important for the smoke line extraction of the system. Once the packaging study has been finished and the prototype has been built, coding the device can begin. This will carry forward into the spring quarter of the academic year. The Gantt Chart contains a more detailed version of tasks in between the major milestones and can be found in Appendix C.

Throughout the project, distribution of tasks was done using a Gantt Chart and after meeting weekly with the adviser. This allowed for the team to keep a tight hold on what needed to be done over the upcoming weeks for short-term planning. Over the course of the spring quarter, COVID-19 disrupted the original workflow of the team. To compensate for this, the team decided to meet up for an additional two hours on the weekend to set up project goals and confirm finished work. This allowed the team to make headway at a constant pace and hit the deadlines for external submissions and internal assignments.

One of the most useful methods for keeping the team on track were external weekly meetings. Outside of the previous positives, these meetings also allowed for workload accountability and team communication. If there were members who had other priorities another teammate could step in and provide help. This way the team managed to effectively distribute the workload while keeping open communication. The method of communication allowed the team to ensure that one person would not be responsible for the entirety of the work or project. It also allowed for a better workload balance between the senior project, other work, and extracurricular activities.

Table 8. Project Timeline up to 6/8/2019

Deliverable	Due Date
Choosing a Project	9/26/2019
Identifying Technical Challenges	10/8/2019
Product and Patent Research	10/14/2019
QFD	10/15/2019
Scope of Work	10/18/2019
Preliminary Design Review (PDR)	11/15/2019
Interim Design Review	1/16/2020
Critical Design Review (CDR)	2/7/2020
Manufacturing and Test Review	3/12/2020
Senior Expo	6/8/2020
Final Design Review (FDR)	6/4/2020

8.2 Special Techniques for Solving the Problem

This project is heavily focused on creating a more economic version of an existing calorimeter. The oxygen consumption calorimeter that currently exists on the market is used for large scale fire experiments. Because this technology already exists, this project will be primarily focused on sourcing sensors and components that will be both economic and accurate for smaller fire experiments. The second half of the project will be about creating code that will calculate the heat rate of the fire test and function as a graphical user interface. This process will be iterative. The code will have to be refined so that it will run efficiently as well as be easy to change in the future. This means that each iteration of the code will have to be documented so that each step can be reviewed if changes need to be made. This would work as a paper trail for the coding process, as there are many ways to code a certain type of interaction into a system. Once the bulk of coding for calculations is done, the next step will be to design and create a user interface that will be easy to use. Having an accessible user interface will allow the user to focus on the experiment on hand and not setting up the testing software.

9. Conclusion

This section outlines the results, the recommendations, future steps, reflection, and the challenges the team faced during the project.

9.1 Next Steps

Future work to be completed by the sponsor will include calibration of the NDIR sensor, testing the calibrated device using actual fire experiments, and setting up the computer software. In order to calibrate the device, SPAN gases will need to be purchased. This cost has been accounted for in the budget, however quarantine prevented the team from acquiring the gases.

There are also a few manufacturing steps that need to be done - the fume hood extraction piece needs to be manufactured and built into the fume hood in the Combustion Lab. This will allow the device to obtain the data more effectively from the fire and return the smoke into the system in a safer manner. Another piece of manufacturing that could be added into the system is a dehumidifying component. While the oxygen and NDIR sensors are robust and can be used in an environment where the relative humidity is 99%, the water vapor in the system can be purged to ensure that the electrical components will last for a longer period. Ideally, there would also be a flowmeter connected to the system to ensure that the air's flowrate is in the ideal range for the NDIR sensor.

The software side of the system could also be improved with further work. The team was not able to get the MATLAB script to talk to the host program for the NDIR sensor. Essentially, the two programs need to be run simultaneously for there to be a visible output. This is a cumbersome way of achieving the goal and can confuse the user if they are not getting the correct outputs. MATLAB can be configured to send serial commands to the host program. This will allow the MATLAB script to communicate with the host program without having to operate both programs at the same time. This would reduce several of the operating procedures and reduced and confusion that may arise due to the two different operating software. If the team had more time to work on this project, they would spend more time researching appropriate MATLAB syntax for achieving this goal. MATLAB syntax for achieving this goal.

Another option for solving this issue is instead of using the breakout board the Crestline software to operate the sensor, one can connect the RX and TX serial data lines to a microcontroller such as an Arduino or Raspberry Pi and program the microcontroller to read the data and plot the results. This would allow for easier use of the system in general but coding a microcontroller would involve building the software and GUI from scratch.

For using the device out in the field, the next steps would consist building a portable fume hood or other enclosure that can collect and direct the smoke of a burning substance through the tubes on the device.

9.2 Project Summary and Reflection

This document shows the work that the team has made towards the final design. The goal of this project, which was to create an oxygen consumption calorimeter that will be under $3000 and portable, has been achieved. The team's concept prototype was the result of brainstorming ways to achieve portability and user-friendly requirements. Additionally, specific sensors, pumps, and coding languages were researched and analyzed to find the best ones for this application. After finding a reasonably priced NDIR sensor, the team was able to move ahead with building their concept and came in under budget at around $1300. The team investigated potential risks involved in the product and noted that there was not anything of concern. The biggest risk is the potential for users to be exposed to heat and smoke, but the team has added safety measures to protect against harm from these elements. As much of the final assembly was built as was possible by the team under the current circumstances due to social distancing measures from COVID-19. As such, the sponsor and team members will continue to refine and test the final product, as well as make modifications to the Combustion lab's exhaust duct, once they are able.

This year-long project provided an amazing learning opportunity to the team to become more knowledgeable about fire research and safety along with developing skills in project management, safety, design, and testing. If the team were to begin this project over again, they would spend more time during the brainstorming and researching phase designating specific roles to each team member. Additionally, the team would have chosen a different coding program than MATLAB. Although MATLAB was what the team was most familiar with, another program such as C+ would have allowed for a more robust GUI that would make student use easier.

The team would like to thank Dr. Peter Schuster and Dr. Richard Emberley for their mentorship and advice this past year.

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Appendix A: Patents

1. Heat Release Rate for Milligram Samples (US Patent #6464391 B2)

Abstract: A calorimeter that measures heat release rates of very small samples (on the order of one to 10 milligrams) without the need to separately and simultaneously measure the mass loss rate of the sample and the heat of combustion of the fuel gases produced during the fuel generation process. The sample is thermally decomposed in a small volume pyrolysis chamber. The resulting fuel gases are immediately swept by an inert gas stream from the pyrolysis chamber into a combustion furnace in a plug-like flow. This plug flow substantially synchronizes the emerging fuel gases with the mass loss rate of the sample. Oxygen is metered into the fuel gas stream just before it enters the combustion furnace where the fuel gases are completely oxidized. The effluent from the furnace is analyzed to determine the amount of oxygen consumed per unit time and the heat release rate is computed without the need to separately measure the mass loss rate of the sample.

2. Method for Measuring Heat Release of Polymeric Compounds (US Patent #0034580 A1)

Abstract: The invention provides a method for measuring the heat release rate of a flame retardant compound in a microscale combustion calorimeter.

3. Coal Calorimetry System (European Patent #88105006.6)

Abstract: A calorimetry system which is especially suitable for on-line, continuous measurement of the heating value of coal and which provides heating value data which may be used to control coal-fired furnaces in public utility power plants has a calorimeter with a combustor and a mixing unit wherein heat from the combustion gases is transferred to air. The system has apparatus for pulverizing the coal and a gravimetric feeder for providing pulverized coal at a measured mass feed rate to the combustor. The system also has devices for preheating the combustor and initiating self-sustained combustion of the coal therein without the need for further supporting fuel gases. Instrumentation in the system measures the flow rates of the cooling air, primary and secondary -, combustion air as well as the mass flow rates of the coal into the combustor. A computer is provided with input/output devices which is responsive to the measuring instruments (thermocouples and pressure gauges) for controlling the feeding of the coal and fuel gases during initiation of combustion and for computing the heating value of the coal. The computer may have a memory with storage for specific heat values of the constituents of the products of combustion of various ranks of coal (bituminous, subbituminous, lignite, etc.) and the average mass fraction of each constituent in the coal by rank so that the heating value thereof can be determined with accuracy. The combustor and mixing unit are constructed in a manner to return to the combustion gas and to the combined combustion gas and cooling air most of the radiant and convective heat losses in the system thereby minimizing the effect of heat loss and the effect of ambient environmental (temperature and pressure) changes on the accuracy of the measurement.

4. Bomb Type Calorimeter (US Patent #4511263)

Abstract: A bomb-type conduction calorimeter consists of a bomb separated from a substantially infinite heat sink by several heat flow detecting elements. The bomb is enclosed by an inner copper box having a cylindrical interior and a polygonal exterior. The inner copper box is enclosed by an outer copper box having a polygonal interior. The heat flow detecting means may be several thermopiles in contact with the inner and outer polygonal surfaces. The infinite heat sink may be a constant temperature water bath. Heat flow directly from the test substance is measured, as opposed to the heat flow dissipated to the environment of the bomb. The calorific values determined are independent of the amount of water in the water bath.

5. Cone Calorimeter (Chinese Patent #105424748 A)

Abstract: The invention discloses a cone calorimeter. The cone calorimeter comprises a main control computer, an auxiliary control computer, a combustion and irradiation device, a smoke discharging assembly and a gas analysis device, wherein the auxiliary control computer is provided with a heat flux meter assembly and a water-cooled circulating system of the heat flux meter assembly; the combustion and irradiation device comprises an ignition assembly, a heat radiation assembly and a sampling assembly; the smoke discharging assembly is provided with a measuring assembly and is used for connecting the combustion and irradiation device with an external waste gas treatment device; the smoke discharging assembly is connected with the gas analysis device through a collecting device. In an experimental process, the main control machine is used for controlling all components and receiving a feedback signal, the auxiliary control machine is used for controlling the combustion and irradiation device to test the performance of a flame-retardant material, a generated gas can be sent from the smoke discharging assembly to the gas analysis device so as to be subjected to analysis treatment, a testing result can be obtained by the measuring assembly on the smoke discharging assembly and the gas analysis device, the needs of a test all-in-one machine used in a laboratory scale can be met, and the cone calorimeter can be widely applied to various fields.

Appendix B: QFD

Correlations	
Positive	+
Negative	−
No Correlation	

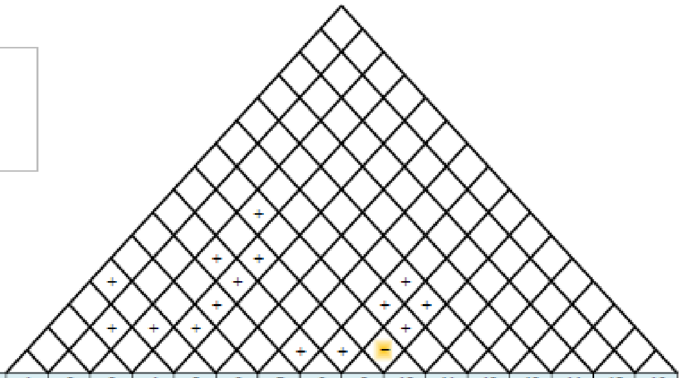
Relationships	
Strong	●
Moderate	○
Weak	▽

Direction of Improvement	
Maximize	▲
Target	◇
Minimize	▼

QFD House of Quality

Project: Oxygen Consumption Calorimeter

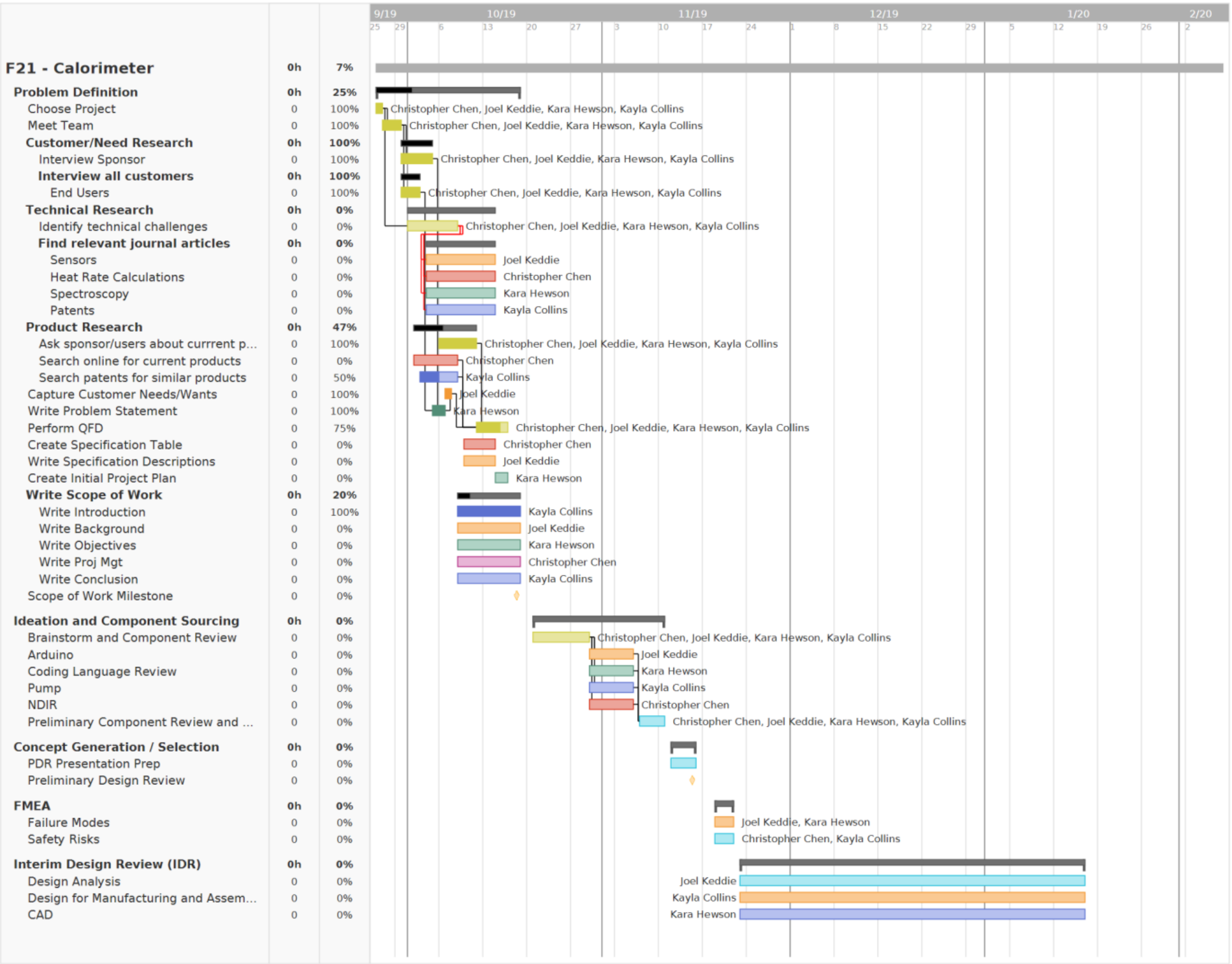
Revision Date: 10/17/2019



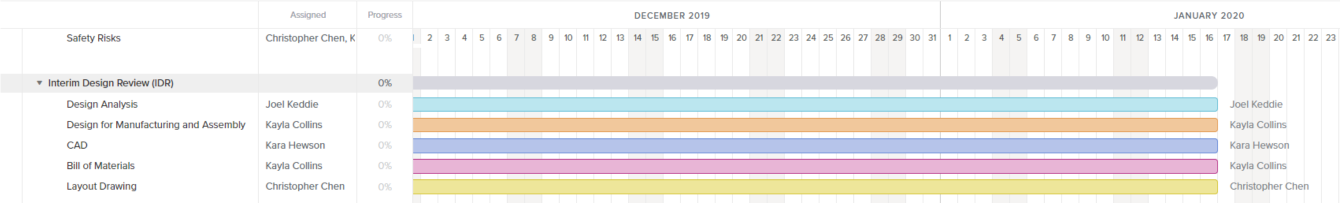
	WHO: Customers							Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	NOW: Curr. Products					
								Direction of Improvement	◇	▼	◇	▲	◇	▲	▲	▲	▲	▼	▲	▼										
Row #	Weight Chart	Relative Weight	Professor Emberley	Students	Researchers		Maximum Relationship	HOW: Engineering Specifications (Tests) WHAT: Customer Requirements (Needs/Wants)	Smoke Extraction	Dimensions	Heat Release Values	User Testing Survey	Thermal Analysis	Software Testing	Testing with other lab devices or apparatuses	Travel Testing	Structural Integrity Factor	Weight	Electrical Wiring Safety	Heat Exposure					Our Current Product	Bomb Calorimeter	Cone Calorimeter	Constant Pressure Calorimeter	Calvet Type	Row #
1	▮	11%	10	6	10		9	Portability		●						●	○	●		▽					1	5	2	5	3	1
2	▮	10%	7	10	7		9	Easy to use		●	▽	●		●	○	○				▽					2	3	2	5	2	2
3	▮	10%	7	10	7		9	GUI						●											3	3	3	1	3	3
4	▮	9%	9	7	5		9	Compatability	●					○	●										5	1	3	1	4	4
5	▮	6%	5	2	7		9	Cost	●	○	●						○	○		○					1	5	4	5	3	5
6	▮	6%	7	2	6		9	Maintenance		●			●					▽	○						2	1	3	5	2	6
7	▮	10%	8	9	8		9	Documentation	●		▽	●		●											5	3	3	1	5	7
8	▮	9%	8	7	8		9	Precision				○	●	○											3	3	5	2	5	8
9	▮	11%	10	7	10		9	Accuracy			●	●	●	○	○										3	4	5	2	3	9
10	▮	9%	6	9	6		9	Durability				●				●	●	●	●	●					4	4	3	1	2	10
11	▮	10%	9	7	8		9	Safety									●	●	●	●					4	3	4	5	3	11
12		0%																												12
13		0%																												13
14		0%																												14
15		0%																												15
16		0%																												16

		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
	HOW MUCH: Target Values	Pass	24 in long x 24 in wide x 12 in tall (+/- 5 in)	Calibration Accuracy (+/- 5%)	Majority of Positive Responses	Accurate to within 5%	Less than 1 minute	Pass	Pass	Less than a 3 inch deflection	Less than 30 lbs	Pass	Pass				
	Max Relationship	9	9	9	9	9	9	9	9	9	9	9	9				
	Technical Importance Rating	221	255.9	170.3	388	238.2	358.8	140.2	203.4	215.4	284.9	184.8	204.2	0	0	0	0
	Relative Weight	8%	9%	6%	14%	8%	13%	5%	7%	8%	10%	6%	7%	0%	0%	0%	0%
Curr. Products	Our Current Product	1	1	3	2	5	2	3	4	5	5	3	3				
	Bomb Calorimeter	1	5	4	3	5	3	1	3	5	3	3	5				
	Cone Calorimeter	3	2	4	3	5	3	4	2	3	1	3	4				
	Constant Pressure Calorimeter	1	5	1	3	1	1	1	1	1	5	5	5				
	Calvet Type Calorimeter	1	5	5	3	5	5	2	1	4	1	3	3				
	Column #	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16

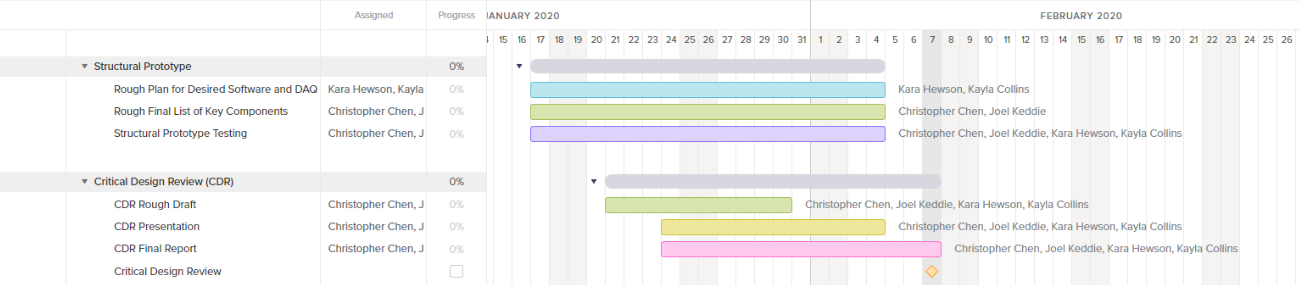
Appendix C: Gantt Chart



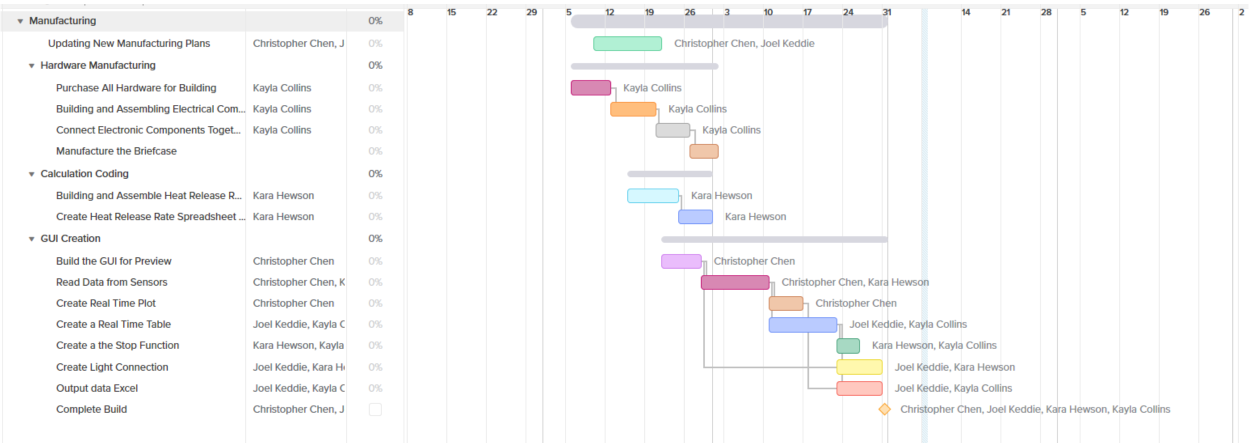
F21 - Calorimeter	**0h**	**7%**	
Problem Definition	**0h**	**25%**	
Choose Project	0	100%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Meet Team	0	100%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Customer/Need Research	**0h**	**100%**	
Interview Sponsor	0	100%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Interview all customers	**0h**	**100%**	
End Users	0	100%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Technical Research	**0h**	**0%**	
Identify technical challenges	0	0%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Find relevant journal articles	**0h**	**0%**	
Sensors	0	0%	Joel Keddie
Heat Rate Calculations	0	0%	Christopher Chen
Spectroscopy	0	0%	Kara Hewson
Patents	0	0%	Kayla Collins
Product Research	**0h**	**47%**	
Ask sponsor/users about currrent p...	0	100%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Search online for current products	0	0%	Christopher Chen
Search patents for similar products	0	50%	Kayla Collins
Capture Customer Needs/Wants	0	100%	Joel Keddie
Write Problem Statement	0	100%	Kara Hewson
Perform QFD	0	75%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Create Specification Table	0	0%	Christopher Chen
Write Specification Descriptions	0	0%	Joel Keddie
Create Initial Project Plan	0	0%	Kara Hewson
Write Scope of Work	**0h**	**20%**	
Write Introduction	0	100%	Kayla Collins
Write Background	0	0%	Joel Keddie
Write Objectives	0	0%	Kara Hewson
Write Proj Mgt	0	0%	Christopher Chen
Write Conclusion	0	0%	Kayla Collins
Scope of Work Milestone	0	0%	◆
Ideation and Component Sourcing	**0h**	**0%**	
Brainstorm and Component Review	0	0%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Arduino	0	0%	Joel Keddie
Coding Language Review	0	0%	Kara Hewson
Pump	0	0%	Kayla Collins
NDIR	0	0%	Christopher Chen
Preliminary Component Review and ...	0	0%	Christopher Chen, Joel Keddie, Kara Hewson, Kayla Collins
Concept Generation / Selection	**0h**	**0%**	
PDR Presentation Prep	0	0%	
Preliminary Design Review	0	0%	◆
FMEA	**0h**	**0%**	
Failure Modes	0	0%	Joel Keddie, Kara Hewson
Safety Risks	0	0%	Christopher Chen, Kayla Collins
Interim Design Review (IDR)	**0h**	**0%**	
Design Analysis	0	0%	Joel Keddie
Design for Manufacturing and Assem...	0	0%	Kayla Collins
CAD	0	0%	Kara Hewson



	Assigned	Progress	
Safety Risks	Christopher Chen, K	0%	
▾ Interim Design Review (IDR)		0%	
Design Analysis	Joel Keddie	0%	Joel Keddie
Design for Manufacturing and Assembly	Kayla Collins	0%	Kayla Collins
CAD	Kara Hewson	0%	Kara Hewson
Bill of Materials	Kayla Collins	0%	Kayla Collins
Layout Drawing	Christopher Chen	0%	Christopher Chen



	Assigned	Progress
Structural Prototype		0%
Rough Plan for Desired Software and DAQ	Kara Hewson, Kayla	0%
Rough Final List of Key Components	Christopher Chen, J	0%
Structural Prototype Testing	Christopher Chen, J	0%
Critical Design Review (CDR)		0%
CDR Rough Draft	Christopher Chen, J	0%
CDR Presentation	Christopher Chen, J	0%
CDR Final Report	Christopher Chen, J	0%
Critical Design Review		☐



Manufacturing		0%
Updating New Manufacturing Plans	Christopher Chen, J	0%
Hardware Manufacturing		0%
Purchase All Hardware for Building	Kayla Collins	0%
Building and Assembling Electrical Com...	Kayla Collins	0%
Connect Electronic Components Toget...	Kayla Collins	0%
Manufacture the Briefcase		0%
Calculation Coding		0%
Building and Assemble Heat Release R...	Kara Hewson	0%
Create Heat Release Rate Spreadsheet ...	Kara Hewson	0%
GUI Creation		0%
Build the GUI for Preview	Christopher Chen	0%
Read Data from Sensors	Christopher Chen, K	0%
Create Real Time Plot	Christopher Chen	0%
Create a Real Time Table	Joel Keddie, Kayla C	0%
Create a the Stop Function	Kara Hewson, Kayla	0%
Create Light Connection	Joel Keddie, Kara H	0%
Output data Excel	Joel Keddie, Kayla C	0%
Complete Build	Christopher Chen, J	☐

FRD Report		0%
Update Testing Plans	Joel Keddie, Kayla C	0%
Update Manufacturing Section	Christopher Chen	0%
Create Public Video	Christopher Chen, K	0%
Create Engineering Video	Joel Keddie, Kara H	0%
Update DVP, Risk, Operator's Manual	Joel Keddie	0%
Cost Feature Analysis	Christopher Chen	0%
Update FMEA	Kayla Collins	0%
Write Software Manufacturing Plan	Kara Hewson	0%
Update Pictures	Christopher Chen, J	0%

Appendix D: Idea Lists

User Friendly:

Automatically stores data on external device	Support structure	Instructional video
Emails data	Instructor signaling button	Interface with Outlook or Google Drive
That was easy button (feedback)	Quick to install or attach to system	Consistent in design
App that connects	Compact	Clear code commenting for back end
Other languages	Easy to see all buttons/labels	Racing stripes
Flame decals	Smokey the bear mascot	Clear directions
Multiple ports for data outputs	Animations	Soft colors
Sturdy, doesn't jitter apart	Automatically exports to excel or MATLAB, etc.	A good font
Large button	colorful	Clear plexiglass
Sleek smooth design	Easy to navigate through	Keep it clear, no clutter
Remote controls	Comic Sans	Explain figures
Fool proof	Search bar/help button	Concise code so it runs efficiently
Diagrams	Picture instructions	Local fluid dynamic indicators (yarn)
Pamphlet	Glossary	Minimal moving parts
Clean presentation	Color coded wiring	Datasheets for components easily accessible
Container to store all components that has a place for each component	Clear descriptions	Components list and how they interface with one another

Portability:

Wheels/cart	Pump alternative	Rechargeable batteries
Brief case	Portable power supply	Be able to switch between battery and plug
Easily assembled/disassembled for storage	Long hoses/cord so it doesn't have to be close to duct.	Packing efficiency
Compact components	suitcase	Carbon fiber case
Use tablet – remote form system	backpack	Combine sensors
Small laptop	Light components	Build our own sensors
Separate sensors + equipment	Levitate	Integrate into a golf cart
Develop an app	Sling to hold it	Handles

Air Extraction:

Bike pump	Increase flow of duct system (pitot tube design)	Hydraulic Piston
Fans	Heat rises, use cold air, dry ice, etc.	Osmosis (Filter)
Running to increase air flow	Water wheel suction with compressed air	Compressed air
Rotate the device	Pumps	Bladder system
Pull starter	Rocket	Hand crank
Weather balloon	Plunger	Create a pressure difference (u-tube manometer)

Appendix E: Decision Matrices

Programming Language Decision Matrix

	Weight	C++	Python	LabView	Java
Team Experience	3	3	0	1	1
Online libraries (large database)	4	3	2	2	3
Easy to learn and code in	4	4	2	3	2
Runs natively (on multiple devices)	3	4	4	2	2
User friendly compilers	2	3	3	4	3
Total	**Total**	**55**	34	37	35

CO2, CO, and Integrated Sensors Decision Matrix

	Weight	#1	#2	#3	#4	#5	#6	#7	#8	#9
Cost	4	1	1	1	4	4	3	1	3	1
Integrated Sensor	3	3	4	4	0	0	0	4	0	0
Response Time	3	2	3	4	2	1	3	3	2	3
Size	4	1	3	4	3	3	3	2	4	3
Weight	2	1	3	3	3	3	3	2	4	4
Arduino Compatibility	2	0	2	3	3	4	3	3	3	3
Total		25	47	**56**	46	45	45	40	48	39

Note: Each number denotes a specific sensor that is listed below.

#1 is the PureAire Dual O2/CO2 Monitor, 0-25% and 0-10,000 ppm.

#2 is the Andros 6511 OEM Gas Analyzer for Greenhouse Gas Detection and Monitoring.

#3 is the Crestline 7911/7912 OEM Gas Analyzer.

#4 is the Gravity: Analog Infrared CO2 Sensor for Arduino (0~5000 ppm) (MH-Z16).

#5 is the MH-Z14A NDIR CO2 Sensor.

#6 ExplorIR – W 100% CO2 Sensor (COZIR) or (SPRINTIR)

#7 is the Infrared CO Carbon Monoxide GasSense NDIR sensor.

#8 is the Alphasense 5,000 ppm Carbon Monoxide Smart EC Sensor

#9 Edinburgh Sensors Gascard NG

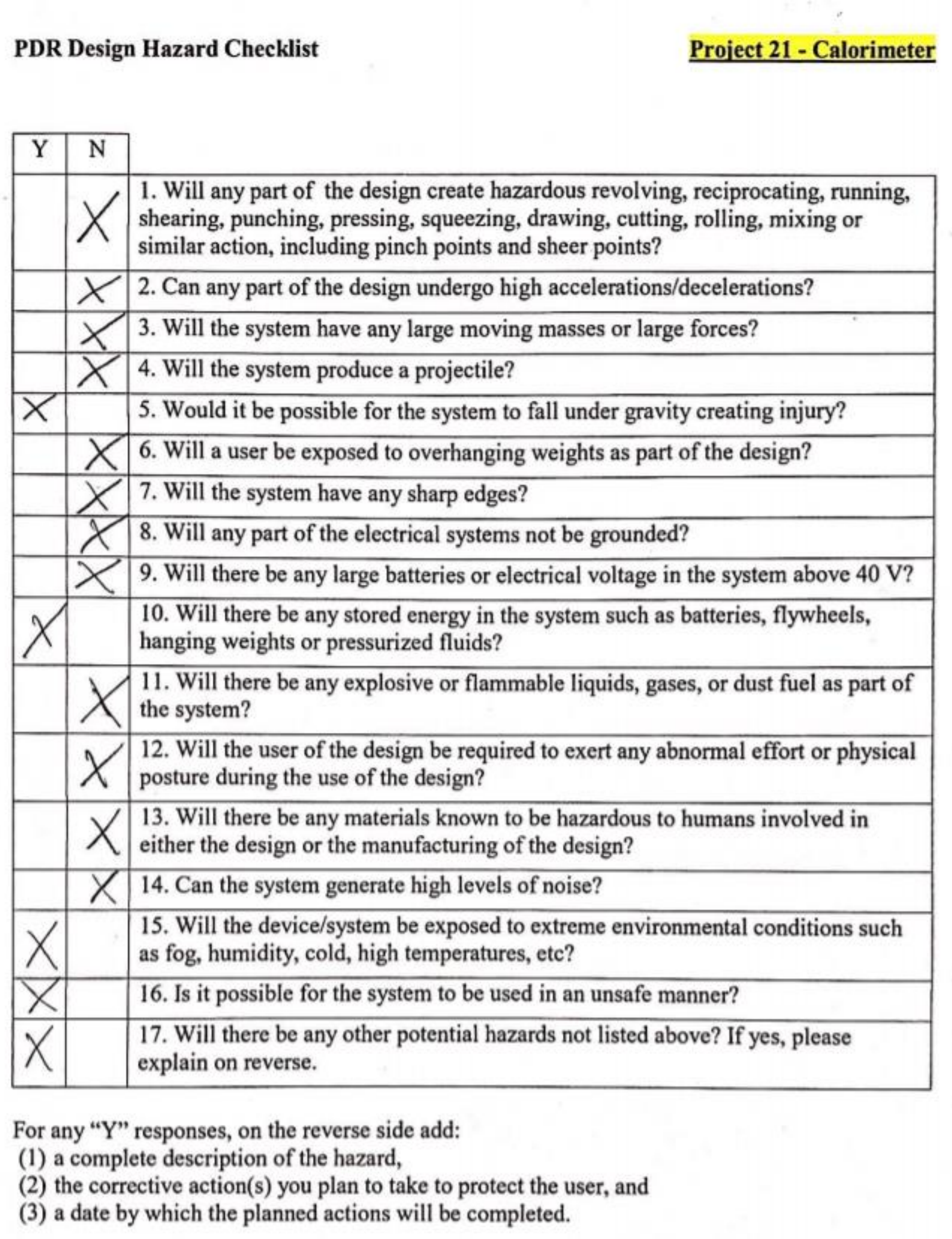
O2 Decision Matrix (Scale 1-5, 5 is best)

	Weight	AO2 CiTicel	Zirconia Bulb	Oxygen Optode	Laser Reader
Accuracy	5	5	2	2	3
Price	4	2	5	4	1
Weight	3	4	4	4	4
Compatibility	4	5	2	2	4
Power Requirements	2	3	4	4	3
	Total	**71**	58	54	53

Pump Decision Matrix (Scale 1-5, 5 is best)

	Weight	#1	#2	#3	#4	#5
Cost	2	3	5	5	1	1
Volume (size)	2	1	4	5	2	2
Weight	3	1	4	5	3	1
Flowrate	3	5	4	4	1	1
Accessibility	1	5	5	5	3	3
	Total	31	47	**52**	21	15

Appendix F: Design Hazard Checklist

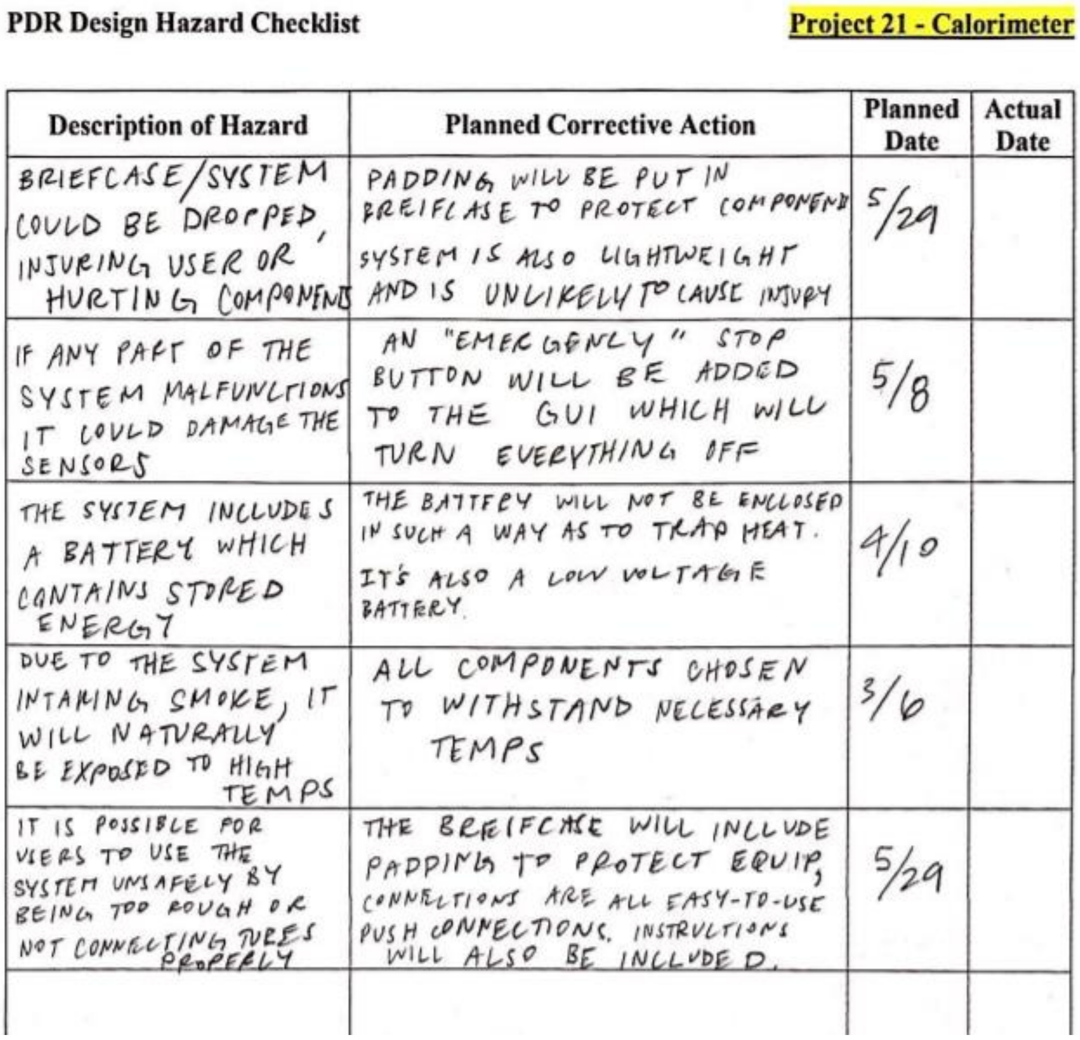


PDR Design Hazard Checklist

Project 21 - Calorimeter

Y	N	
	X	1. Will any part of the design create hazardous revolving, reciprocating, running, shearing, punching, pressing, squeezing, drawing, cutting, rolling, mixing or similar action, including pinch points and sheer points?
	X	2. Can any part of the design undergo high accelerations/decelerations?
	X	3. Will the system have any large moving masses or large forces?
	X	4. Will the system produce a projectile?
X		5. Would it be possible for the system to fall under gravity creating injury?
	X	6. Will a user be exposed to overhanging weights as part of the design?
	X	7. Will the system have any sharp edges?
	X	8. Will any part of the electrical systems not be grounded?
	X	9. Will there be any large batteries or electrical voltage in the system above 40 V?
X		10. Will there be any stored energy in the system such as batteries, flywheels, hanging weights or pressurized fluids?
	X	11. Will there be any explosive or flammable liquids, gases, or dust fuel as part of the system?
	X	12. Will the user of the design be required to exert any abnormal effort or physical posture during the use of the design?
	X	13. Will there be any materials known to be hazardous to humans involved in either the design or the manufacturing of the design?
	X	14. Can the system generate high levels of noise?
X		15. Will the device/system be exposed to extreme environmental conditions such as fog, humidity, cold, high temperatures, etc?
X		16. Is it possible for the system to be used in an unsafe manner?
X		17. Will there be any other potential hazards not listed above? If yes, please explain on reverse.

For any "Y" responses, on the reverse side add:
(1) a complete description of the hazard,
(2) the corrective action(s) you plan to take to protect the user, and
(3) a date by which the planned actions will be completed.

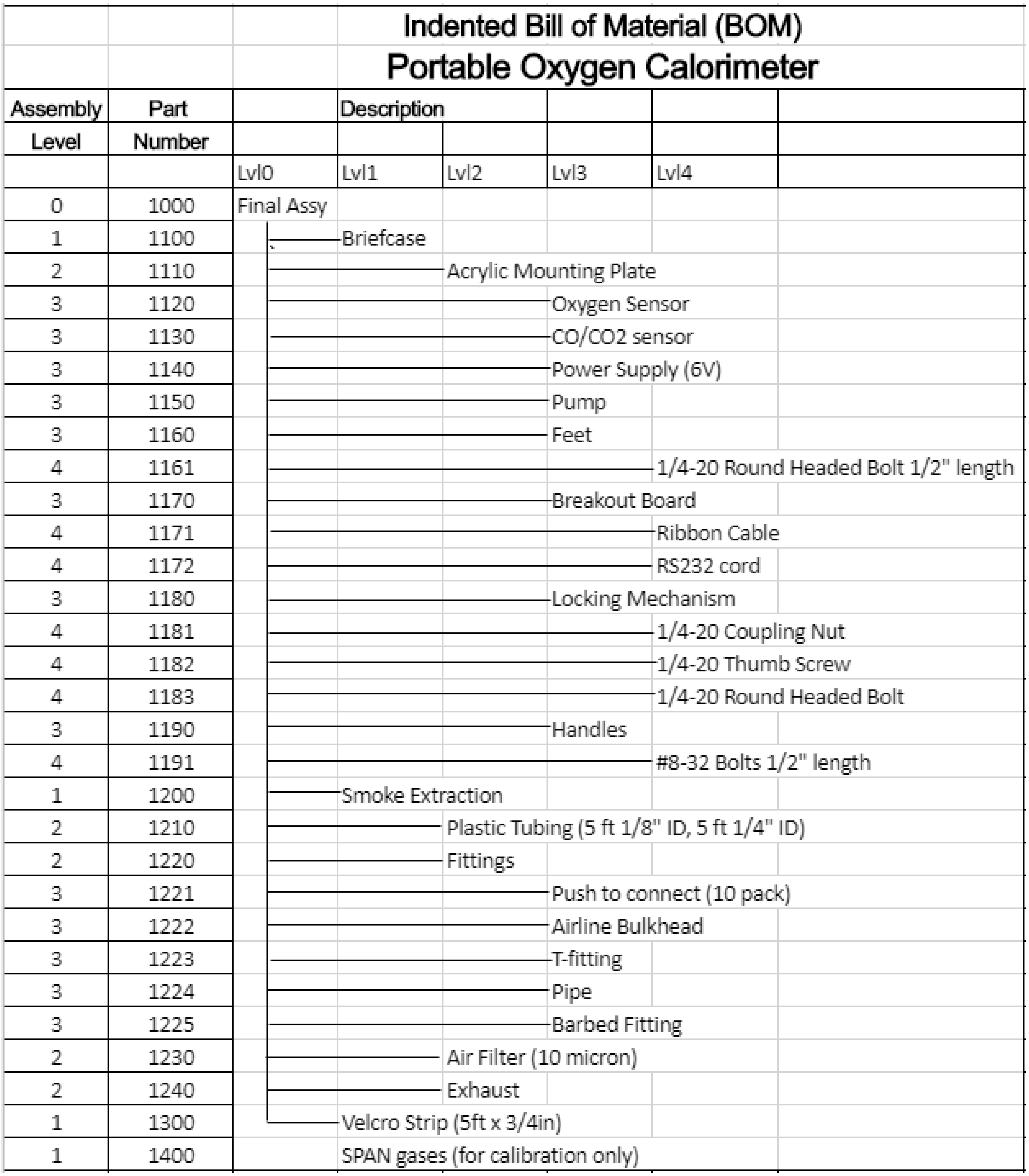


PDR Design Hazard Checklist

Project 21 - Calorimeter

Description of Hazard	Planned Corrective Action	Planned Date	Actual Date
BRIEFCASE/SYSTEM COULD BE DROPPED, INJURING USER OR HURTING COMPONENTS	PADDING WILL BE PUT IN BREIFCASE TO PROTECT COMPONENTS SYSTEM IS ALSO LIGHTWEIGHT AND IS UNLIKELY TO CAUSE INJURY	5/29	
IF ANY PART OF THE SYSTEM MALFUNCTIONS IT COULD DAMAGE THE SENSORS	AN "EMERGENCY" STOP BUTTON WILL BE ADDED TO THE GUI WHICH WILL TURN EVERYTHING OFF	5/8	
THE SYSTEM INCLUDES A BATTERY WHICH CONTAINS STORED ENERGY	THE BATTERY WILL NOT BE ENCLOSED IN SUCH A WAY AS TO TRAP HEAT. IT'S ALSO A LOW VOLTAGE BATTERY.	4/10	
DUE TO THE SYSTEM INTAKING SMOKE, IT WILL NATURALLY BE EXPOSED TO HIGH TEMPS	ALL COMPONENTS CHOSEN TO WITHSTAND NECESSARY TEMPS	3/6	
IT IS POSSIBLE FOR USERS TO USE THE SYSTEM UNSAFELY BY BEING TOO ROUGH OR NOT CONNECTING TUBES PROPERLY	THE BREIFCASE WILL INCLUDE PADDING TO PROTECT EQUIP, CONNECTIONS ARE ALL EASY-TO-USE PUSH CONNECTIONS. INSTRUCTIONS WILL ALSO BE INCLUDED.	5/29	

Appendix G: Indented Bill of Materials

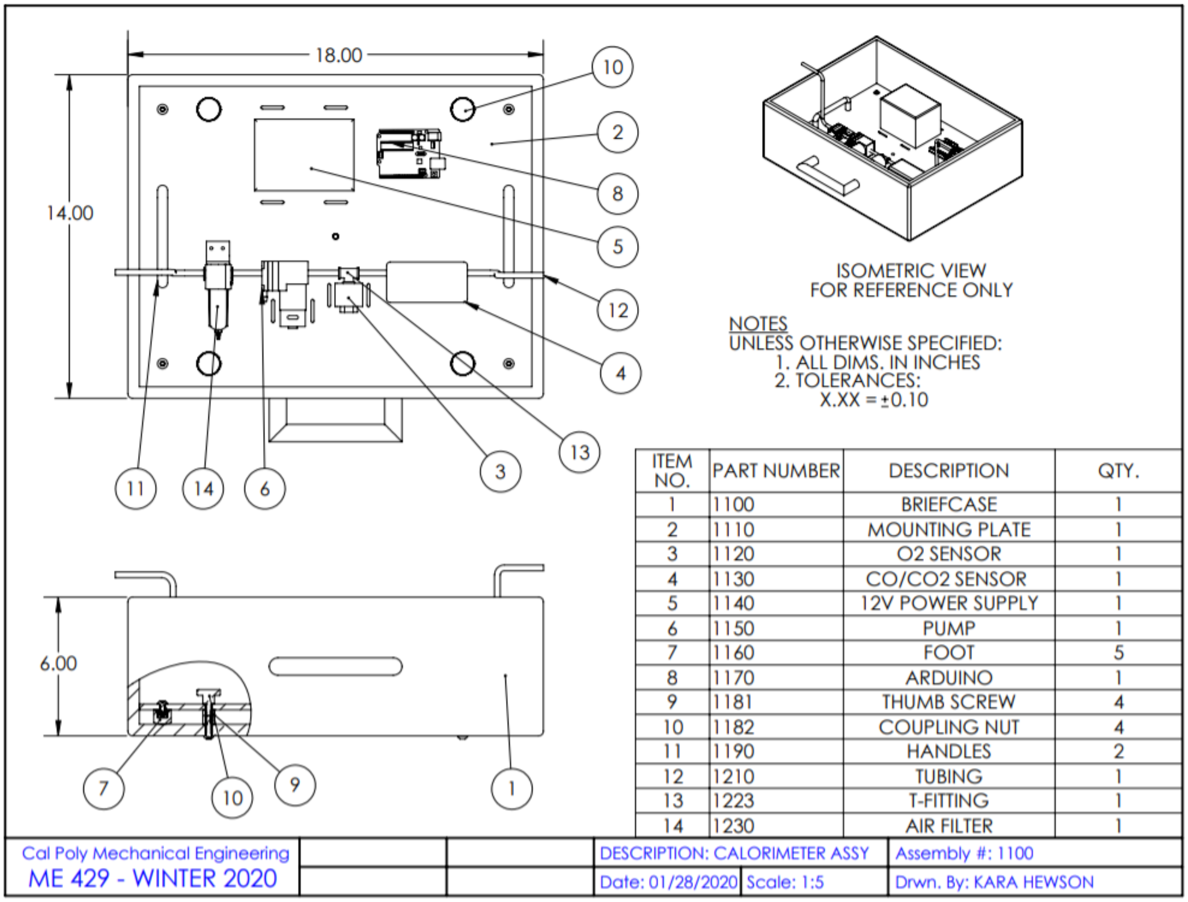


Indented Bill of Material (BOM)

Portable Oxygen Calorimeter

Assembly Level	Part Number		Description			
		Lvl0	Lvl1	Lvl2	Lvl3	Lvl4
0	1000	Final Assy				
1	1100		Briefcase			
2	1110			Acrylic Mounting Plate		
3	1120				Oxygen Sensor	
3	1130				CO/CO2 sensor	
3	1140				Power Supply (6V)	
3	1150				Pump	
3	1160				Feet	
4	1161					1/4-20 Round Headed Bolt 1/2" length
3	1170				Breakout Board	
4	1171					Ribbon Cable
4	1172					RS232 cord
3	1180				Locking Mechanism	
4	1181					1/4-20 Coupling Nut
4	1182					1/4-20 Thumb Screw
4	1183					1/4-20 Round Headed Bolt
3	1190				Handles	
4	1191					#8-32 Bolts 1/2" length
1	1200		Smoke Extraction			
2	1210			Plastic Tubing (5 ft 1/8" ID, 5 ft 1/4" ID)		
2	1220			Fittings		
3	1221				Push to connect (10 pack)	
3	1222				Airline Bulkhead	
3	1223				T-fitting	
3	1224				Pipe	
3	1225				Barbed Fitting	
2	1230			Air Filter (10 micron)		
2	1240			Exhaust		
1	1300		Velcro Strip (5ft x 3/4in)			
1	1400		SPAN gases (for calibration only)			

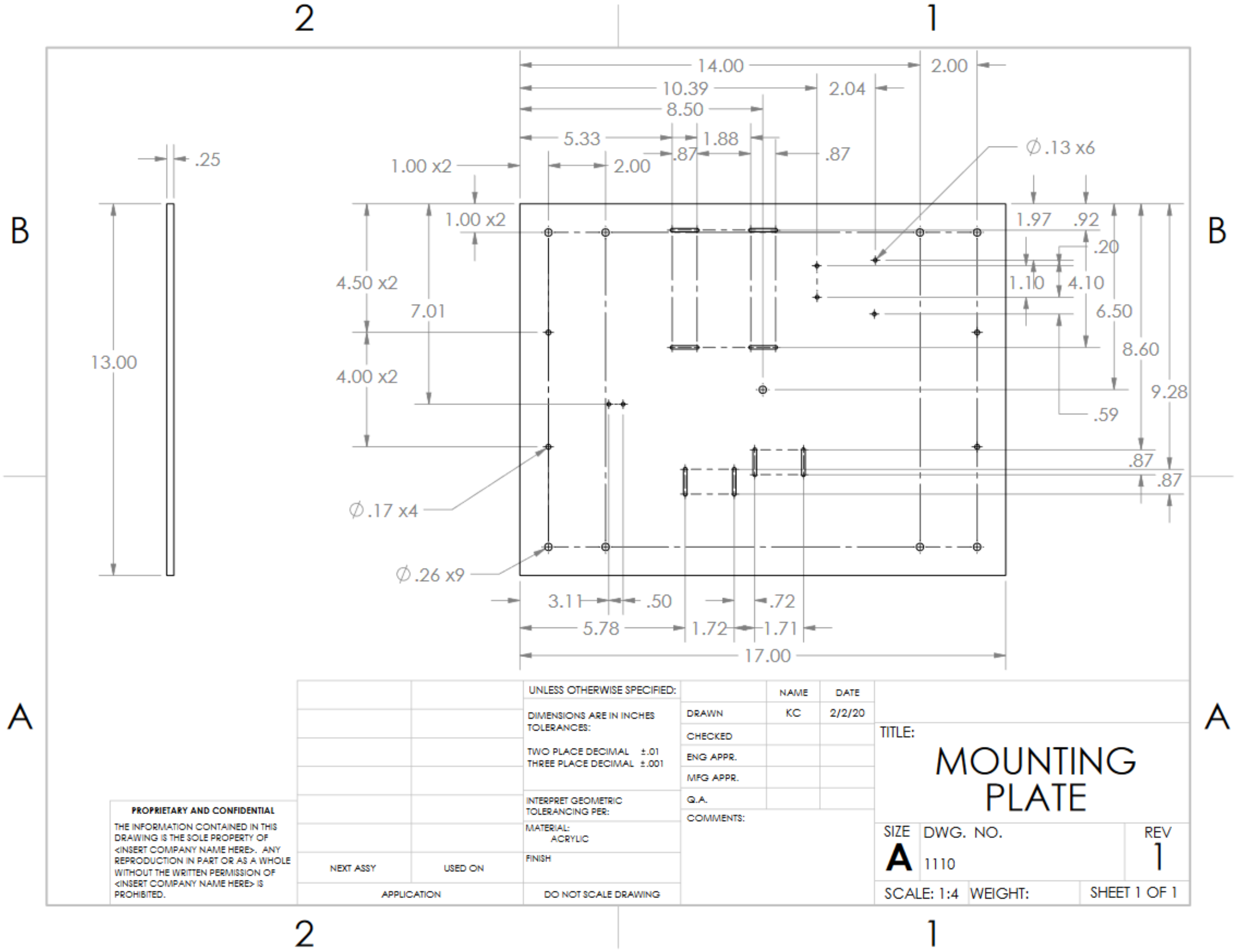
Appendix H: Drawing Package



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ±0.10

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1100	BRIEFCASE	1
2	1110	MOUNTING PLATE	1
3	1120	O2 SENSOR	1
4	1130	CO/CO2 SENSOR	1
5	1140	12V POWER SUPPLY	1
6	1150	PUMP	1
7	1160	FOOT	5
8	1170	ARDUINO	1
9	1181	THUMB SCREW	4
10	1182	COUPLING NUT	4
11	1190	HANDLES	2
12	1210	TUBING	1
13	1223	T-FITTING	1
14	1230	AIR FILTER	1

Cal Poly Mechanical Engineering			DESCRIPTION: CALORIMETER ASSY	Assembly #: 1100
ME 429 - WINTER 2020			Date: 01/28/2020 Scale: 1:5	Drwn. By: KARA HEWSON



UNLESS OTHERWISE SPECIFIED:
DIMENSIONS ARE IN INCHES
TOLERANCES:
TWO PLACE DECIMAL ±.01
THREE PLACE DECIMAL ±.001
INTERPRET GEOMETRIC TOLERANCING PER:
MATERIAL: ACRYLIC
FINISH
DO NOT SCALE DRAWING

NEXT ASSY
USED ON
APPLICATION

	NAME	DATE
DRAWN	KC	2/2/20
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

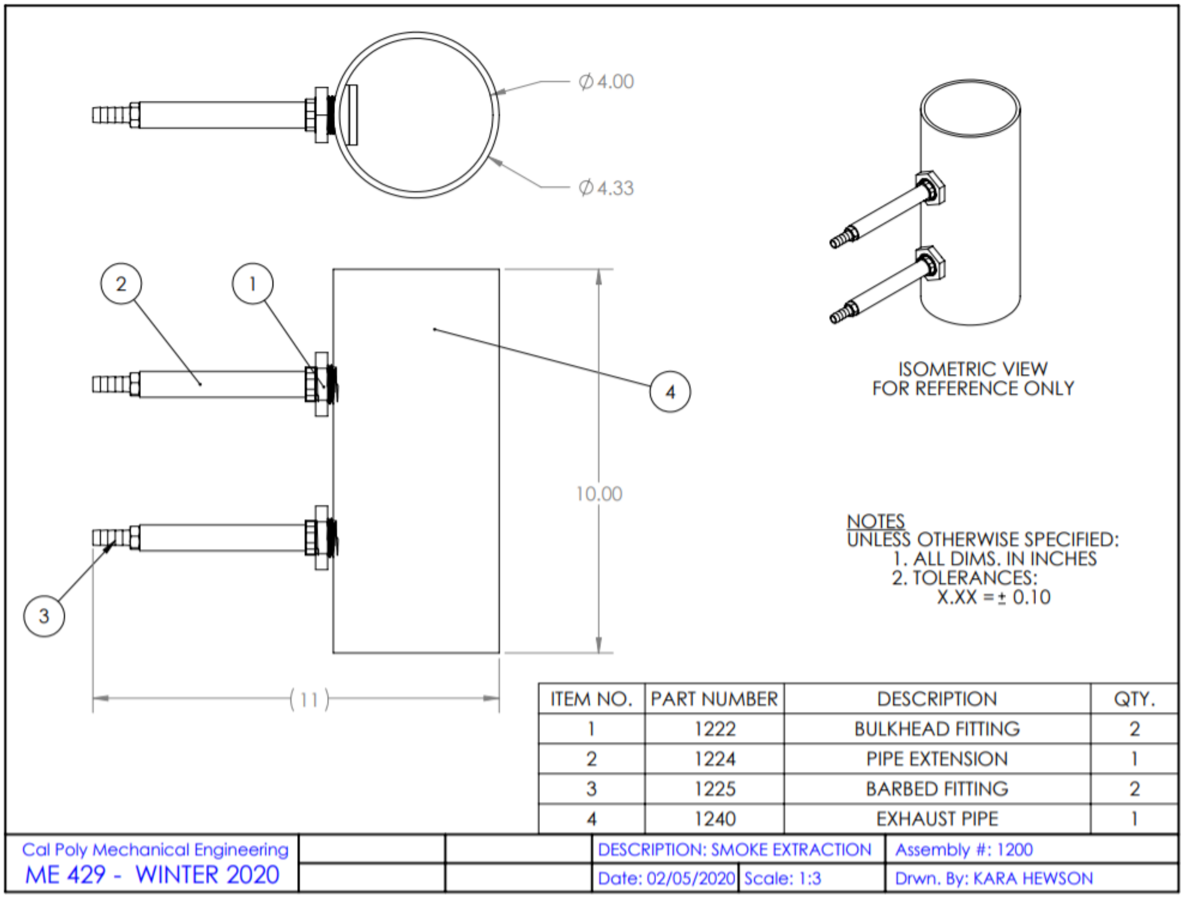
TITLE:

MOUNTING PLATE

SIZE A
DWG. NO. 1110
REV 1
SCALE: 1:4
WEIGHT:
SHEET 1 OF 1

PROPRIETARY AND CONFIDENTIAL

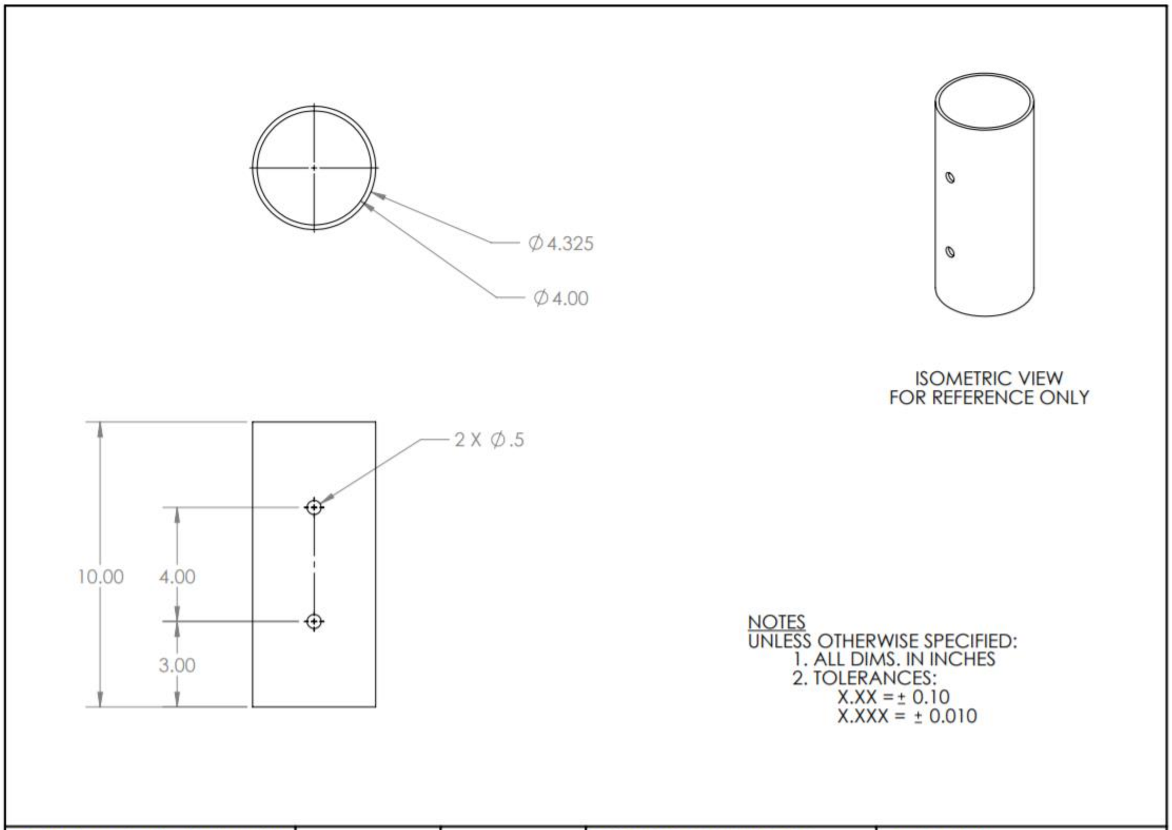
THE INFORMATION CONTAINED IN THIS DRAWING IS THE SOLE PROPERTY OF <INSERT COMPANY NAME HERE>. ANY REPRODUCTION IN PART OR AS A WHOLE WITHOUT THE WRITTEN PERMISSION OF <INSERT COMPANY NAME HERE> IS PROHIBITED.



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.10

ITEM NO.	PART NUMBER	DESCRIPTION	QTY.
1	1222	BULKHEAD FITTING	2
2	1224	PIPE EXTENSION	1
3	1225	BARBED FITTING	2
4	1240	EXHAUST PIPE	1

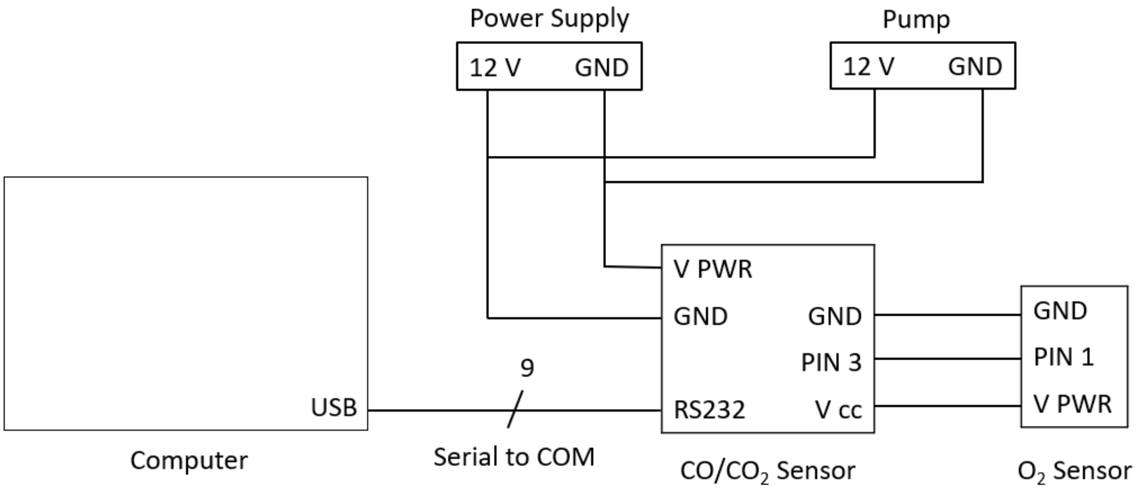
Cal Poly Mechanical Engineering
ME 429 - WINTER 2020
DESCRIPTION: SMOKE EXTRACTION
Assembly #: 1200
Date: 02/05/2020
Scale: 1:3
Drwn. By: KARA HEWSON



NOTES
UNLESS OTHERWISE SPECIFIED:
1. ALL DIMS. IN INCHES
2. TOLERANCES:
X.XX = ± 0.10
X.XXX = ± 0.010

Cal Poly Mechanical Engineering			DESCRIPTION: EXHAUST PIPE	Part #: 1240
ME 429 - WINTER 2020			Date: 02/06/2020 Scale: 1:4	Drwn. By: KARA HEWSON

Appendix I: Electrical Diagram



Appendix J: Pseudocode

Calculate before test:

Mole fraction of water vapor, $X_{H_2O}^{O}\ can\ be\ calculated\ by$:

$$X_{H_2O}^{O} = \frac{RH}{100}\frac{p_sT}{p_a}$$

RH is relative humidity, p_s is the saturation pressure of water vapor (read from a graph), T is the air temperature, and p_a is air pressure.

Calculate each time:

Collect CO, O_2, and CO_2 concentrations from sensors: $X_{CO}^{A}\ , X_{O_2}^{A}\ , and\ X_{CO_2}^{A}$

The oxygen depletion factor, ϕ, is the fraction of the incoming air that is fully depleted of its oxygen and is calculated using the equation below.

$$\phi = \frac{X_{O_2}^{A^o}(1 - X_{CO}^{A} - X_{CO_2}^{A}) - X_{O_2}^{A}(1 - X_{CO_2}^{A^o})}{(1 - X_{O_2}^{A} - X_{CO}^{A} - X_{CO_2}^{A})X_{O_2}^{A^o}}$$

Constants used in equation that do not change:

Mass flowrate, $\dot{m}_e$, will be calculated with a flowmeter after the system is put together

E_{CO}, the net heat release per unit mass of O_2 consumed for combustion of CO and CO_2 is 17.6MJ/kg of O_2

E, heat released per unit mass of O_2 consumed is 13.1 MJ/kg of O_2

$\alpha, a\ constant\ ratio\ is\ 1.105$

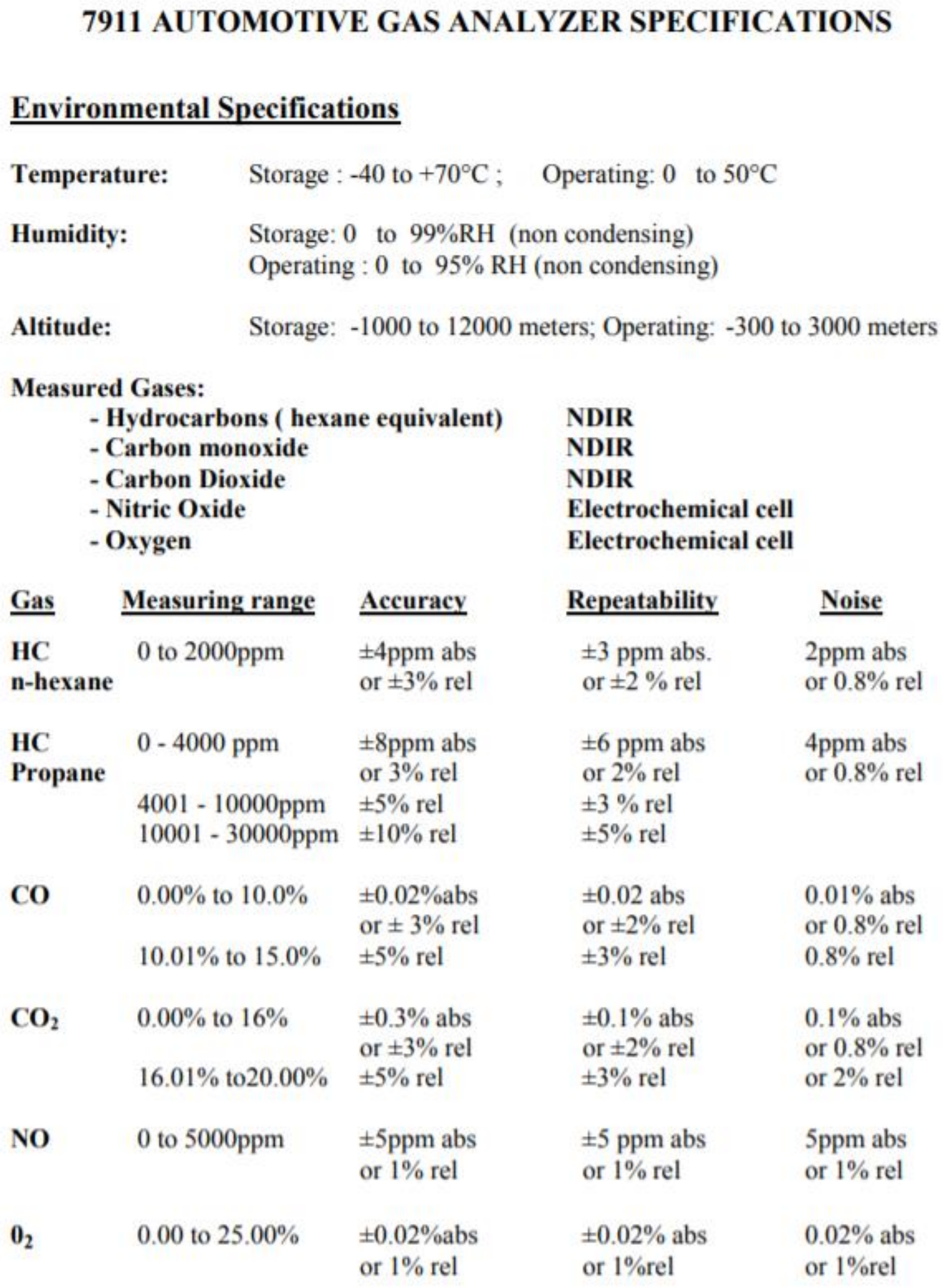
Molecular weights are known constants: $M_{O_2}\ and\ M_o$

Use values above and plug in to the heat rate equation below:

$$\dot{q} = \left[E\phi - (E_{CO} - E)\frac{1 - \phi}{2}\frac{X_{CO}^{A}}{X_{O_2}^{A}}\right]\frac{\dot{m}_e}{1 + \phi(\alpha - 1)}\frac{M_{O_2}}{M_o}(1 - X_{H_2O}^{O})X_{O_2}^{A^o}$$

Plot qdot against time in real time.

Appendix K: Product Literature for Purchased Parts



7911 AUTOMOTIVE GAS ANALYZER SPECIFICATIONS

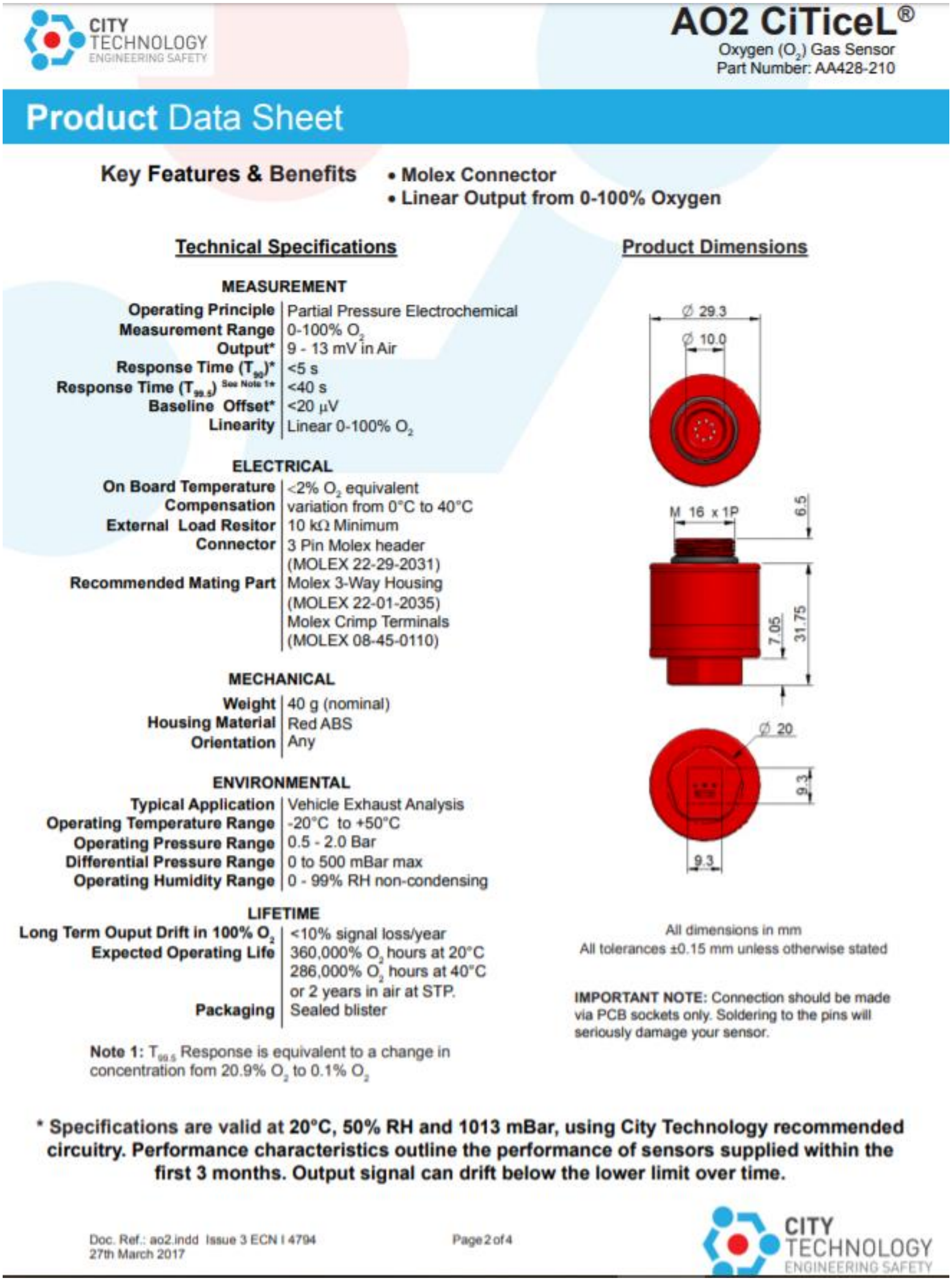
Environmental Specifications

Temperature:	Storage : -40 to +70°C ; Operating: 0 to 50°C
Humidity:	Storage: 0 to 99%RH (non condensing) Operating : 0 to 95% RH (non condensing)
Altitude:	Storage: -1000 to 12000 meters; Operating: -300 to 3000 meters

Measured Gases:

- Hydrocarbons (hexane equivalent)	**NDIR**
- Carbon monoxide	**NDIR**
- Carbon Dioxide	**NDIR**
- Nitric Oxide	**Electrochemical cell**
- Oxygen	**Electrochemical cell**

Gas	Measuring range	Accuracy	Repeatability	Noise
HC n-hexane	0 to 2000ppm	±4ppm abs or ±3% rel	±3 ppm abs. or ±2 % rel	2ppm abs or 0.8% rel
HC Propane	0 - 4000 ppm	±8ppm abs or 3% rel	±6 ppm abs or 2% rel	4ppm abs or 0.8% rel
	4001 - 10000ppm	±5% rel	±3 % rel	
	10001 - 30000ppm	±10% rel	±5% rel	
CO	0.00% to 10.0%	±0.02%abs or ± 3% rel	±0.02 abs or ±2% rel	0.01% abs or 0.8% rel
	10.01% to 15.0%	±5% rel	±3% rel	0.8% rel
CO_2	0.00% to 16%	±0.3% abs or ±3% rel	±0.1% abs or ±2% rel	0.1% abs or 0.8% rel
	16.01% to20.00%	±5% rel	±3% rel	or 2% rel
NO	0 to 5000ppm	±5ppm abs or 1% rel	±5 ppm abs or 1% rel	5ppm abs or 1% rel
0_2	0.00 to 25.00%	±0.02%abs or 1% rel	±0.02% abs or 1%rel	0.02% abs or 1%rel



CITY TECHNOLOGY
ENGINEERING SAFETY

AO2 CiTiceL®

Oxygen (O_2) Gas Sensor
Part Number: AA428-210

Product Data Sheet

Key Features & Benefits

- **Molex Connector**
- **Linear Output from 0-100% Oxygen**

Technical Specifications

MEASUREMENT

Operating Principle	Partial Pressure Electrochemical
Measurement Range	0-100% O_2
Output*	9 - 13 mV in Air
Response Time (T_{90})*	<5 s
Response Time ($T_{99.5}$) See Note 1*	<40 s
Baseline Offset*	<20 µV
Linearity	Linear 0-100% O_2

ELECTRICAL

On Board Temperature Compensation	<2% O_2 equivalent variation from 0°C to 40°C
External Load Resitor	10 kΩ Minimum
Connector	3 Pin Molex header (MOLEX 22-29-2031)
Recommended Mating Part	Molex 3-Way Housing (MOLEX 22-01-2035) Molex Crimp Terminals (MOLEX 08-45-0110)

MECHANICAL

Weight	40 g (nominal)
Housing Material	Red ABS
Orientation	Any

ENVIRONMENTAL

Typical Application	Vehicle Exhaust Analysis
Operating Temperature Range	-20°C to +50°C
Operating Pressure Range	0.5 - 2.0 Bar
Differential Pressure Range	0 to 500 mBar max
Operating Humidity Range	0 - 99% RH non-condensing

LIFETIME

Long Term Ouput Drift in 100% O_2	<10% signal loss/year
Expected Operating Life	360,000% O_2 hours at 20°C 286,000% O_2 hours at 40°C or 2 years in air at STP.
Packaging	Sealed blister

Note 1: $T_{99.5}$ Response is equivalent to a change in concentration fom 20.9% O_2 to 0.1% O_2

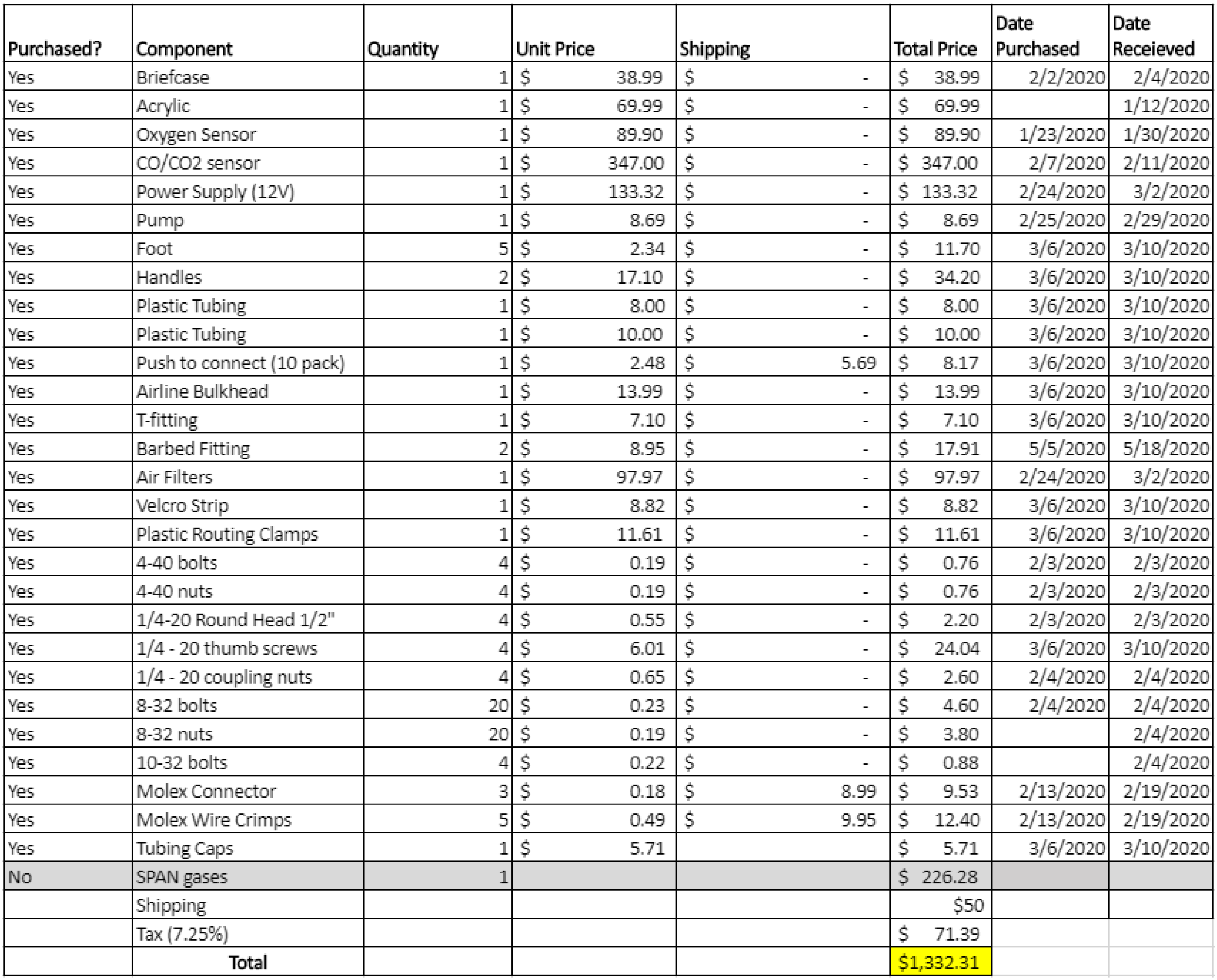
Product Dimensions

All dimensions in mm
All tolerances ±0.15 mm unless otherwise stated

IMPORTANT NOTE: Connection should be made via PCB sockets only. Soldering to the pins will seriously damage your sensor.

*** Specifications are valid at 20°C, 50% RH and 1013 mBar, using City Technology recommended circuitry. Performance characteristics outline the performance of sensors supplied within the first 3 months. Output signal can drift below the lower limit over time.**

Appendix L: Project Budget



Purchased?	Component	Quantity	Unit Price	Shipping	Total Price	Date Purchased	Date Receieved
Yes	Briefcase	1	$ 38.99	$ -	$ 38.99	2/2/2020	2/4/2020
Yes	Acrylic	1	$ 69.99	$ -	$ 69.99		1/12/2020
Yes	Oxygen Sensor	1	$ 89.90	$ -	$ 89.90	1/23/2020	1/30/2020
Yes	CO/CO2 sensor	1	$ 347.00	$ -	$ 347.00	2/7/2020	2/11/2020
Yes	Power Supply (12V)	1	$ 133.32	$ -	$ 133.32	2/24/2020	3/2/2020
Yes	Pump	1	$ 8.69	$ -	$ 8.69	2/25/2020	2/29/2020
Yes	Foot	5	$ 2.34	$ -	$ 11.70	3/6/2020	3/10/2020
Yes	Handles	2	$ 17.10	$ -	$ 34.20	3/6/2020	3/10/2020
Yes	Plastic Tubing	1	$ 8.00	$ -	$ 8.00	3/6/2020	3/10/2020
Yes	Plastic Tubing	1	$ 10.00	$ -	$ 10.00	3/6/2020	3/10/2020
Yes	Push to connect (10 pack)	1	$ 2.48	$ 5.69	$ 8.17	3/6/2020	3/10/2020
Yes	Airline Bulkhead	1	$ 13.99	$ -	$ 13.99	3/6/2020	3/10/2020
Yes	T-fitting	1	$ 7.10	$ -	$ 7.10	3/6/2020	3/10/2020
Yes	Barbed Fitting	2	$ 8.95	$ -	$ 17.91	5/5/2020	5/18/2020
Yes	Air Filters	1	$ 97.97	$ -	$ 97.97	2/24/2020	3/2/2020
Yes	Velcro Strip	1	$ 8.82	$ -	$ 8.82	3/6/2020	3/10/2020
Yes	Plastic Routing Clamps	1	$ 11.61	$ -	$ 11.61	3/6/2020	3/10/2020
Yes	4-40 bolts	4	$ 0.19	$ -	$ 0.76	2/3/2020	2/3/2020
Yes	4-40 nuts	4	$ 0.19	$ -	$ 0.76	2/3/2020	2/3/2020
Yes	1/4-20 Round Head 1/2"	4	$ 0.55	$ -	$ 2.20	2/3/2020	2/3/2020
Yes	1/4 - 20 thumb screws	4	$ 6.01	$ -	$ 24.04	3/6/2020	3/10/2020
Yes	1/4 - 20 coupling nuts	4	$ 0.65	$ -	$ 2.60	2/4/2020	2/4/2020
Yes	8-32 bolts	20	$ 0.23	$ -	$ 4.60	2/4/2020	2/4/2020
Yes	8-32 nuts	20	$ 0.19	$ -	$ 3.80		2/4/2020
Yes	10-32 bolts	4	$ 0.22	$ -	$ 0.88		2/4/2020
Yes	Molex Connector	3	$ 0.18	$ 8.99	$ 9.53	2/13/2020	2/19/2020
Yes	Molex Wire Crimps	5	$ 0.49	$ 9.95	$ 12.40	2/13/2020	2/19/2020
Yes	Tubing Caps	1	$ 5.71		$ 5.71	3/6/2020	3/10/2020
No	SPAN gases	1			$ 226.28		
	Shipping				$50		
	Tax (7.25%)				$ 71.39		
	Total				$1,332.31		

Appendix M: Failure Mode and Effects Analysis

System / Function	Potential Failure Mode	Potential Effects of the Failure Mode	Severity	Potential Causes of the Failure Mode	Current Preventative Activities	Occurence	Current Detection Activities	Detection	Priority	Recommended Action(s)	Responsibility & Target Completion Date	Actions Taken	Severity	Occurence	Criticality
Power System/ power sensors	Doesn't supply power	Sensor cannot collect data	5	1) Battery is unplugged or removed from the system. 2) A short in the system.	A diagram of the system will be in manual	2	Can see it is unplugged Use multimeter	2	20						
Air Extraction/ extract smoke from exhaust duct	Too high or too little flow rate to draw in smoke	Sensor cannot collect data acurately	4	1) Pump is using too much power 2) System is not hooked up correctly	A diagram of the system will be in manual	3	Can check manual if not hooked up correctly	1	12						
	System leaks	a) Sensor cannot read data b) Smoke gets into the air	4	1) Hose is damaged from something hitting it or due to wear 2) Pump is damaged 3) System not installed correctly	Ensure the fittings are connected properly	2	Can see damage and incorrect setup	1	8						
	Soot filter lets particles through	Particles clog the pump and/or sensor	5	1) Filter isn't replaced as often as it should be	Manual will have information on how often the filter needs to be replaced	2	Clear plastic lines, able to visually see smoke particles	1	10						
Data Collection System / measure the amount of CO, CO2, and O2 in extracted smoke	Calibrates incorrectly	Readings will be inaccurate	6	1) System isn't calibrated when data is collected. 2) System is calibrated to incorrect smoke readings	Insturctions on how to callibrate the system will be provided in manual	2	Known heat release rate of fire to compare values	5	60	Spend time calibrating system with Dr. Emberley and assess what may cause the system to become uncalibrated	Kayla, 4/30/20	The data was calibrated to the published data the Dr. Emberley had sent. However, due to Covid-19 we vould only rely on published data and were unable to do real testing.	6	1	30
	Sensor stops working	Data will not be collected	4	1) Sensors have been damaged from impact 2) Soot residue in sensor causes it to stop functioning	Handles on the housing will help the user be able to carry the system easier and instructions on when to change the soot filter are provided in manual	4	Real time output of system on laptop screen	3	48						
Software System / display data and store it in an excel file	Program stops working (data isn't displayed)	User cannot get data from experiment	5	1) Issue in the code 2) System not turned on properly 3) Computer crashes	1) Review Code 2) Set starting processes/standard	8	Laptop screen will not display real time results	4	160	Thoroughly debug code, run many tests to figure out what may cause issues in the code, comment code to make revision easier	Kara and Chris, 4/15/2020	The software has been throughouly checked for bugs that interfere with the working process.	5	4	80
	Files aren't stored and exported	User isn't able to get a copy of the data from the experiment	5	1) Issue in the code 2) Computer crashes	1) Ensure code functions 2) Proper connection with computer	7	See file location in storage	4	140	Have very well documented code and written out manual for other users to understand how it works and what possibly went wrong. Also do a lot of testing with the program to check for bugs/potential software issues that could happen	Joel, 4/15/2020	The software now has the function to export the data to an excel file after the sensor reads the data. It is also stored as a text file in the host program archive.	5	4	80
Housing / keep everything together	The mount or handles break	a) Sharp edges b) Hardware is damaged c) User is injured	6	1) System is dropped 2) Something was dropped on the system or another impact load	1) Sand down the exterior of the system 2) Make sure safety procedures are known	5	Can see damage to housing Can test components to see if they are damaged	1	30						

Appendix N: Design Verification Plan

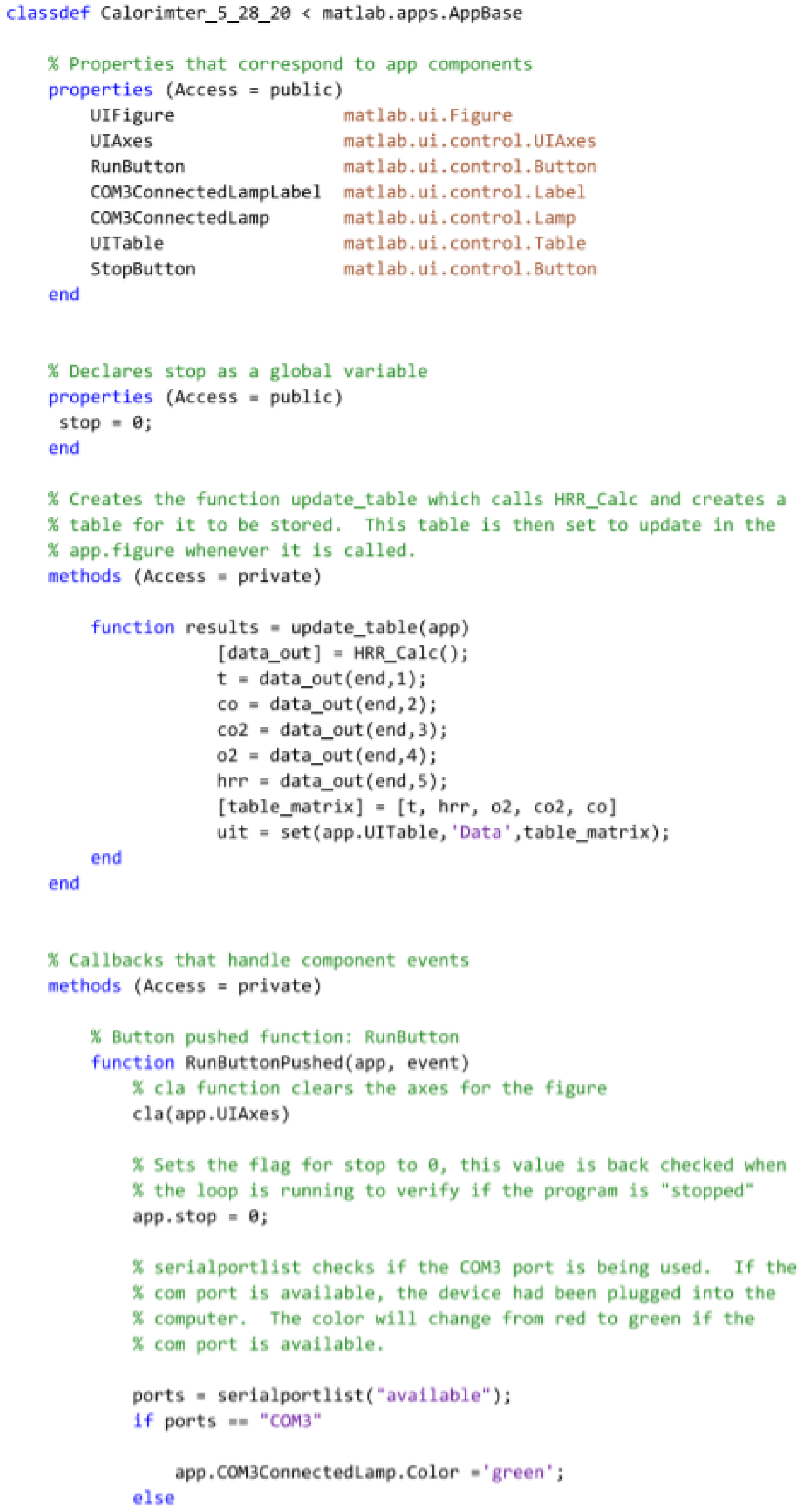
Senior Project DVP&R

Date: 2/4/2020	Team: Portable Calorimeter	Sponsor: Dr. Emberley	Description of System: Portable device to measure the heat release rate of a combustion reaction	DVP&R Engineer: Joel Keddie

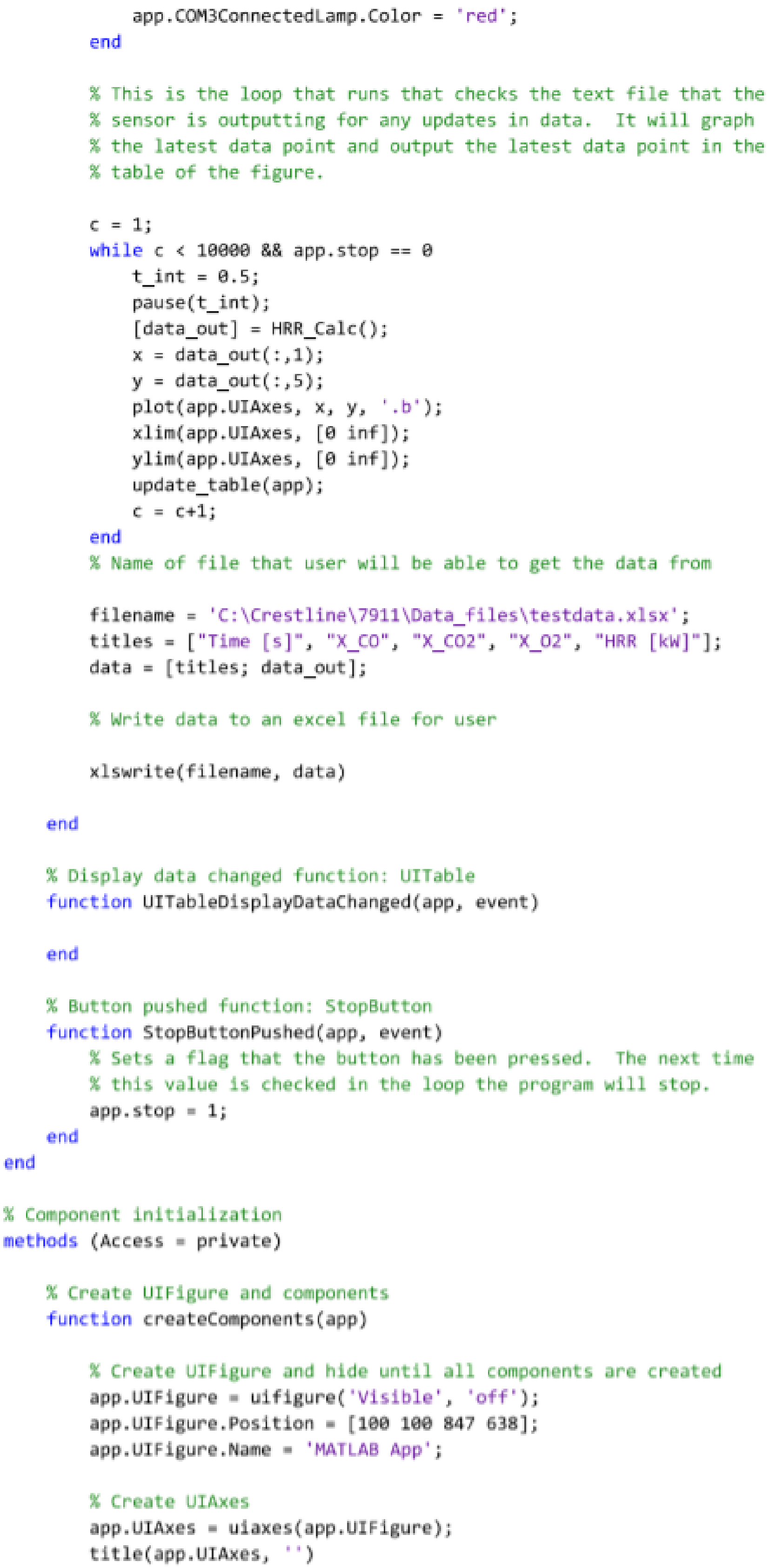
TEST PLAN										TEST REPORT			
Item No	Specification #	Test Description	Acceptance Criteria	Test Responsibility	Test Stage	SAMPLES		TIMING		TEST RESULTS			NOTES
						Quantity	Type	Start date	Finish date	Test Result	Quantity Pass	Quantity Fail	
1	Smoke Extraction System	No smoke leaks from the system, with flowrate between 0.5 liters/min and 1.5 liters/min	flowrate between 0.5 liters/min and 1.5 liters/min	Joel	FP	1	Sub	4/7/2020	N/A				Will need to be completed later due to COVID-19
2	Dimensions	Measure the dimensions of the calorimeter.	Max of 24 in long by 24 in wide by 12 in tall	Kayla	CP, SP, FP	1	Sys	2/4/2020	3/10/2020	Success			Fits inside briefcase
3	Heat Release Values	Calibration accuracy of the calorimeter for heat release rate from a known sample.	Less than 5% difference	Kara	FP	1	Sys	4/7/2020	5/20/2020	Success	Less than 2% difference (Excel data)		MATLAB code works with known Excel values, haven't tested with actual combustion
4	User Testing Survey	Survey for Ease of Use and Test Response of the calorimeter	4 out of 5 people systems find the system easy to use	Chris	FP	1	Sys	4/7/2020	N/A				Will need to be completed later due to COVID-19
5	Thermal Analysis	Calculated results match experimental (measure with thermocouple)	+/- 5%	Joel	FP	1	Sys	4/7/2020	N/A				Will need to be completed later due to COVID-19
6	Software Testing	Run the code and see how long it takes to run.	Less than 10 seconds	Kara	FP	1	Sub	4/7/2020	5/17/2020	Success	2 seconds		MATLAB begins to run in about 2 seconds
7	Testing with other lab devices or apparatuses	Hook up the device to the fume hood in the lab and ensure it's compatible with the setup.	Is compatible	Kayla	FP	1	Sys	4/14/2020	N/A				Will need to be completed later due to COVID-19
8	Travel Testing	Able to withstand impacts and bumps (from travel)	Withstands bumps	Joel	SP, FP	1	Sys	4/7/2020	N/A				Will need to be completed later due to COVID-19
9	Structural Integrity Factor	Apply a 50lb load on the device and record the deflection.	Less than 3 inch deflection	Kayla	SP, FP	1	Sys	2/4/2020	3/8/2020	Success	0.18 in	1 in	Aluminium case does not significantly deform under loads
10	Weight	Measure the weight of the device on a scale.	Less than 15 lbs	Kara	CP, SP, FP	1	Sys	2/4/2020	4/15/2020	Success	12 lbs		Under 15 lbs
11	Electrical Wiring Safety	Take a multimeter and record voltage across every connection.	No shorts, wires are properly insulated	Chris	FP	1	Sys	4/7/2020	N/A				Will need to be completed later due to COVID-19
12	Heat Exposure	Measure the temperature of the fittings atubing close to the exhaust.	Tubing is safe to touch and components are under allowable temperatures	Chris	FP	1	Sys	4/7/2020	N/A				Will need to be completed later due to COVID-19

Appendix O: MATLAB Code

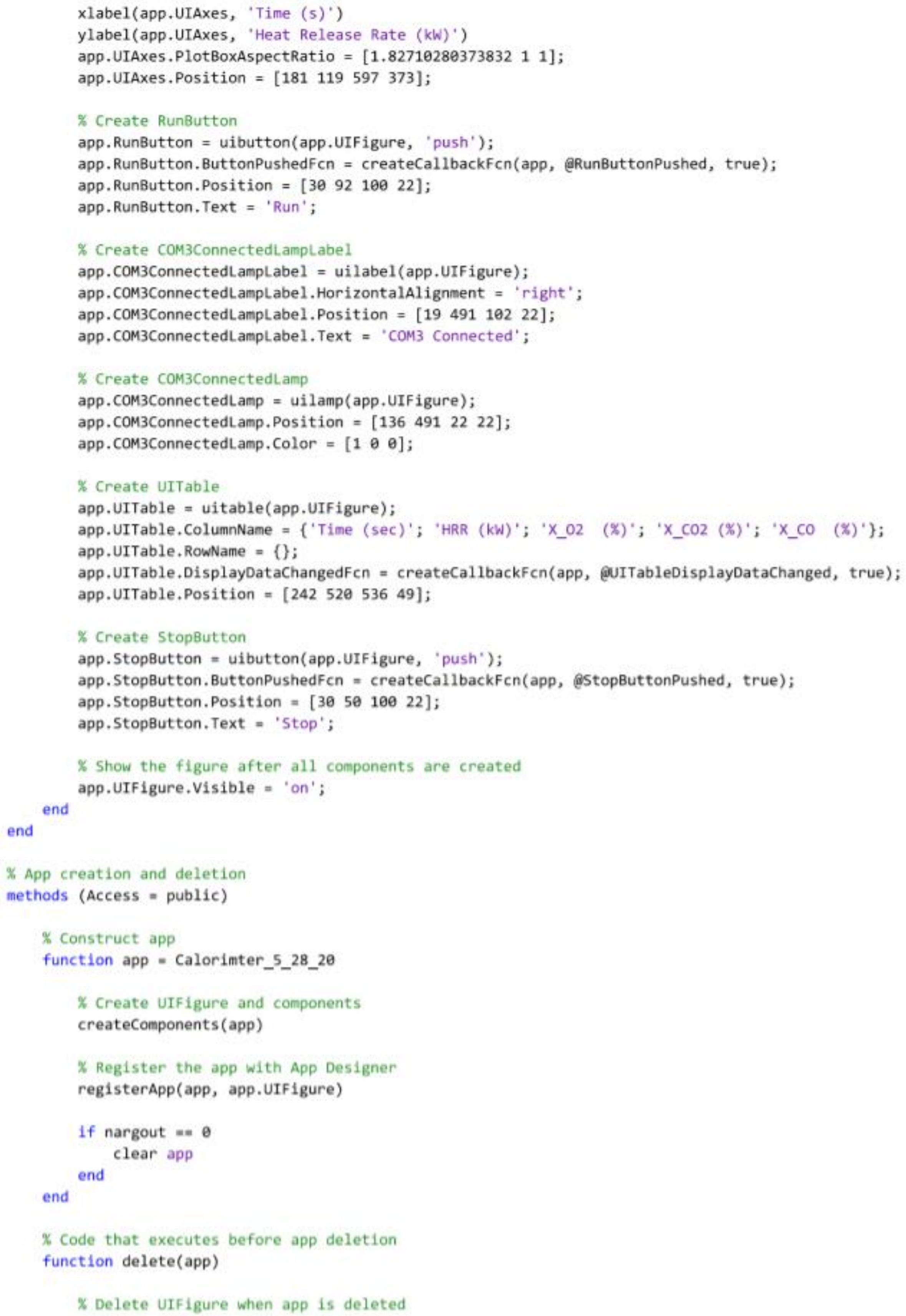
GUI Code (MATLAB's App Designer):



```
classdef Calorimter_5_28_20 < matlab.apps.AppBase

    % Properties that correspond to app components
    properties (Access = public)
        UIFigure                matlab.ui.Figure
        UIAxes                  matlab.ui.control.UIAxes
        RunButton               matlab.ui.control.Button
        COM3ConnectedLampLabel  matlab.ui.control.Label
        COM3ConnectedLamp       matlab.ui.control.Lamp
        UITable                 matlab.ui.control.Table
        StopButton              matlab.ui.control.Button
    end


    % Declares stop as a global variable
    properties (Access = public)
     stop = 0;
    end

    % Creates the function update_table which calls HRR_Calc and creates a
    % table for it to be stored.  This table is then set to update in the
    % app.figure whenever it is called.
    methods (Access = private)

        function results = update_table(app)
                    [data_out] = HRR_Calc();
                    t = data_out(end,1);
                    co = data_out(end,2);
                    co2 = data_out(end,3);
                    o2 = data_out(end,4);
                    hrr = data_out(end,5);
                    [table_matrix] = [t, hrr, o2, co2, co]
                    uit = set(app.UITable,'Data',table_matrix);
        end
    end


    % Callbacks that handle component events
    methods (Access = private)

        % Button pushed function: RunButton
        function RunButtonPushed(app, event)
            % cla function clears the axes for the figure
            cla(app.UIAxes)

            % Sets the flag for stop to 0, this value is back checked when
            % the loop is running to verify if the program is "stopped"
            app.stop = 0;

            % serialportlist checks if the COM3 port is being used.  If the
            % com port is available, the device had been plugged into the
            % computer.  The color will change from red to green if the
            % com port is available.

            ports = serialportlist("available");
            if ports == "COM3"

                app.COM3ConnectedLamp.Color ='green';
            else
```



```
            app.COM3ConnectedLamp.Color = 'red';
        end

        % This is the loop that runs that checks the text file that the
        % sensor is outputting for any updates in data.  It will graph
        % the latest data point and output the latest data point in the
        % table of the figure.

        c = 1;
        while c < 10000 && app.stop == 0
            t_int = 0.5;
            pause(t_int);
            [data_out] = HRR_Calc();
            x = data_out(:,1);
            y = data_out(:,5);
            plot(app.UIAxes, x, y, '.b');
            xlim(app.UIAxes, [0 inf]);
            ylim(app.UIAxes, [0 inf]);
            update_table(app);
            c = c+1;
        end
        % Name of file that user will be able to get the data from

        filename = 'C:\Crestline\7911\Data_files\testdata.xlsx';
        titles = ["Time [s]", "X_CO", "X_CO2", "X_O2", "HRR [kW]"];
        data = [titles; data_out];

        % Write data to an excel file for user

        xlswrite(filename, data)

    end

    % Display data changed function: UITable
    function UITableDisplayDataChanged(app, event)

    end

    % Button pushed function: StopButton
    function StopButtonPushed(app, event)
        % Sets a flag that the button has been pressed.  The next time
        % this value is checked in the loop the program will stop.
        app.stop = 1;
    end
end

% Component initialization
methods (Access = private)

    % Create UIFigure and components
    function createComponents(app)

        % Create UIFigure and hide until all components are created
        app.UIFigure = uifigure('Visible', 'off');
        app.UIFigure.Position = [100 100 847 638];
        app.UIFigure.Name = 'MATLAB App';

        % Create UIAxes
        app.UIAxes = uiaxes(app.UIFigure);
        title(app.UIAxes, '')
```



```
        xlabel(app.UIAxes, 'Time (s)')
        ylabel(app.UIAxes, 'Heat Release Rate (kW)')
        app.UIAxes.PlotBoxAspectRatio = [1.82710280373832 1 1];
        app.UIAxes.Position = [181 119 597 373];

        % Create RunButton
        app.RunButton = uibutton(app.UIFigure, 'push');
        app.RunButton.ButtonPushedFcn = createCallbackFcn(app, @RunButtonPushed, true);
        app.RunButton.Position = [30 92 100 22];
        app.RunButton.Text = 'Run';

        % Create COM3ConnectedLampLabel
        app.COM3ConnectedLampLabel = uilabel(app.UIFigure);
        app.COM3ConnectedLampLabel.HorizontalAlignment = 'right';
        app.COM3ConnectedLampLabel.Position = [19 491 102 22];
        app.COM3ConnectedLampLabel.Text = 'COM3 Connected';

        % Create COM3ConnectedLamp
        app.COM3ConnectedLamp = uilamp(app.UIFigure);
        app.COM3ConnectedLamp.Position = [136 491 22 22];
        app.COM3ConnectedLamp.Color = [1 0 0];

        % Create UITable
        app.UITable = uitable(app.UIFigure);
        app.UITable.ColumnName = {'Time (sec)'; 'HRR (kW)'; 'X_O2  (%)'; 'X_CO2 (%)'; 'X_CO  (%)'};
        app.UITable.RowName = {};
        app.UITable.DisplayDataChangedFcn = createCallbackFcn(app, @UITableDisplayDataChanged, true);
        app.UITable.Position = [242 520 536 49];

        % Create StopButton
        app.StopButton = uibutton(app.UIFigure, 'push');
        app.StopButton.ButtonPushedFcn = createCallbackFcn(app, @StopButtonPushed, true);
        app.StopButton.Position = [30 50 100 22];
        app.StopButton.Text = 'Stop';

        % Show the figure after all components are created
        app.UIFigure.Visible = 'on';
    end
end

% App creation and deletion
methods (Access = public)

    % Construct app
    function app = Calorimter_5_28_20

        % Create UIFigure and components
        createComponents(app)

        % Register the app with App Designer
        registerApp(app, app.UIFigure)

        if nargout == 0
            clear app
        end
    end

    % Code that executes before app deletion
    function delete(app)

        % Delete UIFigure when app is deleted
```

```
            delete(app.UIFigure)
        end
    end
end
```

Heat Release Rate Calculation (MATLAB Script):

Contents

```
function [data_out] = HRR_Calc()
```

```
clear;
format short;
```

Constant Variables

```
E_co = 17.6;     % Net Heat Release Per Unit O2       [kJ/g of O2]
E = 13.1;        % Heat Released Per Unit of Mass O2  [kJ/g]
M_O2 = 32;       % Molecular Weight of O2             [g/mol]
M_N2 = 28.9;     % Molecular Weight of N2             [g/mol]
alpha = 1.105;   % Expansion Factor                   [-]
m_dot = 24*10^3; % Flowrate of the Duct               [g/s]
```

Calculating Mole Fraction of Water Vapor

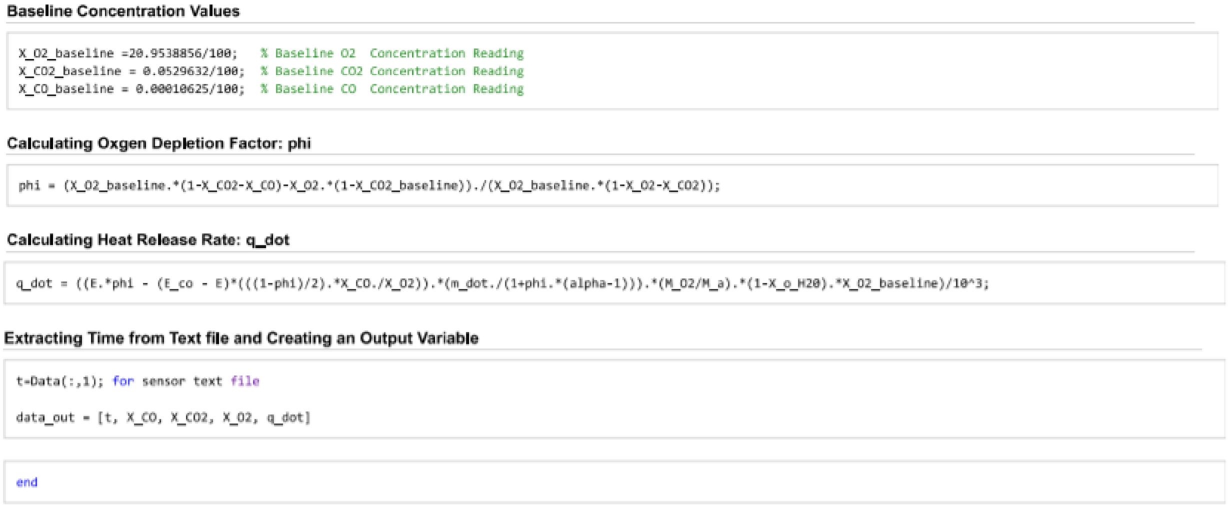
```
RH = 34;                 % Relative Humidity   [%]
p_s = 3156.2;           % Saturation pressure [Pa]
T_air = 25;              % Air temperature     [C]
p_air = 101000;          % Air pressure        [Pa]

X_o_H20 = RH*p_s/(100*p_air);    % Mole fraction of water vapor
```

Calculating the Molecular Weight of the Incoming Air

```
M_dry = 29;   % Molecular weight of dry air [kg/kmol]
M_H20 = 18;   % Molecular weight of H20 [kg/kmol]

M_a = M_dry*(1-X_o_H20)-M_H20*X_o_H20; % Molecular weight of the incoming air
```

Concentration Readings from Sensors

```
Data = xlsread('material_data'); % Read Excel file from known data
% 1st column: Oxygen Concentration
% 2nd column: Carbon Dioxide Concentration
% 3rd column: Carbon Monoxide Concentration

X_O2 = Data(:,5)/100;  % O2  Concentration  [%]
X_CO2 = Data(:,6)/100; % CO2 Concentration  [%]
X_CO = Data(:,7)/100;  % CO  Concentration  [%]


Data = readtable('data'); % Read Textfile from Crestline Sensor
Data = table2array(Data);
% 1st column: Oxygen Concentration
% 2nd column: Carbon Dioxide Concentration
% 3rd column: Carbon Monoxide Concentration

X_O2 = Data(:,6)/100;  % O2  Concentration  [%]
X_CO2 = Data(:,4)/100; % CO2 Concentration  [%]
X_CO = Data(:,5)/100;  % CO  Concentration  [%]
```



Appendix P: Test Procedures

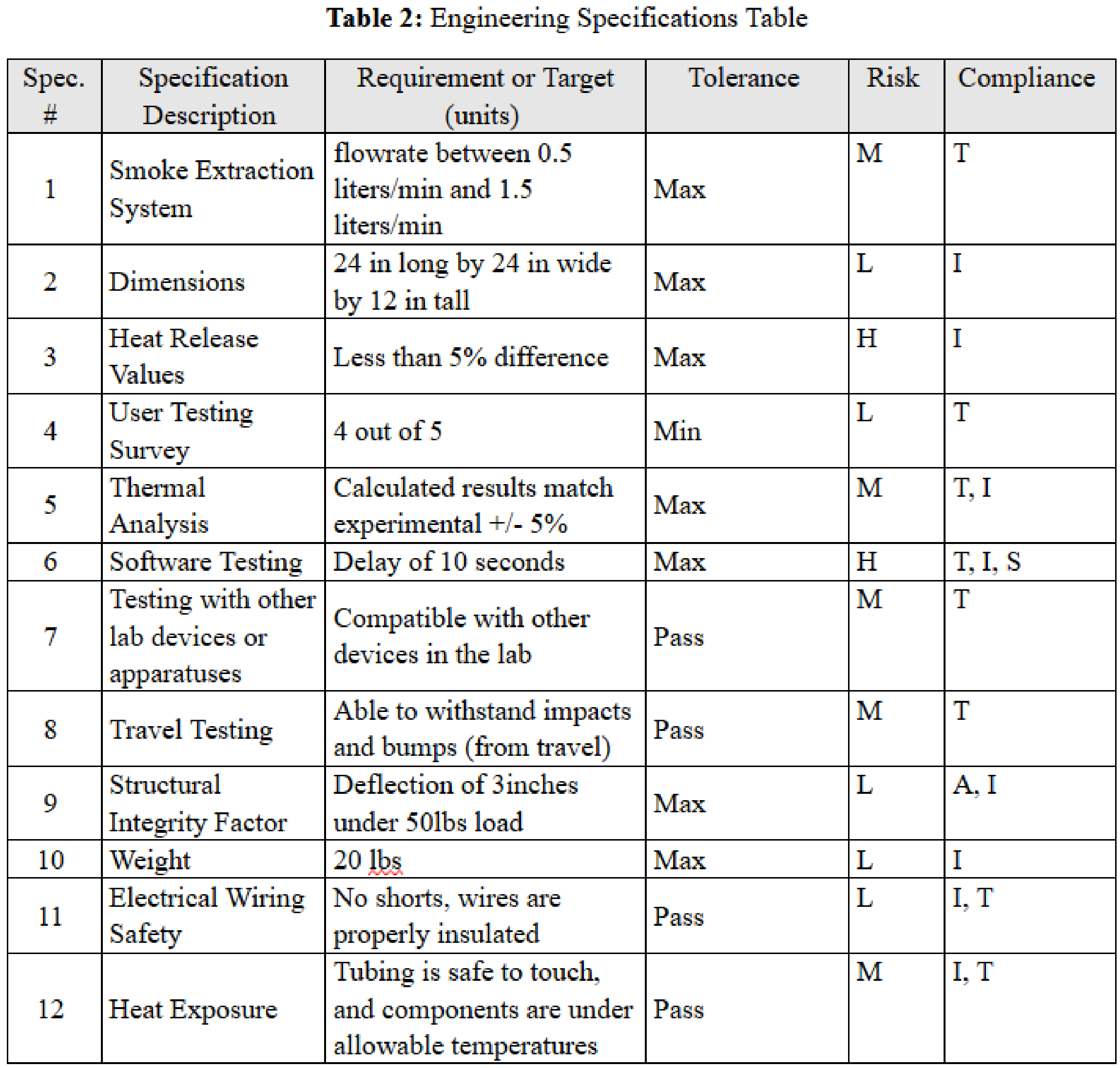


Table 2: Engineering Specifications Table

Spec. #	Specification Description	Requirement or Target (units)	Tolerance	Risk	Compliance
1	Smoke Extraction System	flowrate between 0.5 liters/min and 1.5 liters/min	Max	M	T
2	Dimensions	24 in long by 24 in wide by 12 in tall	Max	L	I
3	Heat Release Values	Less than 5% difference	Max	H	I
4	User Testing Survey	4 out of 5	Min	L	T
5	Thermal Analysis	Calculated results match experimental +/- 5%	Max	M	T, I
6	Software Testing	Delay of 10 seconds	Max	H	T, I, S
7	Testing with other lab devices or apparatuses	Compatible with other devices in the lab	Pass	M	T
8	Travel Testing	Able to withstand impacts and bumps (from travel)	Pass	M	T
9	Structural Integrity Factor	Deflection of 3inches under 50lbs load	Max	L	A, I
10	Weight	20 lbs	Max	L	I
11	Electrical Wiring Safety	No shorts, wires are properly insulated	Pass	L	I, T
12	Heat Exposure	Tubing is safe to touch, and components are under allowable temperatures	Pass	M	I, T

Engineering Specifications Table from Page 11

Test #1: Calibration of Calorimeter

Description of Test:

Use span gases with known concentrations and compare to the outputs of the calorimeter. It is important to use caution with the span gases, as they have high pressures. This will be completed by Professor Emberley due to COVID-19.

Location:

Cal Poly Combustion Lab

Acceptance Criteria:

The calorimeter is within ±1% of the span gas concentration.

Required Materials:

- CO, CO_2, O_2 Span Gases
- Calorimeter with ¼ inch hose connections
- Hose for connections
- Exhaust Fan
- Proper PPE (safety glasses)

Data:

Span Gas	**Span Gas Concentration [ppm]**	**Calorimeter Concentration [ppm]**	**Percent Difference [%]**
O_2			
CO_2			
CO			

Test #2: Usability

Description of Test:

To test if the calorimeter meets the size and weight requirements the team determined to make the system portable.

Required Materials:

- Tape Measure
- Scale

***Testing Protocol:**

1) Use tape measure to measure the height of the calorimeter briefcase
2) Use tape measure to measure the length of the calorimeter briefcase
3) Use tape measure to measure the width of the calorimeter briefcase
4) Use scale to weigh calorimeter briefcase
    a. Repeat 3 times and use average value

Data:

	Measured Value	Pass/Fail
Height (in)		
Length (in)		
Width (in)		
Weight (lbs)		

*See attached drawing for which sides correspond with height, length, and width

Test #3: Flowrate Test

Description:

Run the system and measure the flowrate to ensure the sensors are collecting data at the proper operating point. This will be completed by Professor Emberley due to COVID-19.

Acceptance Criteria:

Flowrate is between 0.5 and 1.5 Liters per minute.

Required Materials:

- Flowmeter
- Calorimeter

Testing Protocol:

1. Hook up flowmeter
2. Turn on system
3. Read the flowrate of the flowmeter every 30 seconds for 5 minutes

Data:

Time [min]	Flowrate [Liters/min]
0.5	
1	
1.5	
2	
2.5	
3	
3.5	
4	
4.5	
5	

Test #4: Software Testing

Description:

Run the system and measure the time delay from data acquisition to graphing. We'll also have users operate the system and give us feedback.

Acceptance Criteria:

Time response less than 5 seconds.

Required Materials:

- 5 different people
- Computer
- Calorimeter

Testing Protocol:

1. Turn on the system
2. See how long the code takes to run
3. Repeat steps above 3 times
4. Have 5 different people run the code and record what they like/dislike

Data:

	Time Response (s)
Run 1	
Run 2	
Run 3	

User Feedback Notes:

Test #5: Accuracy Testing for the Calorimeter

Decsription:

The calorimeter will be hooked up to the fume hood and a fire made of ethanol will be lit. The device will measure and output the heat release rate of the burning alcohol. This will be completed by Professor Emberley due to COVID-19.

Required Materials:

- Scale
- Alcohol
- Calorimeter
- Fume Hood
- Extraction
- Heat Release Rate Records

Procedure:

1. Test to see if there is gas leakage to the environment
2. Test the Accuracy of the Calorimeter
3. Test to see if the hardware from the calorimter works with the fume hood.

Data:

Measured Gas	Recorded Value	Actual Value	Percent Error
CO			
CO2			
O2			

Test #6: Thermal Testing

Description:

Measuring the temperature of components on or near the duct to ensure they don’t exceed expected temperature. This will be completed by Professor Emberley due to COVID-19.

Required Materials:

- Alcohol
- Calorimeter
- Fume Hood
- Extraction

Procedure:

1. Install thermocouples on fittings and tubing that is close to duct
2. Burn substance under fume hood
3. Record maximum temperature of each thermocouple

Data:

	Max Temperature
Thermocouple 1	
Thermocouple 2	

Test #7: Inspection Testing

Description of Test:

Inspect the calorimeter to ensure that it meets the compatibility with other lab devices, travel testing, structural integrity factor, weight, electrical wiring safety, and heat exposure specifications are properly met. The portions of testing that take place in the lab will be completed by Professor Emberley due to COVID-19.

Location:

Cal Poly Combustion Lab

Acceptance Criteria:

All inspections pass successfully, according to each specific criteria.

Required Materials:

- Other lab devices (fume hood, cone calorimeter)
- Tape measure
- Scale
- Voltmeter
- Thermocouple

Data:

Inspection	Acceptance Criteria	Results
Compatibility with other lab devices	Compatible with other devices in the lab	
Travel Testing	Able to withstand bumps and impact (from travel)	
Structural Integrity Factor	Deflection of less than 3 inches under 50 pound load	
Weight	20 lbs or less	
Electrical wiring safety	No shorts, properly insulated wires	
Heat Exposure	Tubing is safe to touch	

Test #8: Filter Life Testing

Description of Test:

Measure the flow rate in the system after the filter and record the time it takes to dip below 0.5 Liters per minute (outside of the range of operation the calorimeter). That is a general estimate life of the filter and should be replaced whenever that approximate time has elapsed during normal calorimeter operation. The portions of testing that take place in the lab will be completed by Professor Emberley due to COVID-19.

Location:

Cal Poly Combustion Lab

Required Materials:

- Calorimeter
- Fume Hood
- Extraction
- Flowmeter

Procedure:

1. Install flowmeter after the filter
2. Turn on the smoke extraction system
3. Ignite the sample in the fume hood
4. Measure the flowrate while operating the filter, while also keeping track of the time spent running the system
5. After the flowrate has dipped below 0.5 Liters per minute (outside of the range of operation the calorimeter), stop the timer
6. Record the total time of operation
7. Extinguish any remaining combustion products and turn off the smoke extraction system

Data:

	Total Time of Calorimeter Operation
Flowrate is less than 0.5 L/min	

Appendix Q: Operator’s Manual

Hardware Set-up:

Step 1: Ensure oxygen sensor is connected to CO/CO2 sensor. (See Figure 1)

Figure 1: O2 sensor connected to CO2 sensor

Step 2: Ensure the tubing between each component is connected.

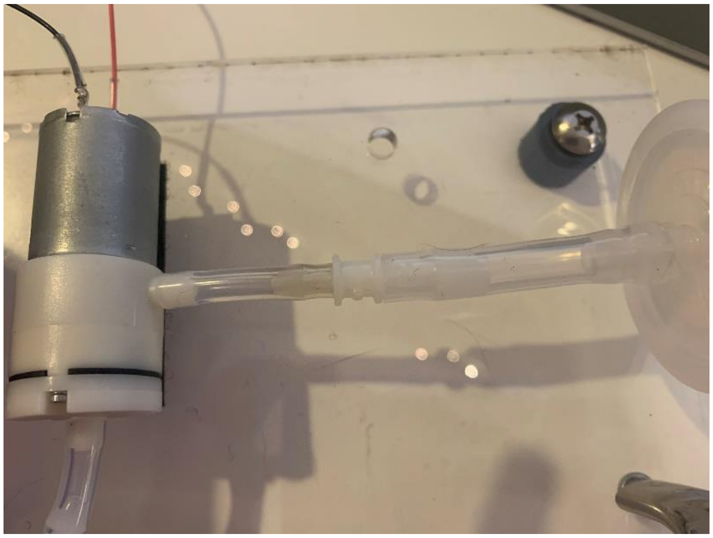


Figure 2: Pump and Filter Tubing Connection

Step 3: Connect battery to pump and CO/CO2 sensor when ready to use device. The red LED will light up on the breakout board (Figure 3 on the right) if there is power to the device.

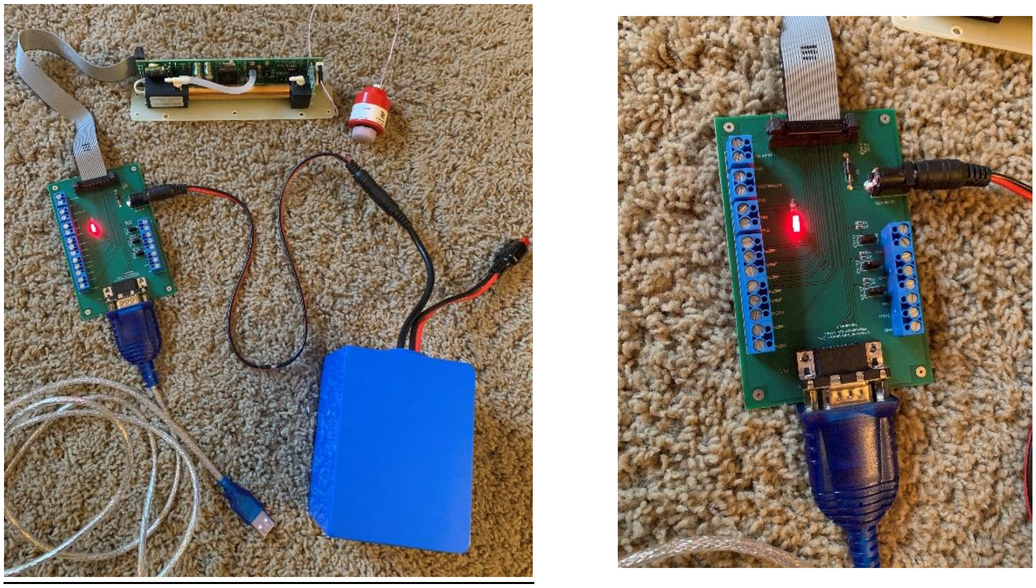


Figure 3: CO/CO2 and O2 Sensor Connected to Battery

Step 4: Connect RS-232 to USB cable with the RS-232 connector into the breakout board and the USB connector into computer. (See Fig 4). There will be a blue light inside the cable if the device is connected properly.

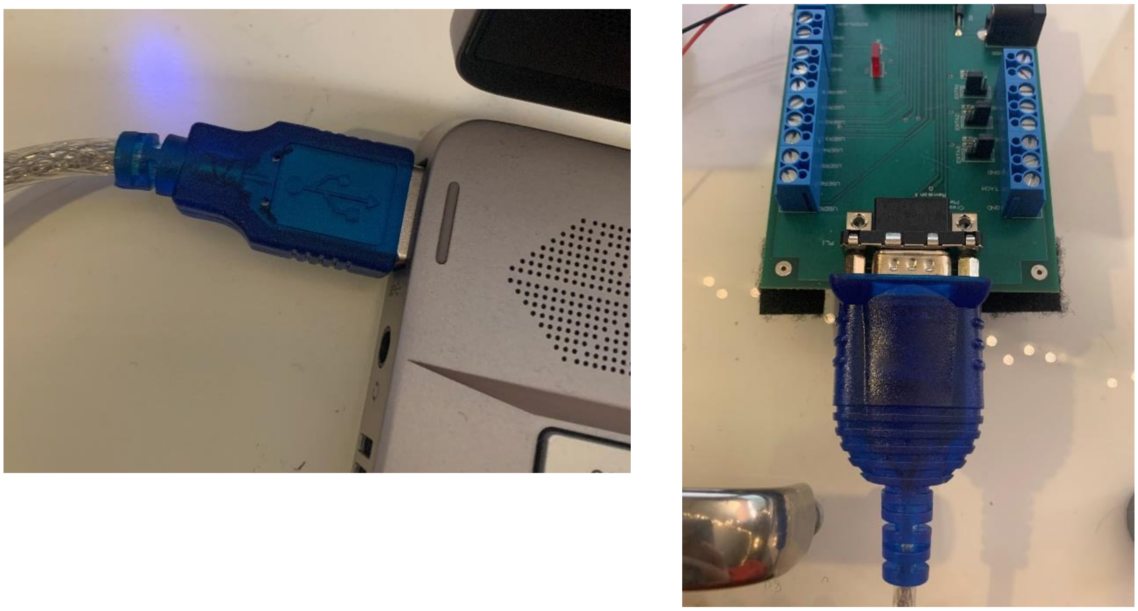


Figure 4: USB connection to the computer (pictured on the left) and the RS-232 Connection to the breakout board (pictured on the right)

Software

Crestline:

Step 1: Download Crestline 7911 sensor software

Step 2: On your device's C: drive, create a folder titled 'Crestline'. Within this folder, create a new folder titled '7911'. Lastly, within that folder create a new folder called 'Data_files'. This is where text files will automatically save to. *It is important for proper operation that the file structure described is matched exactly

Step 3: Move the Host Program into the '7911' folder you created. Double click on the Host Program file to open the program.

Step 4: Upon opening, the program will ask for the correct COMS port. In order to figure out which COMs port you are connected to, open your device manager and click on the arrow next to 'Ports' (see Fig. 5). In the example, the device is connected to COM3.

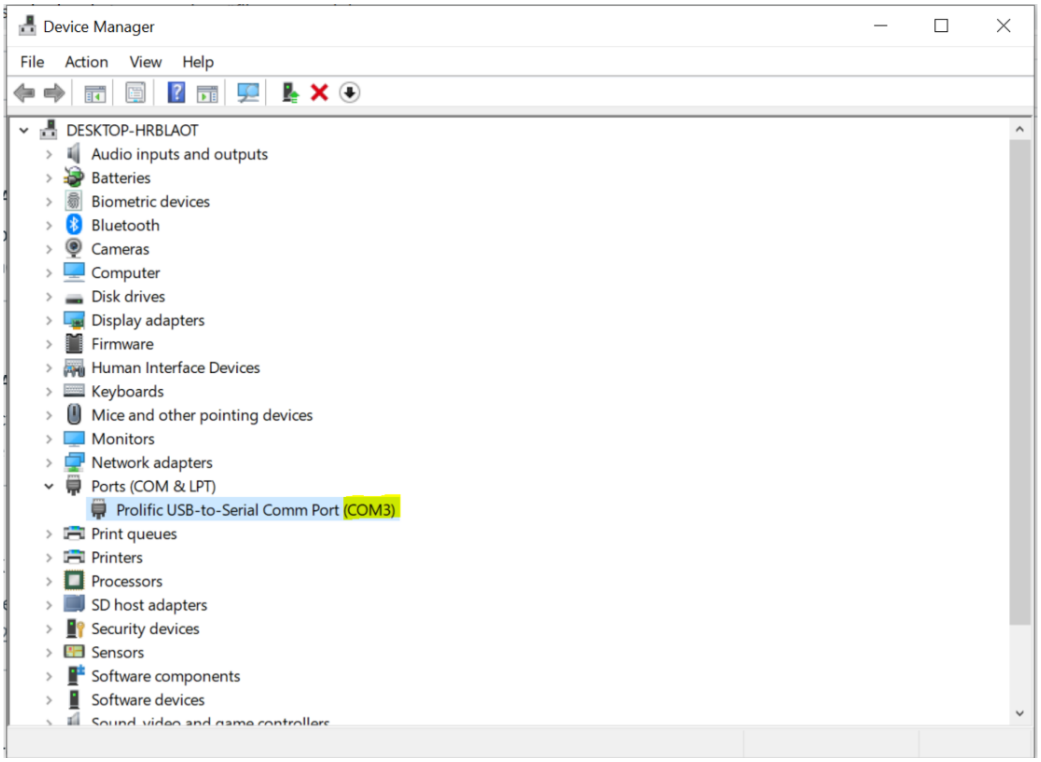


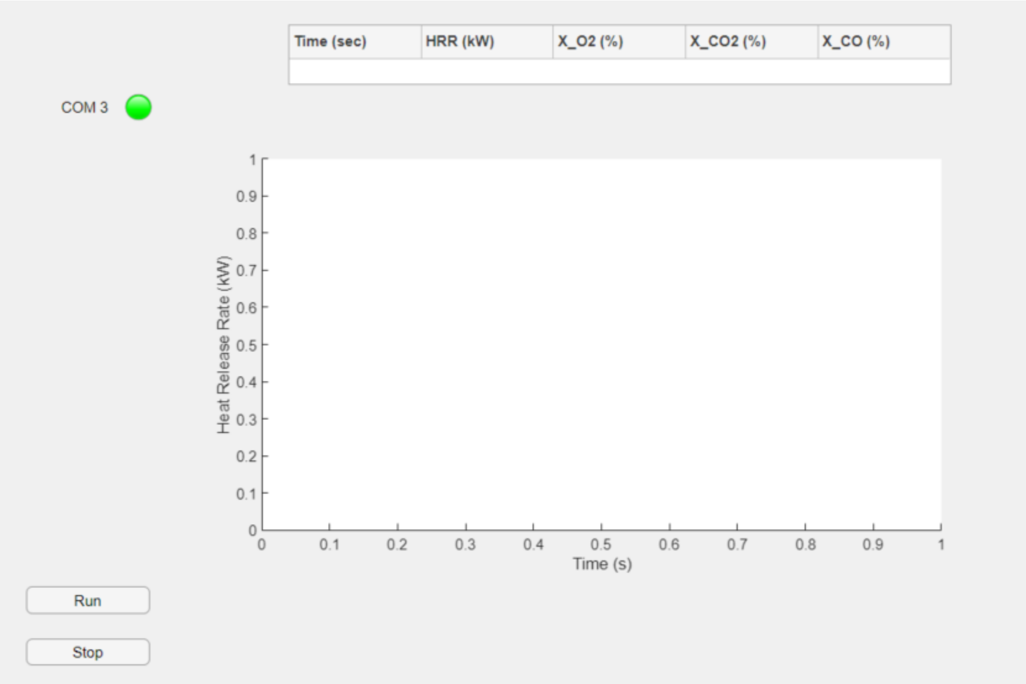
Figure 5: Device Manager in Windows, highlighted section is the COM port

Step 5: Press F1 on your device to open the main menu of commands. See the Crestline Software Manual for descriptions of each command.

MATLAB:

Step 1: Download MATLAB script: P_oxygen_cons_cal.m

Step 2: Open the file and wait for the GUI to appear.



Time (sec)	HRR (kW)	X_O2 (%)	X_CO2 (%)	X_CO (%)

Figure 6: GUI visible after running the MATLAB File

Step 3: Ensure that Oxygen and CO/CO2 sensors are connected by looking at the boxes in the top-left corner.

Step 4: When ready to collect data, press the start button on the GUI. To stop collecting data press the stop button.

Procedure for Calibration

Warning: Working with compressed gases is hazardous and should be done with proper training as well as according to company safety standards.

Step 1: Connect the inlet hose of the calorimeter to the valve at the end of the SPAN gas.

Step 2: Access the host program called ‘7911 Console Host Program rev 3’ inside the **7911** folder. Inside the host program designate the COM port that the sensor is connected to.

Note: To find the designated COM port that the device is connected to go to the Windows search bar and search for Device Manager. The sensor should read in the port as Prolific USM-to-Serial Comm Port as shown above in Figure 5.

Step 3: Open the MATLAB document named '*Calorimeter.mlapp'* and run it.

Step 4: On the Console Host Program run the calibration on the 7911 NDIR sensor by pressing the 's' key. When the program comes up with gases to select, press no for all options except for CO2 and CO. For CO2 and CO enter the respective concentrations of the gases from the SPAN gas container.

Step 5: Open the valve for the SPAN gas to flow through the system and follow the direction on the Host Program to proceed with the calibration.

Procedure to Measure the Heat Release Rate of a Material

Warning: Working with combustible materials is hazardous and should be done with proper training as well as according to company safety standards.

Step 1: Connect the inlet hose of the calorimeter to the inlet fitting on the exhaust duct of the fume hood.

Step 2: Connect the exhaust hose of the calorimeter to the exhaust fitting on the exhaust duct of the fume hood.

Step 3: Ensure the hoses have airtight seals with the fittings to make sure that no smoke leaks during operation.

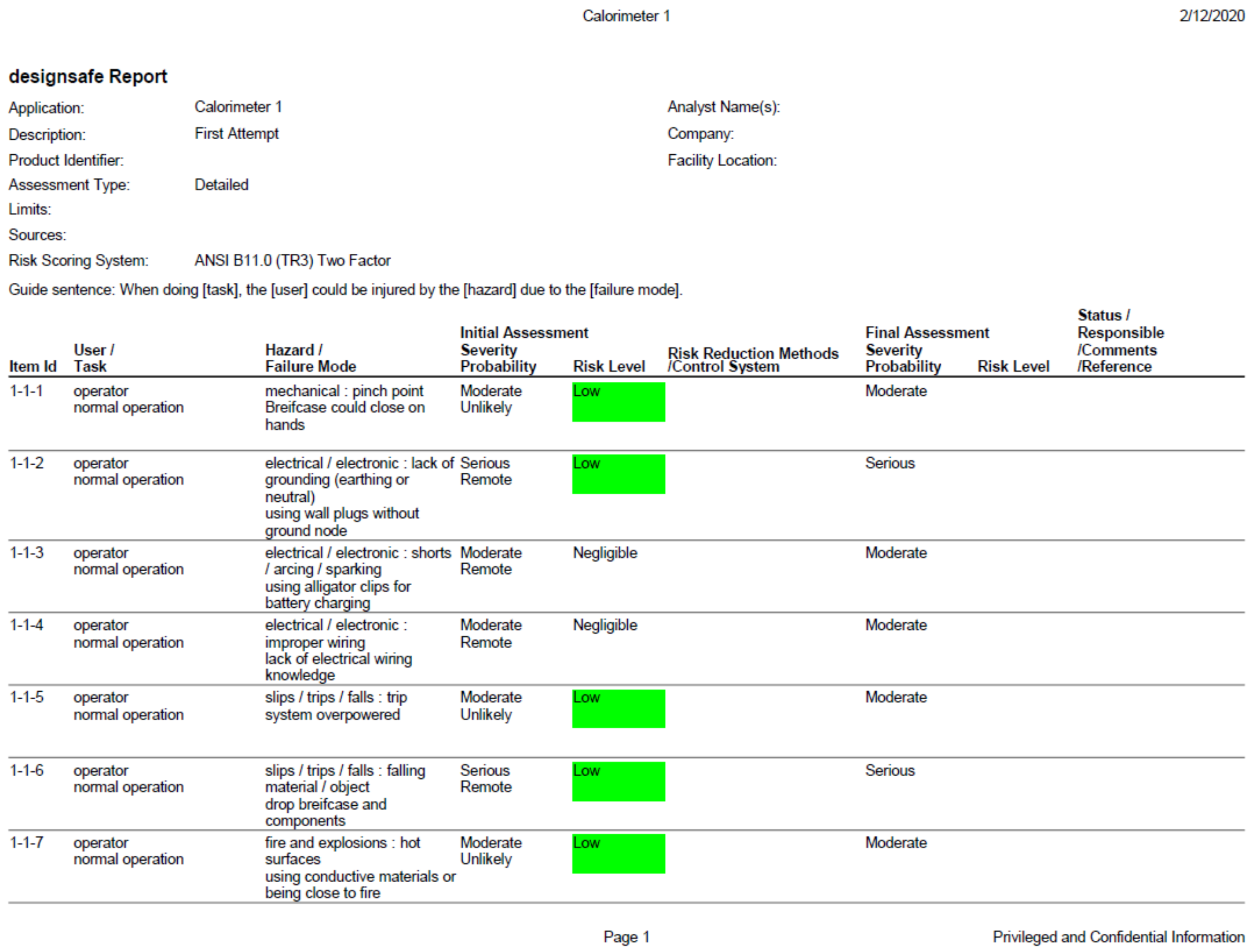
Step 4: Make sure that the CO/CO2 sensor is on by connecting the breakout board to power. The breakout board has a red LED that will light up, the sensor has a light that will blink on the side connected to the ribbon cable. Also ensure all electronic connections are secure. See Hardware Set Up section for more help.

Step 5: Open up the Crestline software on your lab' device (see Crestline under the Software section). Follow the prompt by typing the number of the COM port the device is connected to. Then press "ctrl + l" to start collecting data. You will need to name the file "data" once prompted and select a time interval of .5 seconds unless otherwise instructed.

Step 6: Open the GUI and ensure that both sensors show up as "connected". Click "Start" to begin collecting data.

Step 7: Turn on the pump and light your fire under the fume hood. The onscreen plot should update in real time.

Appendix R: Risk Assessment



Calorimeter 1 2/12/2020

designsafe Report

Application:	Calorimeter 1	Analyst Name(s):	
Description:	First Attempt	Company:	
Product Identifier:		Facility Location:	
Assessment Type:	Detailed		
Limits:			
Sources:			
Risk Scoring System:	ANSI B11.0 (TR3) Two Factor		

Guide sentence: When doing [task], the [user] could be injured by the [hazard] due to the [failure mode].

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-1	operator normal operation	mechanical : pinch point Breifcase could close on hands	Moderate Unlikely	Low		Moderate		
1-1-2	operator normal operation	electrical / electronic : lack of grounding (earthing or neutral) using wall plugs without ground node	Serious Remote	Low		Serious		
1-1-3	operator normal operation	electrical / electronic : shorts / arcing / sparking using alligator clips for battery charging	Moderate Remote	Negligible		Moderate		
1-1-4	operator normal operation	electrical / electronic : improper wiring lack of electrical wiring knowledge	Moderate Remote	Negligible		Moderate		
1-1-5	operator normal operation	slips / trips / falls : trip system overpowered	Moderate Unlikely	Low		Moderate		
1-1-6	operator normal operation	slips / trips / falls : falling material / object drop breifcase and components	Serious Remote	Low		Serious		
1-1-7	operator normal operation	fire and explosions : hot surfaces using conductive materials or being close to fire	Moderate Unlikely	Low		Moderate		

Page 1 Privileged and Confidential Information

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-1-8	operator normal operation	environmental / industrial hygiene : carcinogens inhale smoke	Serious Remote	Low		Serious		
1-1-9	operator normal operation	environmental / industrial hygiene : asphyxiants inhale smoke	Serious Remote	Low		Serious		
1-1-10	operator normal operation	ventilation / confined space : smoke improperly sealed tubing	Serious Remote	Low		Serious		
1-2-1	operator clean up	slips / trips / falls : trip	Moderate Unlikely	Low		Moderate		
1-2-2	operator clean up	slips / trips / falls : falling material / object	Moderate Unlikely	Low		Moderate		
1-2-3	operator clean up	environmental / industrial hygiene : irritants inhaling smoke	Serious Remote	Low		Serious		
1-3-1	operator basic trouble shooting / problem solving	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
1-3-2	operator basic trouble shooting / problem solving	environmental / industrial hygiene : irritants	Moderate Unlikely	Low		Moderate		
1-4-1	operator load / unload materials	slips / trips / falls : fall hazard from elevated work	Moderate Unlikely	Low		Moderate		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
1-4-2	operator load / unload materials	slips / trips / falls : falling material / object	Moderate Unlikely	Low		Moderate		
2-1-1	maintenance technician tool change	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
2-1-2	maintenance technician tool change	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Remote	Negligible		Moderate		
2-1-3	maintenance technician tool change	electrical / electronic : improper wiring	Moderate Remote	Negligible		Moderate		
2-1-4	maintenance technician tool change	environmental / industrial hygiene : irritants	Moderate Remote	Negligible		Moderate		
2-2-1	maintenance technician periodic maintenance	mechanical : pinch point	Moderate Unlikely	Low		Moderate		
2-2-2	maintenance technician periodic maintenance	electrical / electronic : lack of grounding (earthing or neutral)	Moderate Remote	Negligible		Moderate		
2-2-3	maintenance technician periodic maintenance	electrical / electronic : improper wiring	Moderate Remote	Negligible		Moderate		
2-2-4	maintenance technician periodic maintenance	slips / trips / falls : falling material / object	Moderate Unlikely	Low		Moderate		

Item Id	User / Task	Hazard / Failure Mode	Initial Assessment Severity Probability	Risk Level	Risk Reduction Methods /Control System	Final Assessment Severity Probability	Risk Level	Status / Responsible /Comments /Reference
2-2-5	maintenance technician periodic maintenance	environmental / industrial hygiene : irritants	Moderate Remote	Negligible		Moderate		
2-3-1	maintenance technician trouble-shooting / problem solving	electrical / electronic : improper wiring	Moderate Remote	Negligible		Moderate		
3-1-1	passer by / non-user work next to / near machinery	slips / trips / falls : falling material / object	Moderate Unlikely	Low		Moderate		
3-1-2	passer by / non-user work next to / near machinery	ventilation / confined space : smoke	Moderate Remote	Negligible		Moderate		
3-2-1	passer by / non-user walk near machinery	slips / trips / falls : trip	Moderate Unlikely	Low		Moderate		
3-2-2	passer by / non-user walk near machinery	slips / trips / falls : falling material / object	Moderate Unlikely	Low		Moderate		