Sensor Systems For Combustion Control

By

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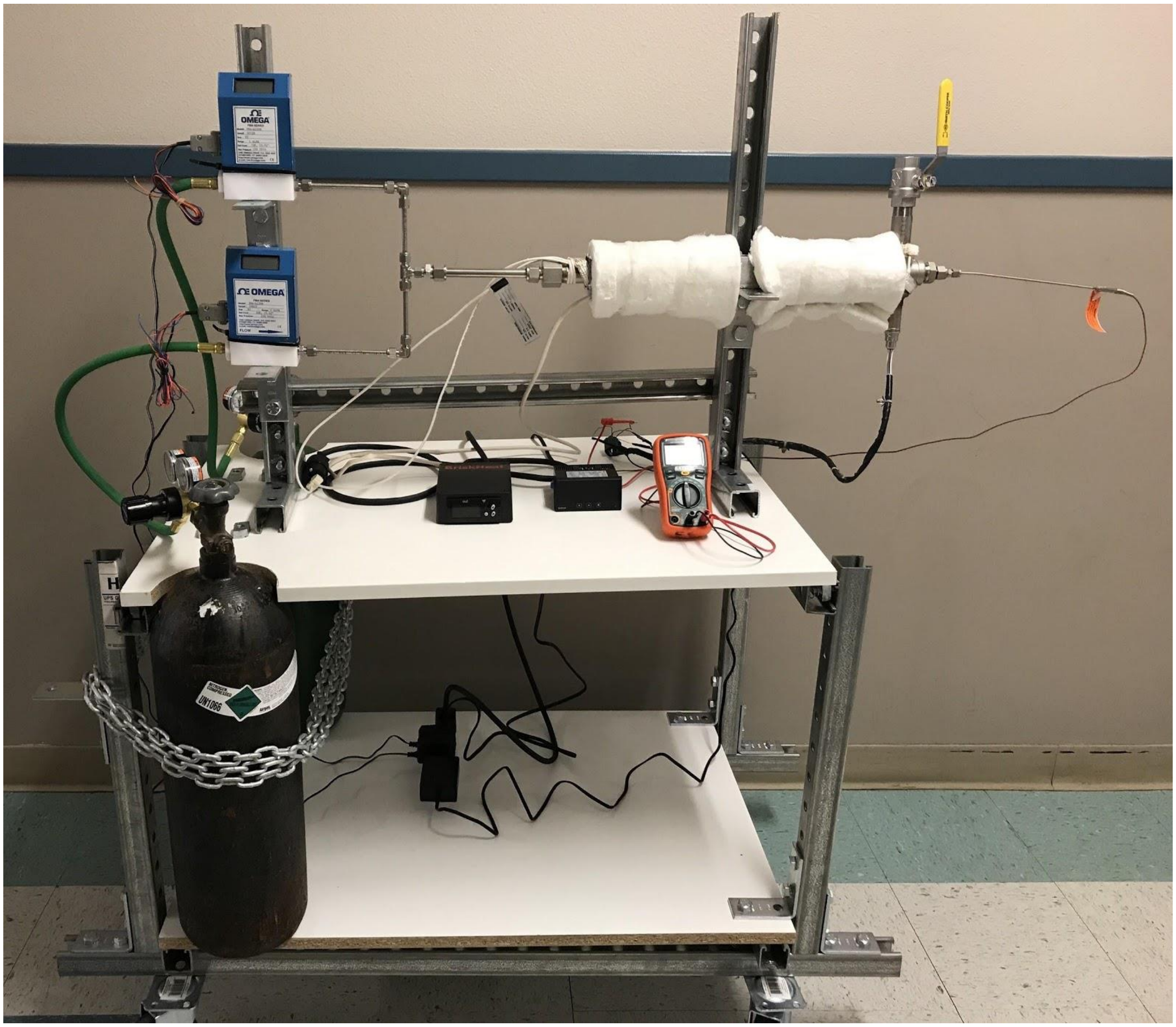

Senior Project

ELECTRICAL ENGINEERING DEPARTMENT

California Polytechnic State University

San Luis Obispo

Spring 2019

Dedicated to all our friends and loved ones

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Acknowledgements

First we would like to give thanks to the Baker Koob Endowment for allowing this project to gain traction through very generous funding. Without their help, none of the work done over the last few months would have been possible.

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Abstract

This project is the first iteration of a larger multi-year project working towards utilizing ammonia (NH_3) as an alternative fuel. The purpose of this iteration is a proof of concept for the creation of a control loop that can measure oxygen levels in a system and control the flow rates of nitrogen and oxygen in order to maintain an ideal ratio metric flow to reduce the overall emissions of the system. It is the hope of this project that the concept can eventually be used to maximally reduce to the point of near complete elimination of NOx emissions from burning ammonia as an alternative fuel. The scope of this project is to act as a starting point for research and testing towards the end goal of a cleaner more sustainable alternative fuel. This project confirms the ability to control flow rates of gases to maintain an ideal ratio of nitrogen to oxygen inside of a heating chamber test system through the measuring of voltage of an O_2 sensor and adjusting of the flow rates of each gas based on the voltage value returned by the sensor.

I. Introduction

For this senior project, the aim is to develop a reliable sensor system for combustion control able to measure the oxygen levels in a heated chamber being filled by oxygen and nitrogen simultaneously with a control loop that will adjust the ratios of each gas to create ideal emission control. It is meant to act as a proof of concept for a larger more in-depth product focused on a control system that detects NOx from burning ammonia as an alternative fuel source to eliminate NOx emission completely from a system. This first iteration of a multiple year project is done in the hopes that future projects utilize the concept of detecting gas levels in a chamber to detect NOx inside a combustion chamber, which is paramount in accurately manipulating the fuel-to-air ratio to neutralize NOx emissions.

II. Background

Renewable energy has manifested into a vital role in addressing some of the key challenges that the entire world faces such as the cost of energy, energy storage, and climate change. Liquid regenerable fuels have served to be very promising due to their chemical storage abilities. Chemical storage of energy can be considered as a "hydrogen or carbon-neutral hydrogen derivative" [1]. These substances can be made by adding energy to air and water; Water and air are returned when the energy is released from its chemical state. The simplest form would be hydrogen; however, hydrogen is incredibly difficult to liquefy due to its boiling point being incredibly low. Currently, fuel cells hydrogen serves as a gaseous state-of-matter storage for renewable sources such as wind and solar. Therefore, the best liquid regenerable fuel (LRF) would be ammonia. Ammonia is attractive because it is made from nitrogen (a main component in air) and water. It can be condensed into a liquid at a significantly higher temperature than hydrogen (approximately 4 times higher) and does not have direct greenhouse gas effects. There are also established and reliable infrastructure for ammonia storage and distribution. An early application of ammonia as fuel could be to power marine gas turbines that drive ammonia tanker ships.

Figure 1: Ammonia Powered Tanker Ship Futuristic Design By C-Job [2]

The primary way of extracting energy from a chemically-based storage such as fossil fuels is through combustion. Combustion of ammonia does not emit carbon-based pollutants, but it does emit pollutants such as NO and NO_2. These nitrogen-based pollutants are commonly referred to as NOx. Although NOx does not have impacting ramifications associated with greenhouse gases, the pollutant is toxic. Thus, suppressing NOx pollutants is absolutely necessary if ammonia is used as a sustainable energy storage. Over the past century, the reduction of NOx was done chemically through the use of a catalytic converter. The catalytic convert utilizes incredibly rare and expensive earth metals: platinum, palladium, and rhodium. As a potential form of energy storage in potentially hundreds of millions of vehicles, this is simply not a viable method due to the expense and rarity of the metals. A proposed solution is to feed NOx back into the input and inject ammonia to suppress the pollutant which will control the fuel-to-air ratio, essentially creating a feedback loop. It is well-known that NOx is suppressed by ammonia (NH_3) through reactions such as this:

$$\mathbf{NH_3 \rightarrow NH_2 + H \text{ followed by } NO + NH_2 \rightarrow N_2 + H_2O.}$$

By intelligently manipulating the fuel-to-air ratio, ideally, NOx emissions should be completely suppressed. Figure 1.2 shows a feedback control system of a combustion engine aftertreatment system to reduce NOx emissions to give readers an idea of what this project plans on building.

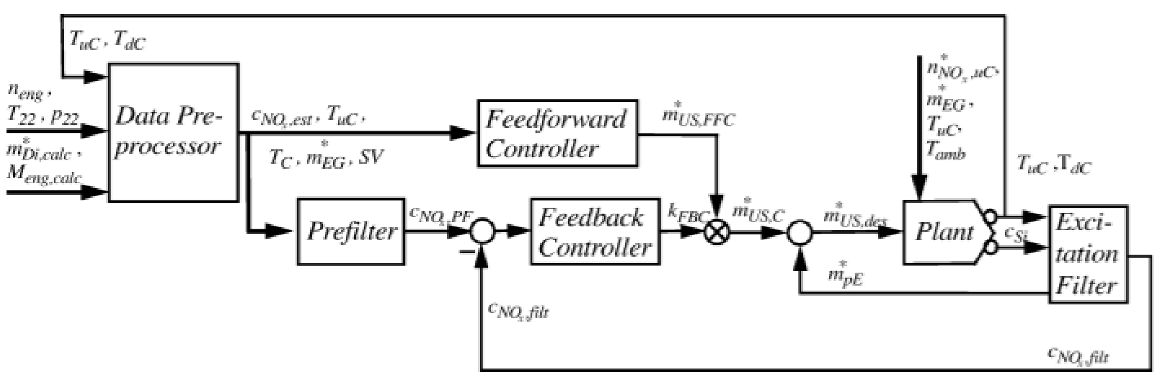

Figure 2: Feedback Control System of a Combustion Engine Aftertreatment System [3]

III. Requirements and Specifications

The goal was to create a platform that accepted nitrogen and oxygen gas inputs and housed an O2 sensor. The system could then control the flow rate of the input gases depending on the oxygen content detected by the O2 sensor. The system had to be built in such a way so that components were interchangeable. This would allow future groups to swap the nitrogen and oxygen gases for ammonia and the O2 sensor for a NOx sensor. With the time provided, the specifications detailed in Table 1 were sufficient for the first stage of the project.

TABLE 1
SENSOR SYSTEM REQUIREMENTS AND SPECIFICATIONS

Marketing Requirements	**Engineering Specifications**	**Justification**
7	The O_2 sensor should output a voltage between -50 mV and 100 mV with an error margin of +/- 5 mV.	The sensor should provide accurate voltages for proper interpretation of the oxygen content present in the system.
2	One mass flow meter monitors the flow rate of each gas input entering the system.	Measuring the flow rate provides more control over the quantity of each gas entering the system.
4	The system should have two variable gas inputs.	Two variable gas inputs provide sufficient variety of input combinations for the scope of the project.
4	The containment unit must withstand temperatures between 600 and 1000 degrees Fahrenheit.	Oxygen sensors have high operating temperatures [4].
7	The thermocouple should measure the internal temperature with an error margin of 10 °F.	An accurate internal temperature measurement can indicate when the O2 sensor reaches operating temperature.
5	The system should operate using 120 VAC within +/- 0.1 V.	Using a single 120 VAC wall outlet provides a convenient way to power the entire system.

1, 3, 4	The sensor system should have an adjustable framework made from steel Unistrut.	Having an adjustable frame allows multiple configurations to fit new components that may be added to the system. The steel material provides high physical and temperature durability.
6	The total price for parts and shipping must fall below $5600.	The allowed budget for this project is $5600.
Marketing Requirements 1. Adjustable framework 2. Controlled inputs 3. High physical durability 4. High temperature durability 5. Powered by common wall outlet 6. Cost efficient 7. Accurate sensor measurements		

Level 0 Block Diagram Primary Input/Output Descriptions

Figure 3 and Table 2 together display the level 0 description of the project. This is the highest-level view, showing only the inputs and outputs of the system. Table 2 summarizes the basic operation of the system.

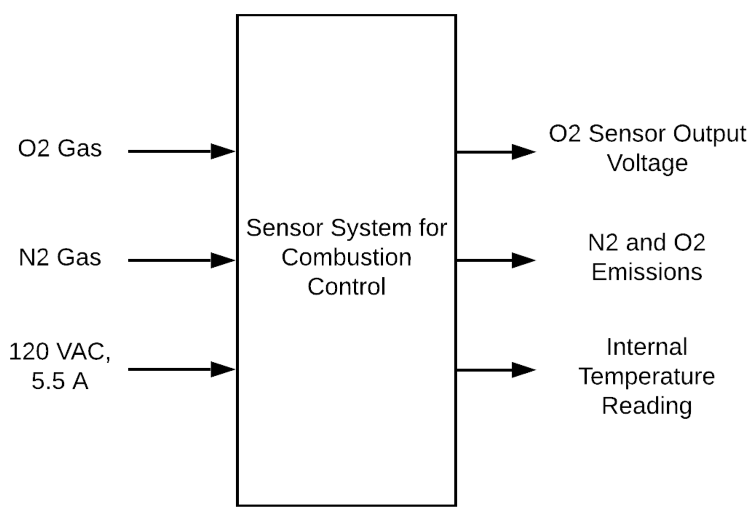

Figure 3: Level 0 Diagram of Sensor System for Combustion Control

TABLE 2
FUNCTIONALITY TABLE FOR LEVEL 0 BLOCK DIAGRAM

Module	Sensor System for Combustion Control
Inputs	O2 Gas, N2 Gas, 120 VAC, 5.5 A
Outputs	O2 and N2 Emissions, O2 Sensor Output Voltage, Internal Temperature Reading
Functionality	The system accepts O2 and N2 gas, heats the gas, and then outputs the gas after passing an O2 sensor. The sensor outputs a voltage depending on the oxygen content present in the system and a thermocouple outputs the internal temperature to ensure that the sensor is at operating temperature.

Level 1 Designed System Block Diagram Description

Figure 4 shows the multiple subsystems present in the sensor system. Tables 3 through 7 discuss each subsystem in more detail.

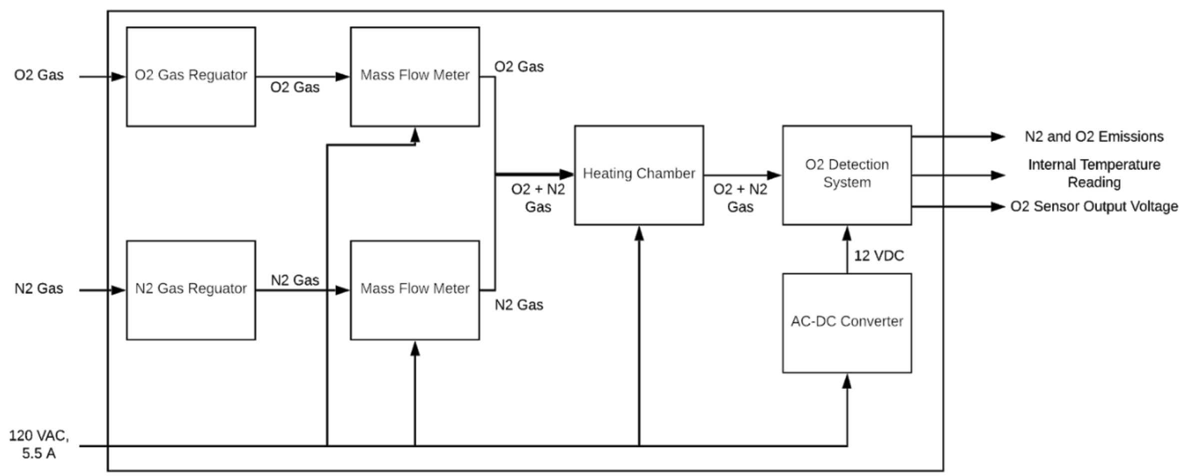

Figure 4: Level 1 Block Diagram of Sensor System for Combustion Control

The gas regulator connects to the gas container and to the mass flow meter. Its purpose is to maintain the output pressure set by the user. The output pressure is displayed on a gauge and can be adjusted using the knob on the device.

TABLE 3
FUNCTIONALITY TABLE FOR GAS REGULATOR

Module	Gas Regulator
Inputs	Gas (O_2 or N_2)
Outputs	Gas (O_2 or N_2)
Functionality	The gas regulator regulates the output pressure of the gas entering the system, ensuring that it does not exceed 10 PSI.

The mass flow meter measures and displays the flow of gas entering the system. The meter is powered by 120 VAC and 150 mA [5].

TABLE 4
FUNCTIONALITY TABLE FOR MASS FLOW METER

Module	Mass Flow Meter
Inputs	Gas (O_2 or N_2), 120VAC, 150 mA
Outputs	Gas (O_2 or N_2)
Functionality	The mass flow meter measures and displays the amount of gas flowing into the system in standard liters per minute (SLM).

The heating chamber has three main parts: the heating tape, the temperature controller, and ceramic fiber insulation. The 470 W heating tape is monitored by the temperature controller. If the temperature of the tape does not match the preset temperature of the controller, the controller adjusts the current going through the tape until it reaches that temperature. The insulation prevents heat from being lost to the surrounding environment.

TABLE 5
FUNCTIONALITY TABLE FOR HEATING CHAMBER

Module	Heating Chamber
Inputs	O_2 and N_2 gas mixture, 120 VAC, 4 A
Outputs	O_2 and N_2 gas mixture
Functionality	The heating chamber heats up the gas before it passes the O_2 sensor and heats the O_2 sensor to bring it up to operating temperature.

The O_2 detection system consists of the O_2 sensor and thermocouple inserted into a stainless-steel pipe cross. The cross is partially wrapped in heating tape to bring the sensor to operating temperature. Additionally, an attached ball valve controls the output flow rate of the gas.

TABLE 6
FUNCTIONALITY TABLE FOR O2 DETECTION SYSTEM

Module	O_2 Detection System
Inputs	O_2 and N_2 gas mixture, 12 VDC, 1 A
Outputs	O_2 and N_2 emissions, O_2 Sensor Output Voltage, Internal Temperature Reading
Functionality	A mixture of N_2 and O_2 gas enter the stainless-steel cross and pass through an O_2 sensor. The O_2 sensor outputs a voltage corresponding to the oxygen content in the system. A thermocouple measures the internal temperature to verify that the O_2 sensor is at its operating temperature. The ball valve controls the output flow rate of the gas.

The O_2 sensor requires approximately 12 VDC to power its internal heater.

TABLE 7
FUNCTIONALITY TABLE FOR AC/DC CONVERTER

Module	AC/DC Converter
Inputs	120 VAC, 1 A
Outputs	12 VDC. 1 A
Functionality	Converts 120 VAC to 12 VDC.

IV. Design

Figure 5 shows the general design of the sensor system. Each regulator regulates the output pressure of their respective gas, ensuring that the output pressure does not exceed 10 PSI, the predetermined maximum output pressure for this project. Each regulator connects to a mass flow meter through ¼” rubber tubing. The mass flow meter measures and displays the flow rate of the gas on an LCD in standard liters per minute (SLM). From the mass flow meter, a combination of ¼” and ½” 304 stainless steel tubing along with an assortment of stainless-steel Swagelok fittings and adapters transport the gas to the heating chamber of the system. The heating chamber consists of ¾” 304 stainless steel pipe, 470 W heating tape, and ceramic fiber insulation. Stainless steel was chosen for many components due to its ability to withstand high temperatures [6]. Heating tape was the best option for heating up the gas and the O2 sensor without using combustion, which will be implemented in future stages of the project. The heating tape wraps around the ¾” stainless steel pipe and part of the stainless-steel cross. The goal is to heat the gas as it enters the cross and to heat up the O2 sensor to its operating temperature of 600 °F. The temperature controller monitors the heating tape and increases the temperature until it reaches the preset temperature of 900 °F. Ceramic fiber insulation wraps around the sections of pipe covered in heating tape to minimize the amount of heat lost to the environment. A thermocouple probes the inside of the cross to measure the internal temperature, since heat loss to the outside environment is inevitable. The sensor at the output of the system will be detecting the amount of oxygen in the gas mixture, representing the reading as an output voltage. The exit ball valve controls the rate of gas leaving the system.

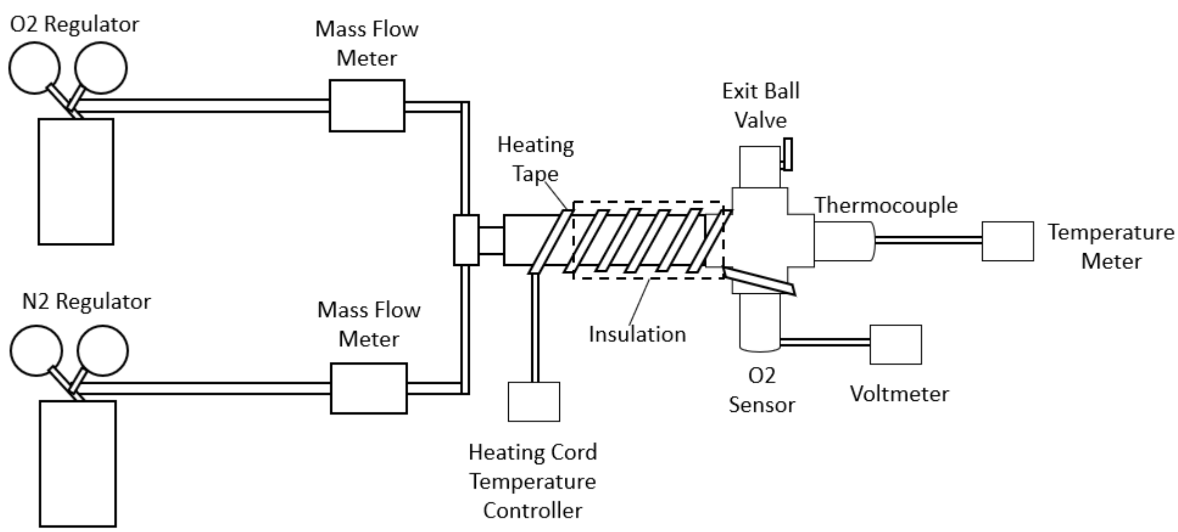

Figure 5: Design of Sensor System

V. Construction

For the construction of the testing apparatus, several components were required for a structurally stable and efficient system. In the first iteration of construction for the testing apparatus, the following components were utilized (see table 8).

TABLE 8
COMPONENTS FOR FIRST ITERATION CONSTRUCTION

Part	Quantity
FMA-A2306 Mass Flow Meter	2
O2 Gas+ Size 60 Container	1
N2 Gas+ Size 60 Container	1
Oxygen Regulator	1
Inert Gas Regulator	1
¼" Grade R Hose	4
12" of ¾" Threaded Stainless Steel Pipe **(18")**	1
¾" Stainless Steel Cross	1
Digital Temperature Controller	1
100 W Heating Tape **(470 W)**	1
12" x 8" Fiberglass Insulation **(Ceramic Fiberglass)**	1
Bosch O2 Sensor	1
K-Type Thermocouple	1
Multi-Volt AC-DC Adapter	1
1-⅝" x 1-⅝", 12 Gauge Steel Unistrut	60
2' x 8' Particle Board	1

These main components along with all the fittings and connectors created the overall system. In the first iteration, a support system which utilized the 1-⅝" steel Unistrut was created in the form of a box support by connecting 4ft and 2ft lengths of Unistrut into a 4' x 2' x 2' box. In addition, two pieces of 2' x 4' particle board were placed on top of and drilled into each of the two layers of the box to create two flat surfaces that the components for the testing apparatus and gas tanks could rest on. Sections of the top board were cut out on either side so oxygen and nitrogen gas tanks could protrude through the top board and connect to regulators with tubing fed into separate mass flow meters. In the interest of mobility, wheels were fashioned on the bottom layer of the support system later so it could be moved to different locations for various tests. To hold up the components for the testing apparatus a simple support using the steel Unistrut was created by connecting the Unistrut in an "H" shape with two additional Unistrut pieces attached to the bottom for stability. This support was placed on the top of the box support and "L" brackets were fashioned to the testing support to hold up the several components of the testing apparatus. For the actual system used in testing, ¼" pipe was connected to the output of the mass flow meters where the two pipes were joined together using a tee to combine/mix the oxygen and nitrogen gases together. The tee connected to a ¼" pipe that fed into a larger ½" pipe 12" in length, used as a heating chamber for the gas. 100 W heating tape was used in the first iteration with fiberglass insulation directly wrapped around the heat tape to try to maintain high temperatures inside the heating chamber. A digital temperature controller measured the temperature of the heating tape and increased the temperature until a minimum of 600 °F was reached. At the end of the heating chamber, a stainless-steel cross was connected with an O2 sensor, thermocouple, and ball valve at each of the three ends. The gas was forced out of the ball valve but not before passing through the O2 sensor to measure the overall oxygen levels in the system and thermocouple to ensure sufficient temperatures internally for accurate readings. A multimeter measured the output voltage of the O2 sensor.

After the initial construction, when performing preliminary tests using the apparatus, it was found that the heating tape took an inordinate amount of time to heat to the temperature required for the O2 sensor to measure accurately and the internal temperature of the gas never reached the minimum of 600 °F. It was also found that direct contact with the heating tape caused the insulation to burn and emit fumes. With this in mind, the heating tape was replaced with 470 W heating tape which vastly decreased the startup time of the system and allowed the internal temperature to increase well past 600 °F along with an added 6” of heating chamber pipe. To avoid direct contact with the heating tape, steel Unistrut was slid over the heating tape and the ceramic fiberglass insulation was wrapped around the Unistrut. This helped maintain a much higher temperature inside the heating chamber. A picture depicting the final overall system can be found below for reference (see figure 6).

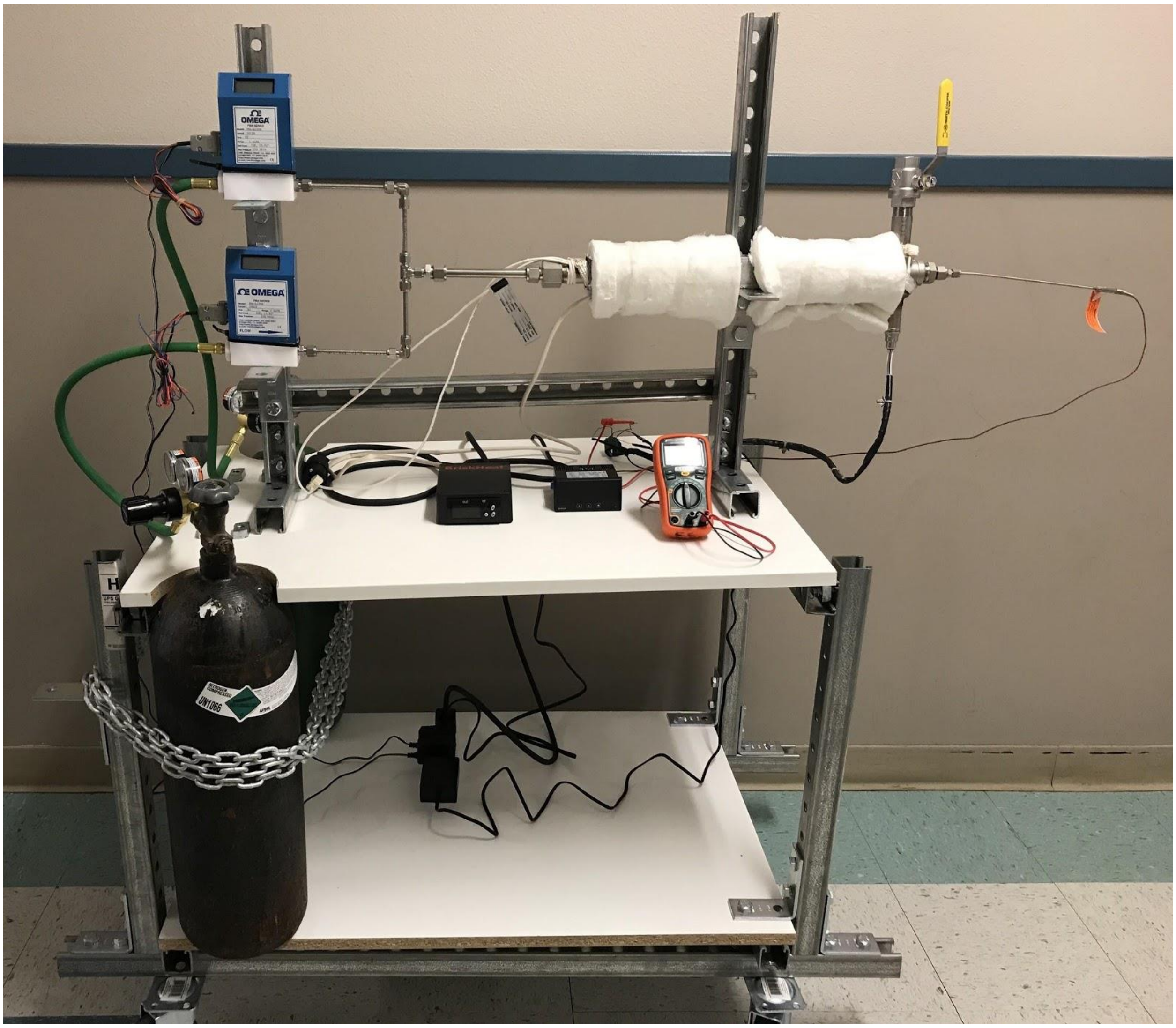

Figure 6: Final Testing System

VI. Testing

When the sensor system apparatus is internally set to a minimum of 600 °F, accurate testing can be obtained. The sensor system apparatus was subjected to a series of voltage measurements obtained from the oxygen sensor at different gas flow rates. The exit ball valve is opened at a chosen opening to maintain consistency of the obtained experimental results. The exit ball valve was specifically opened at the smallest opening possible to allow a healthy flow of mixed gas to accumulate within the system for the sensor to read while allowing enough gas to dissipate so the pressure at the output is not greater than the pressure from the two gas inputs. This way, gas backflow is prevented. The gas flow rate was changed accordingly by adjusting the pressure value of each gas cylinder. A series of gas flow rate combinations were set by adjusting the pressure value of each gas cylinder. The gas flow rate and oxygen sensor output voltage were obtained when the gas flows reached an identifiable steady state value. Below consists of plots from the experiment. Both plots measure voltage in respect with a specific gas flow rate over the total flow rate. Figure 7 displays the sensor voltage versus the nitrogen partial flow of the system. Figure 8 displays the sensor voltage versus the oxygen partial flow of the system.

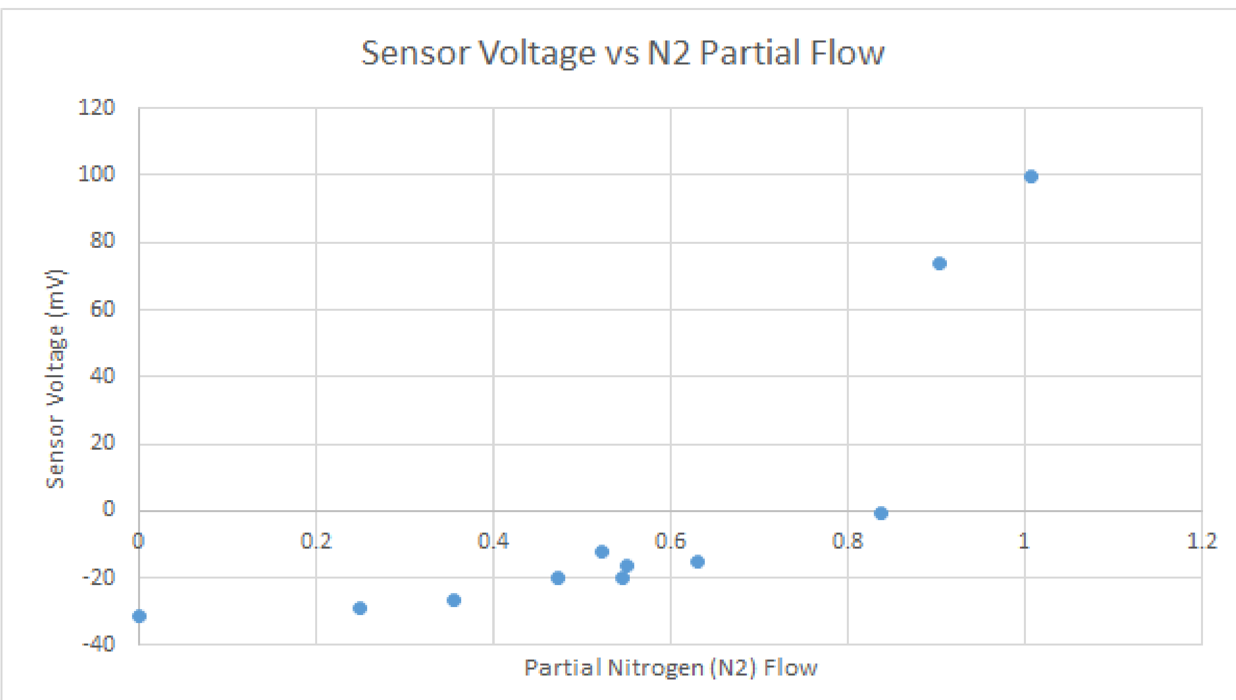

Figure 7: Sensor Voltage vs Partial Nitrogen Flow

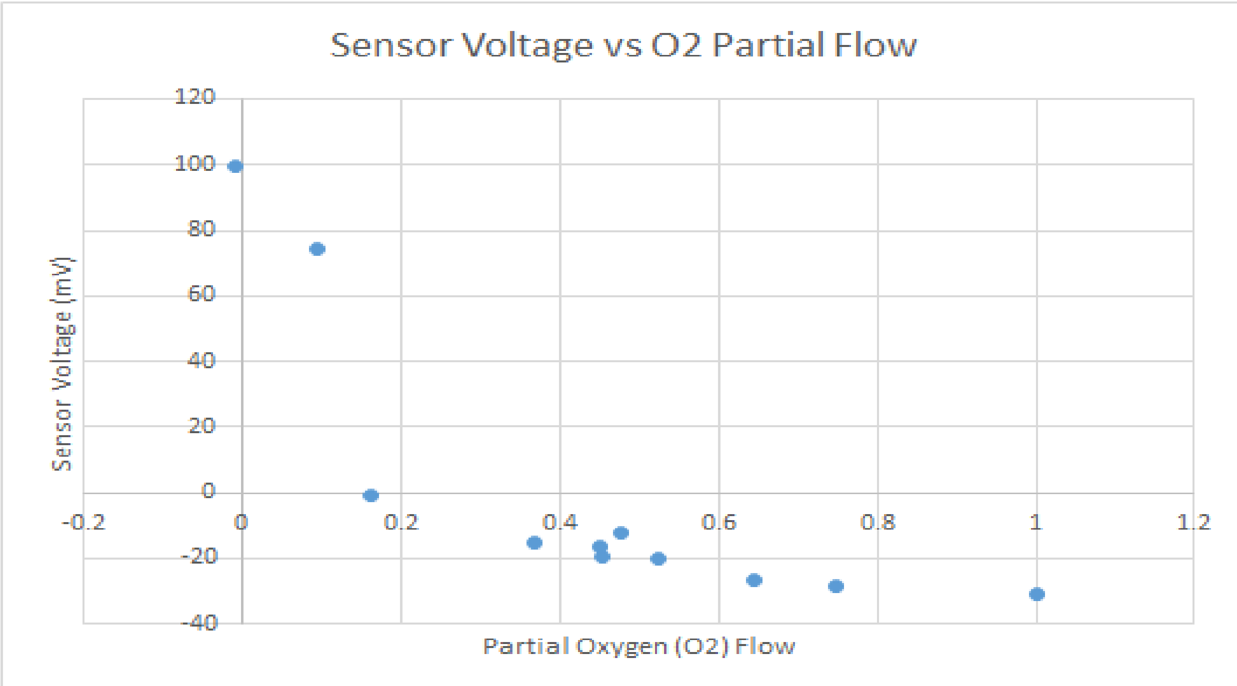

Figure 8: Sensor Voltage vs Partial Oxygen Flow

VII. Conclusions and Recommendations

This project created a reliable sensor system for combustion control. This sensor system serves as a testing apparatus for combustion-based gases such as oxygen and nitrogen. Currently, this system translates the internal oxygen gas concentration into a voltage while reading the gas flow rate from the mass flow meters. A future recommendation is to utilize the voltage as a feedback mechanism. First, a gas flow rate control mechanism is required. The most optimal way is to purchase mass flow controllers. A word of caution: From the numerous web research, mass flow controllers are quite expensive - typically double the cost of a typical mass flow meter. It is highly recommended to a high funding grant, prioritizing mass flow controllers as the first purchase. Then, successfully incorporate a microcontroller from the sensor to the mass flow controllers to establish a feedback system. The feedback system should be able to adjust the flow rate of the controlled gases accordingly based off from the measured voltage. Since the output voltage translates to amount of gas over the total gas within the system, one can control the flow rate of the gases based off the voltage from the oxygen sensor until it reaches a desired voltage. This feedback control is paramount for an ammonia-based combustion unit where NOx is emitted. NOx can be treated with ammonia, thus, by accurately controlling the fuel/air ratio, ammonia can be combusted for energy while treated the generated NOx to result in net zero emissions.

Another option is to keep the testing apparatus as is and incorporate a data acquisition processing system. The data acquisition system was purchased with the remaining funds in expectation that the project would expand to this route. The data acquisition system does exactly as the name entails. The system measures real world signals such as a voltage, current, temperature, or pressure and converts it to digital numerical values that can be read and manipulated by a computer. Through the use of a data acquisition system, students will be able to monitor readings and changes in real time accurately to establish a more reliable and stable feedback system instead of relying on empirical data. This is the recommended approach given the current status and most realistic attainable goal.

A research option this project can expand into would be a process called electrochemical impedance spectroscopy (EIS). As the name suggests, EIS can measure the nonlinearity impedance of different kinds of gases or elemental combinations at different conditions and states at an applied potential. For example, a student could measure the impedance of neon gas over a range of frequencies at a set temperature and generate bode plots for each tested gas. Another condition would be to measure the same neon gas at a set frequency but vary the polarization curve position. These are two examples of many if this project expands to the EIS route. This approach is also recommended and easily achievable.

Although this is quite the reach, assuming that future projects successfully established a reliable feedback system to fully suppress NOx emissions from ammonia combustion, another possible project would be to create an electric generator by installing turbines and power electronics circuitry.

VIII. Bibliography

[1] P.J. Bowen, W.I.F. David, M. Owen-Jones, A. Valera-Medina, and H. Xiao. "Ammonia for Power." *Progress in Energy and Combustion Science,* Vol 69, 2018, pp. 63-102. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S03601285 17302320?via%3Dihub. [Accessed: 17 November 2018].

[2] "Ammonia as Ship's Fuel: C-Job's Future-proof Way of Thinking." *C-Job*, 2017. [Online]. Available: https://c-job.com/ammonia-as-ships-fuel-c-jobs-future-proof-way-of-thinking/. [Accessed: 17 November 2018].

[3] C.H. Onder, C.M. Schar, and H.P. Geering. "Control of an SCR Catalytic Converter System for a Mobile Heavy-Duty Application." *IEEE Transactions on Control Systems Technology,* Vol. 14, 2016, pp. 641-652. [Online]. Available: https://ieeexplore.ieee.org/document/1645116. [Accessed: 17 November 2018].

[4] Omega Engineering, Inc., "GAS MASS FLOW METERS AND CONTROLLERS For Clean Gases With Optional Integral Display," FMA-A2306 datasheet. January 2016.

[5] Ramamoorthy, R., Dutta, P.K., Akbar, S.A., "Oxygen sensors: Materials, methods, designs and applications," *Journal of Materials Science*, vol. 38, no. 21, November 2003. [Online]. Available: https://link.springer.com/article/10.1023/A:1026370729205. [Accessed: 30 November 2018].

[6] Gardner, L., Insausti, A., Ng, K.T., Ashraf, M., "Elevated temperature material properties of stainless steel alloys," *Journal of Constructional Steel Research*, vol. 66, no. 5, May 2010. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0143974X10000027. [Accessed: 10 December 2018].

[7] Ogata, T., "Creep-fatigue damage and life prediction of alloy steels," *Materials at High Temperatures*, vol. 27, no. 1, March 2010. [Online]. Available: https://search-proquest-

com.ezproxy.lib.calpoly.edu/materialscienceengineering/docview/1243350394/fulltextPDF/7C3E3F5AEE4E4A77PQ/1?accountid=10362. [Accessed: 10 December 2018].

[8] ‘Light vehicle retail sales in the United States from 1978 to 2018 (in 1000 units)’, February 2019. Available: https://www.statista.com/statistics/199983/us-vehicle-sales-since-1951/. [Accessed: 16 November 2018].

[9] Adriano, D.C., Dudka, S., “Environmental Impacts of Metal Ore Mining and Processing: A Review,” *Journal of Environmental Quality*, vol. 26, no. 3, p. 590-602, May 1997. [Abstract]. Available: https://dl.sciencesocieties.org/publications/jeq/abstracts/26/3/JEQ0260030590. [Accessed: 1 December 2018].

[10] R. R. Yager, A. J. Grichnik and R. L. Yager, "A Soft Computing Approach to Controlling Emissions Under Imperfect Sensors," in *IEEE Transactions on Systems, Man, and Cybernetics: Systems,* vol. 44, no. 6, pp. 687-691, June 2014. [Online]. Available doi: 10.1109/TSMC.2013.2268735. [Accessed: 10 December 2018].

[11] Weibel, E.R., “Oxygen Effect on Lung Cells,” *Arch Intern Med.*, vol. 128, no. 1, p. 54-56, July 1971. [Abstract]. Available: https://jamanetwork.com/journals/jamainternalmedicine/article-abstract/578124. [Accessed: 16 January 2019].

[12] Abbott, R.C., “Gas heating apparatus and methods,” U.S. Patent 12, 070, 713, 20 February, 2007.

[13] Wang, A., Tolley, H.D., Lee,, M.L., “Gas chromatography using resistive heating technology,” *Journal of Chromatography A*, vol. 1261, p. 46-57, October 2012. [Online]. Available: https://www.sciencedirect.com/science/article/pii/S0021967312007236. [Accessed: 10 January 2019].

Appendices

A. Senior Project Analysis

Project Title: Sensor System for Combustion Control

Student's Name: Aodhan Arias, Joshua Wong, Joeny Zhen

Student's Signature:

Advisor's Name: William L. Ahlgren

Advisor's Initials: WLA

Date: 6/12/19

• 1. Summary of Functional Requirements

The system must accept nitrogen and oxygen gas inputs, measuring the flow rate of each as they enter the system. The heating stage must heat up the mixture of nitrogen and oxygen gas as well as the O2 sensor to operating temperature (at least 600 °F). The O2 sensor outputs a voltage corresponding to the oxygen content in the system.

• 2. Primary Constraints

Significant challenges encountered during the project include implementation and budget costs. Heating the gas and O2 sensor was a major challenge due to the high required operating temperature. A thermocouple was required to provide insight on the internal temperature, indicating whether or not the sensor had reached the required temperature. Since the system reaches high temperatures, materials with high temperature tolerance were used to prevent deformation of the components. The provided project budget limited implementation as well. Mass flow meters can reach prices of over $700 each and heating tape with a temperature controller can cost over $300. With a $5000 budget, selecting quality parts was difficult. To allow future groups to advance development easier, an adjustable framework was constructed so that it can be configured in such a way that it fits any new additions or changes to the system.

• 3. Economic

The system requires high financial capital due to expensive temperature controller and mass flow meter costs. Mass flow meters alone can cost over $700 each. Multiple disciplines including electrical engineering, mechanical engineering, and chemistry must work together and apply their knowledge to create the system. This results in a high human and manufactured capital. Natural capital includes oxygen and nitrogen. Natural capital also includes metals used to construct the framework and the components of the system itself.

There were significant initial costs to build the system in the beginning of the project's life cycle, but the benefits began to accrue during the testing phases of the project. When components needed to be changed, the dimensions of the system would also change in such a way that the framework couldn't support it correctly. By building the framework out of reusable unistrut, a new framework did not have to be built since it was made to be adjustable. In the long term, a lot of money and time was saved by using the unistrut.

The project required oxygen and nitrogen gas, as well as 120 VAC from a wall outlet to power all of the electronics. The estimated cost of parts settled close to $5000. The actual final cost of the project was $3325.01 (see Bill of Materials in Appendix B). The project itself does not earn any money, but future groups who continue this project will benefit from the system that is made to work with interchangeable components. It is a convenient platform upon which further advancements can take place.

The product should last at least 5 years before needing replacement. Operating costs may include replacing the sensors used in the system and replacing the stainless steel pipes due to wear and tear [7]. The project reached completion on May 31, 2019. In the future, hopefully groups will continue to work on this project to eventually implement ammonia combustion.

• 4. If manufactured on a commercial basis:

This project is like a simple version of a catalytic converter without the feedback loop, since this project does not have the capability to control the ratio of the gas inputs. This project simply reads the voltages from the O2 sensor. If the estimated manufacturing cost could be reduced to $1800 and the product sold for $2000 each, then the profit for each product is $200. Approximately 15 million light vehicles are sold in the U.S. each year [8]. Assuming each vehicle had a catalytic converter built in, the profit would approximately be $3 billion. The customer should not have to maintain the product. However, if the catalytic converter needed to be replaced for the assumed 5 year lifespan, then the operating cost would approximately be $400/year.

• 5. Environmental

Many components of the project are made of stainless steel. Mining metals has a severe impact on environmental degradation. A huge amount of waste is produced in the mining process because "the ore is only a small fraction of the total volume of the mined material [9]." There are also gaseous and solid wastes associated with smelting and refining the metals.

The project directly uses oxygen and nitrogen gas, which can be found in the air. Indirectly, the project utilizes oxygen released by plants and ore that is naturally formed in the Earth. The project harms ecosystems indirectly by producing a lot of waste during metal processing. The habitats of other species could have been potentially destroyed in the process.

• 6. Manufacturability

Manufacturing issues may include malfunctioning products due to faulty sensors. Inaccurate measurements may lead to incorrect interpretations of the contents of the system. A software approach can compensate for imperfect sensors [10].

• 7. Sustainability

Nitrogen and oxygen, the main inputs of the system, are commonly found in the air, making them a sustainable and easily accessible resource. Main issues with maintaining the system include changing the sensors. Sensors in vehicle emission control systems wear down and sometimes need replacement. The high cost of sensors make replacement a hassle. Building the sensors out of a more durable material can reduce the frequency of sensor replacement. However, more durable materials results in a higher cost for the manufacturer and the customer. Using recycled materials may provide a sustainable building option.

• 8. Ethical

This project is the first iterative step towards utilizing ammonia as an alternative fuel. The overall goal of the project is to find a fuel source that is zero carbon. If the project progresses enough, it can show that ammonia is a viable zero-carbon fuel. Everyone benefits since using a zero carbon fuel reduces contribution to global warming. While the sensor system can provide benefits when used correctly, misuse can lead to life-threatening conditions. Improper use of the heating materials can cause harm to others and damage property. Misuse of the gases used in the project can lead to respiratory problems, potentially suffocating or poisoning others in the vicinity. To ensure the project does not void IEEE ethics guidelines, research was conducted to determine the value of the project as a whole. Accurate measurements collected during testing showed the functionality of the structure and the convenience of the setup. There are many safety precautions associated with the project. These precautions were made public knowledge to the group members and whoever is involved. Using the heating apparatus to harm others is an example of an unethical application of this project. Safety standards and precautions are intended to prevent such applications.

• 9. Health and Safety

Humans need to breathe oxygen to survive. This project works with pure nitrogen gas. If the testing environment becomes filled with pure nitrogen, then there is no oxygen left to breathe, leading to lethal consequences. The project also uses pure oxygen. Breathing pure oxygen for a long period of time can result in damage to lung cells [11]. To avoid the dangers of having too much of either gas, the system should be operated in well ventilated areas. Additional caution must be taken when working with the oxygen. The area must be clear of fire since oxygen can escalate the severity of the fire. Heating tape is used to bring the O2 sensor and gas mixture to operating temperature. This tape can reach almost 1000 °F and is a fire hazard. The power must be turned off after use for safety.

• 10. Social and Political

Since this project is a multi-year project, future groups that continue the project are the direct stakeholders. This project provides a structure upon which they can continue to advance the system and implement new components, saving both time and money. Future groups also have a responsibility to uphold the safety standards that come with the project. Standards must be kept to prevent damage to the system and to the surrounding lab environment. California Polytechnic State University is an indirect stakeholder of the project. It is stored and tested in Cal Poly labs. If the primary stakeholders fail to uphold safety measures and an accident occurs, the school may potentially be held responsible for damages. An accident of a larger scale may attract bad publicity to Cal Poly, affecting the reputation of the STEM program, potentially harming graduates' chances for jobs. It is unfair for others to suffer consequences when safety hazards can easily be controlled.

• 11. Development

Heating the O2 sensor was a crucial task in the project. The sensor needed to reach a temperature of 600°F in order to operate properly. Since oxygen was being used in the project, heating using fire was out of the question for safety reasons. An alternative solution was required. Through research, multiple heating methods were found. One method described a "thermal spray coating process [that] can be used to deposit coatings that behave as heaters when electrically energized [12]." Another method involved using a resistive heating element [13]. Although the thermal spray heater is more efficient, the resistive heating element was chosen due to its ease of use and accessibility.

B. Parts List and Costs

Table 9 below lists all of the parts used in the project. The table details the part used, price per part in USD, the quantity of that particular part used, and the total price of the parts in USD.

TABLE 9
BILL OF MATERIALS

Part	Price ($)	Quantity	Total Price ($)
FMA-A2306 Mass Flow Meter	715.58	2	1431.16
O2 Gas+ Size 60 Container	175.86	1	175.86
N2 Gas+Size 60 Container	177.17	1	177.17
Oxygen Regulator	100.02	1	100.02
Inert Gas Regulator	100.00	1	100.00
¼” Grade R Hose	1.27/ft	4	5.08
Brass Inert Gas Male Nut ARC	1.89	1	1.89
Oxygen Hose Nut	1.85	1	1.85
¼” Brass Barbed Nipple	1.85	1	1.85
Inert Gas Barbed Hose Nipple	2.98	1	2.98
¼” Tube x ¼” MPT Male Connector	2.84	2	5.68
6 ft. ¼” Stainless Steel Tubing	26.06	1	26.06
6 ft. of ½” Stainless Steel Tubing	25.05	1	25.05
½” Tube x ¾” FNPT	30.84	1	30.84
¼” Union Tee	25.16	1	25.16
½” Tube x ¼” Tube Adapter Reducer	20.53	1	20.53
¼” Union Elbow	17.90	2	35.80
¼” Tube x ¼” MNPT Connector	8.00	2	16.00
18” of ¾” Threaded Stainless Steel Pipe	17.55	1	17.55
¾” Stainless Steel Cross	11.20	1	11.20
Digital Temperature Controller	277.00	1	277.00

470 W Heating Tape	90.00	1	90.00
12” x 8” Ceramic Fiber Insulation	18.80	1	18.80
Bosch O2 Sensor	55.78	1	55.78
O2 Sensor Fitting	18.35	1	18.35
¾” Ball Valve	23.97	1	23.97
⅜” Tube x ¾” MNPT Connector	19.06	1	19.06
⅛” x ⅜” Bored-Through Reducer	12.85	1	12.85
K-Type Thermocouple	37.31	1	37.31
Panel Meter	110.00	1	110.00
12 ft. of 3/16” Chain	47.10	1	47.10
Bolt Snap	7.48	1	7.48
Multi-Volt AC-DC Adapter	29.99	1	29.99
Generic Outlet Plug	4.99	1	4.99
6 Outlet Power Strip	4.24	1	4.24
20 Pk. 14” Cable Ties	3.78	1	3.78
23.75” x 48” Melamine Boards	15.96	2	31.92
5” Rubber Caster	11.97	4	47.88
5/16” Washers	1.18	3	3.54
5/16” Jam Nuts	1.18	2	2.36
5/16” x 2” Carriage Bolts	0.41	16	6.56
1-⅝” x 1-⅝”, 12 Guage Unistrut	2.03/ft.	60	121.80
4 Hole 90 Degree Bracket	2.22	20	44.44
½”-13 Channel Nut	0.68	80	55.01
½” x 1-¼” Hex Bolt	0.16	80	13.01

C. Schedule - Time Estimates

Table 10 below lists major deadlines throughout Winter 2019 and Spring 2019. These deadlines are benchmarks that keep the project on track to completing on time.

TABLE 10
SENSOR SYSTEM DELIVERABLES

Delivery Date	Deliverable Description
1/14/19	Design Review
3/8/19	EE 461 demo
3/15/19	EE 461 report
5/31/19	EE 462 demo
5/31/18	ABET Sr. Project Analysis
5/31/18	Sr. Project Expo Poster
5/31/18	EE 462 Report

Figures 9 to 11 below are gantt charts for the project. Each gantt chart shows the progress of multiple tasks throughout the year. Following the gantt charts helped keep the project on schedule and completed on time.

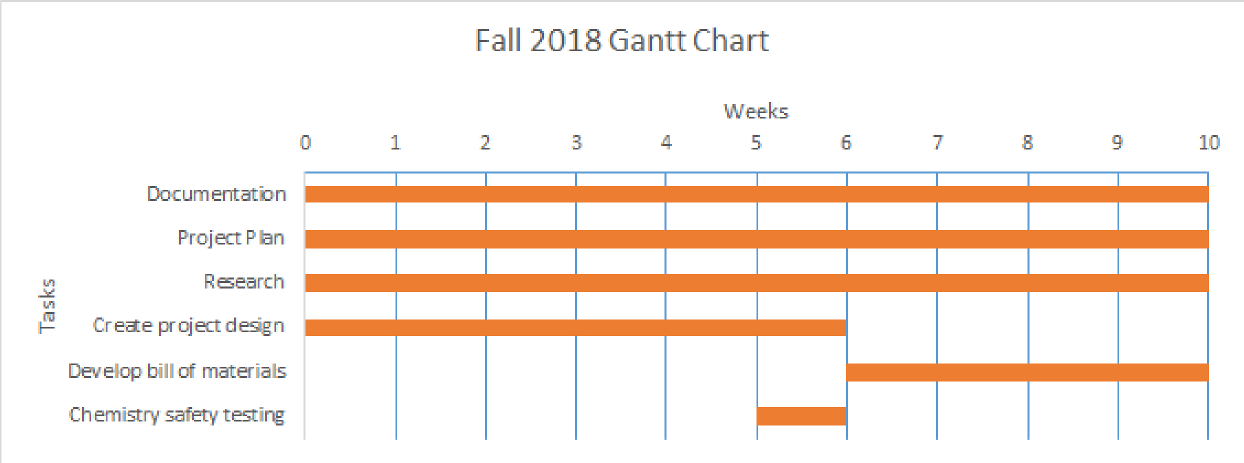

Figure 9: Gantt Chart for Fall 2018 Quarter

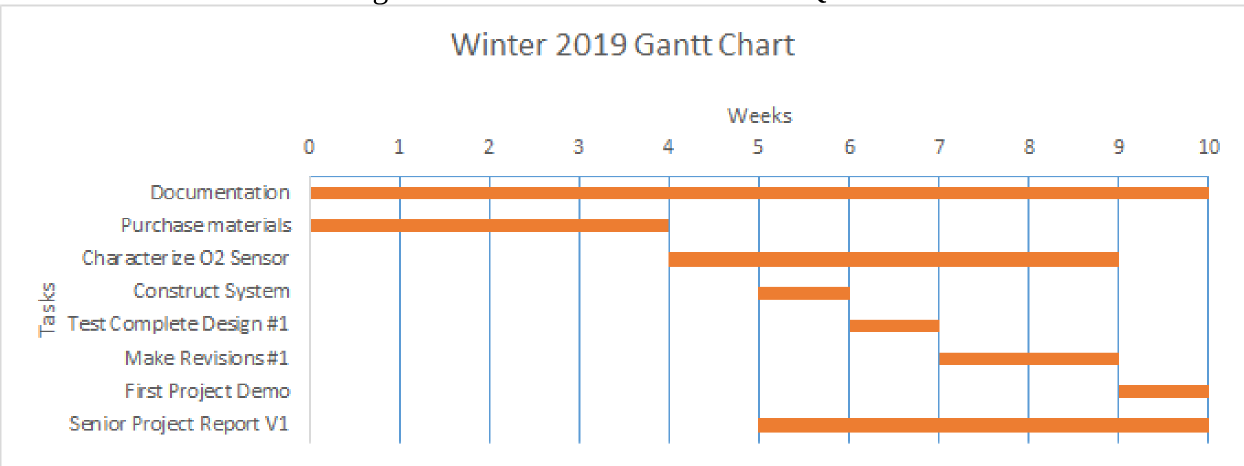

Figure 10: Gantt Chart for Winter 2019 Quarter

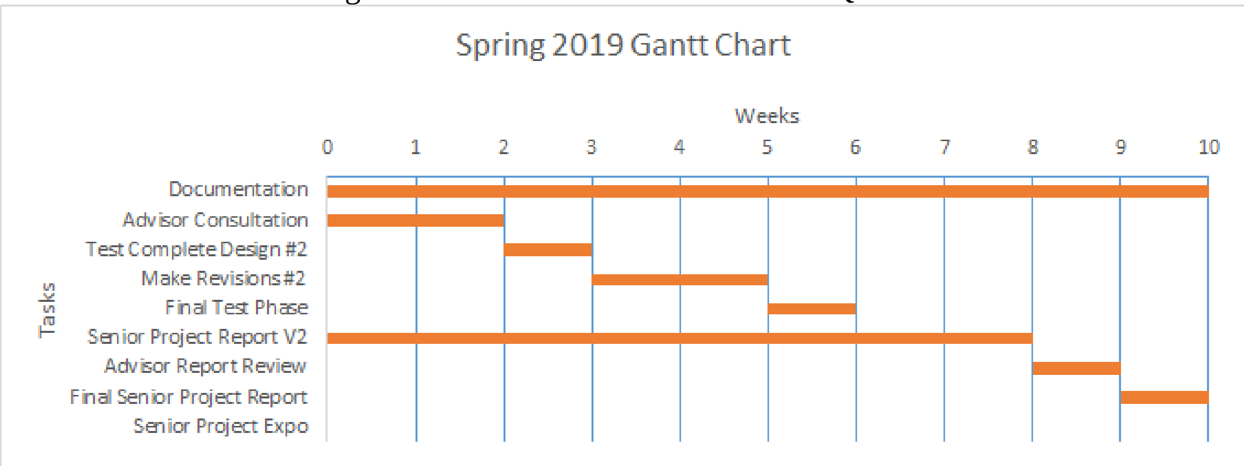

Figure 11: Gantt Chart for Spring 2019 Quarter