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Methane Sensing in the Field

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Methane Sensing in the Field

A Senior Project submitted to
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of
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by
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Abstract

Is renewable energy as beneficial to our environment as we think? The demand for renewable energy has drastically increased over the last century due to the overuse of most fossil fuels, but the possible side effects of these new forms of energy must be carefully considered. One particular case of interest is that of methane emission from reservoirs formed behind hydropower dams. Due to the anaerobic bacteria decomposition of plant matter under water, methane is emitted from these types of wetland areas. This research thesis aims to investigate the feasibility of remote-controlled methane sensing which would provide concentration data at desired locations near or above the surface of any wetland formed behind a hydropower dam. This data would provide insights into how these greenhouse gas emissions should be factored into an overall cost-benefit analysis of the renewable energy produced by the hydropower system.

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Dedication

For my Mother and Father who have supported me continuously throughout my life.

Acknowledgments

The creation of this Senior Project would not have been possible without the assistance of the following individuals:

I would first like to express my gratitude to my advisor, Professor Matthew Deady of the Physics Department. His endless assistance spanning all areas of my undergraduate study has made a profound impact on my experience at Bard College as well as my future endeavors. Over the years Professor Deady has not only been a mentor but has also become a role model and truly a close friend.

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Last but not least, I would like to express my appreciation towards my Mother and Father, as well as the rest of my family for their consistent interest and support throughout my life and this research. They have continuously pushed me to reach my full potential and without them I would not be where I am today.

1

Introduction

1.1 Overview

Greenhouse emissions have become a pressing threat to the future of the planet. Greenhouse gasses are a major concern for the long-term sustainability of our environment and has emerged as a particular greenhouse gas that exacerbates climate change/global warming. These types of gasses increase the temperature of the atmosphere by absorbing heat and they include carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), and halocarbons (a group of gases containing fluorine, chlorine or bromine) which come from industrial processes carried out by humans[1]. Over the last one hundred years alone, methane levels have risen over fifty percent[1]. Between the years 1500 and 1800, there was a steady average of slightly less than 700 parts per billion (PPB) of methane in the earth's atmosphere. However, methane levels have alarmingly risen over fifty percent just within the last one hundred years. Methane levels reached a record 1860 PPB in 2018[1]. As shown in Figure 1.1.1, after thousands of years of stable methane levels, human civilization has dramatically increased concentrations to a dangerous level.

Although methane only accounts for about ten percent of all greenhouse gases produced by human activity in the United States, it remains one of the most efficient gases at

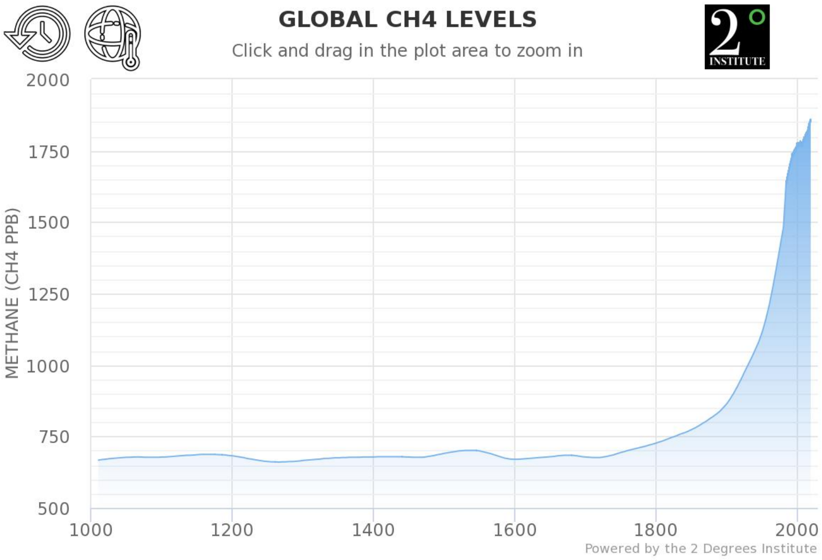

Figure 1.1.1. Global CH_4 Levels from ∼1000 to 2018[17]

absorbing solar radiation. Methane is initially far more devastating than gases such as carbon dioxide and causes sharper short-term warming even though its effects dissipate much more quickly than other greenhouse gases. Methane is 84 times more potent than carbon dioxide in the first two decades after its release[4].

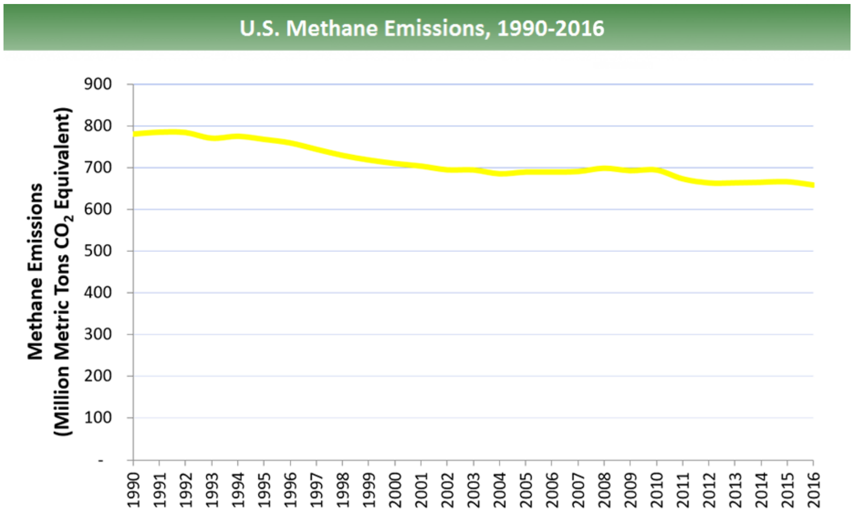

Figure 1.1.2. U.S. Methane Emissions, 1990-2016[2]

As shown by Figure 1.1.2, methane emissions have slowly decreased between 1990 and 2016. During this period, methane emissions coming from agricultural sources slightly increased while emissions from sources associated with coal mining, landfills, and the distribution of petroleum products and natural gas decreased[2]. Although this may be a step in the right direction with regards to protecting the future of our atmosphere and biosphere, there is still a long way to go before mankind should feel at ease.

1.2 Methane Emission

Methane comes from many sources, both natural and manmade. The largest sources of industrial emissions are the petroleum systems and natural gas industry. Natural gas is a commonly used fuel source composed of roughly 90 percent methane[6]. The natural gas which reaches your home to produce heat is almost purely methane. Before natural gas reaches your home, it is pumped from wells that are drilled to obtain natural gas. From there, the gas is then pumped through a complex array of pipelines which include many connections, fittings, and valves where the gas could potentially leak out into the atmosphere. Since the production, refinement, transportation, and storage of petroleum is usually accompanied by gas, these processes are often sources of methane emission as well[2]. Methane can also be released if there are any leaks during the drilling process for natural gas. Another significant source of methane production is from domestic livestock in the agricultural sector. As part of their standard digestive process, animals such as goats, sheep, buffalo, and cattle produce large quantities of methane. From cattle in particular, burps are how methane is released from their bodies. According to the Environmental Protection Agency (EPA), this enteric fermentation within the cows' stomachs that produces methane is responsible for 26 percent of methane emissions in the United States. This makes livestock the second largest methane emission source in the U.S.[7]. Management and storage of livestock manure also contributes to methane emission. Because humans raise these animals for their potential resources, the methane emissions they emit are considered to be human-related[5]. Another source of methane emission occurs during the coal mining process when pockets of this gas are released into the atmosphere. A usually unidentified location where methane is emitted is in marshy or swampy areas. These locations are usually home to copious amounts of decaying underwater plants and a lack of oxygen, creating conditions in which bacteria live and produce methane. These bacteria are known as Methanogens, microorganisms that produce methane as a metabolic byproduct in oxygen-starved environments.

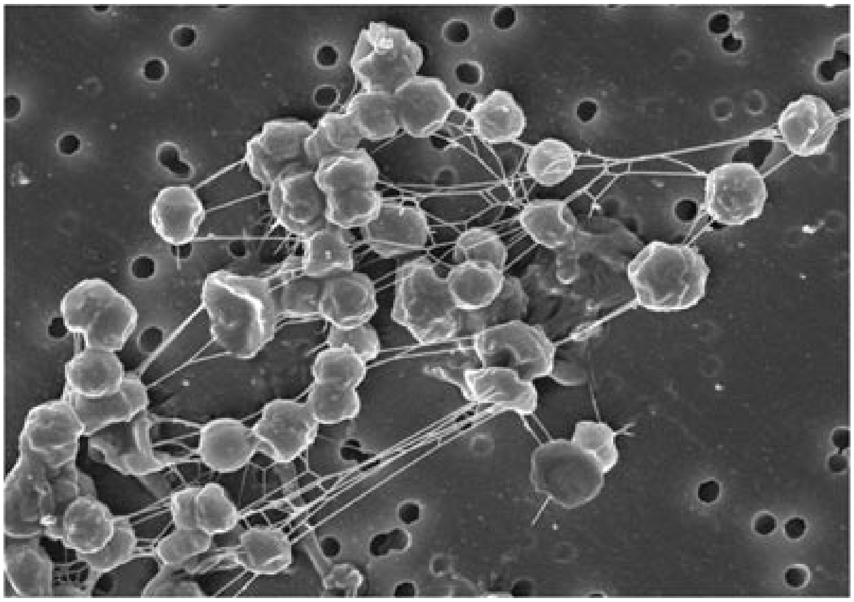

Figure 1.2.1. Methanogens[18]

Methanogens eat away at decaying organic matter just as animals and humans consume food for energy. However, instead of producing carbon dioxide, these microbes release methane into their surroundings through a process identified as methanogenesis[7]. These microbes are very similar to those that exist in landfills and in the stomachs of livestock[7]. As the methane is released from the methanogens, it will rise to the water's surface as bubbles and be released into the atmosphere. There are also certain factors that affect how much methane a reservoir may emit. Similar to other organisms, methanogens will live a more productive life if they consume foods that are nutrient-rich. This means that if reservoirs are located closer to agriculturally active areas, then there will be more runoff carrying nutrient-rich water and algae to these methanogens. Ultimately, these microbes will produce much more methane.

1.3 Attempted Solution: Renewable Energy

People continuously attempt to create methods of clean and renewable energy which will limit the amount of harmful gases released into the atmosphere. One form of renewable energy which is being implemented around the world is hydroelectric power. Hydropower refers to the conversion of kinetic energy from flowing or falling water into electrical energy. Hydroelectric power can be generated in multiple ways such as a 'run-of-river' installation or with a traditional dam. A run-of-river installation uses naturally flowing water to turn one or more turbines and dams that are used to store the water's energy. A hydroelectric dam obstructs a flowing body of water and blocks its path downstream. Water collects on the upstream side of the dam, forming a reservoir.

Although hydropower is often associated with saving the environment, it may be time to reassess all potential impacts of a hydropower setup on the environment. Over the past several decades, hydropower has taken off in an effort to reduce mankind's footprint on Earth. This concept of using natural resources to fuel our never-ending desires and ambitions seems like a win-win situation. When renewable energy is used instead of burning fossil fuels, the atmosphere is protected and mankind benefits from electricity produced in the process. However, an unfortunate side effect of this clean energy is the amount of methane that is indirectly released into the atmosphere. Although hydropower creates clean and reusable energy, methane production from behind hydropower dams is rarely considered. As previously discussed, methane is produced in marshy areas where oxygen is scarce and anaerobic decomposition occurs. By constructing dams and implementing hydropower in one of society's sources of energy, we may actually be increasing the amount of methane sources across the globe. Researchers previously believed that roughly twenty percent of man-made methane emissions comes from the surface of reservoirs[7]. It is now believed that this percentage is much larger than previously expected, yeta lack of available data makes it difficult to estimate this value. Because very little is known about emissions from man-made reservoirs, we are desensitized to just how much methane is emitted from these reservoirs. One comparison that can be made is between the quantity of methane being released from these reservoirs and from actual livestock. In 2012, Harsha Lake, a large reservoir near Cincinnati, Ohio, released as much methane into the atmosphere as roughly 5,800 cattle would have released over the course of a year[7]. This should warn us that hydroelectric dams may not be entirely environmentally friendly. The increased methane emissions from the reservoir formed behind the dam combined with the increased carbon dioxide output by the implementation of the hydroelectric turbine itself raise enough concern for hydropower's implementation to be carefully monitored and studied. According to a study conducted by a team of researchers from Harvard and several other institutions, methane levels may be much higher than previously believed[8]. Primarily in south-central United States, livestock operations are suspected to emit twice the amount of methane than what was formerly understood[9]. This study also suggests that all larger reservoirs could potentially emit up to 104 teragrams of methane annually on a global scale[7]. There were also a series of tests performed near Harsha Lake reveal that the spot at which the river flows into the man-made lake has a larger reading for methane emission than the rest of the lake overall[7]. There is likely little research that maps methane emissions as a function of position over a reservoir and as a result, the quantity of methane released into the atmosphere may once again be underestimated. To put this in perspective, NASA has previously estimated that worldwide methane emissions that are related to the burning of fossil fuels range between 80 and 120 teragrams annually [7]. Although questions circulate around the topic of reservoir methane emission, there is still a lack of data recorded which could help researchers identify the necessary steps to reduce the emission of such a harmful greenhouse gas.

1.4 How to Study the Emissions

Ultimately, there remains an urgent need for more information on how much methane is being released into the atmosphere from specific locations such as swamps or marshes behind dams. Ideally, this data would help us determine the amount of methane that is emitted from many previously unknown areas. This information would also help us understand the various benefits of clean energy sources by comparing their renewable energy output to their detrimental effects on the environment. As previously discussed, these second-hand effects could include increased methane emission from a reservoir behind a newly constructed dam. Above all, the question of accessibility must factor into consideration when measurements are inevitably taken in remote locations. Certain areas may be difficult or impossible to access by foot, while some locations may be too dangerous for people to access without significant safety gear and precautions. One proposed solution is to have a small and easily maneuverable methane sensor that would be able to access remote regions. In order for this sensor to have the desired characteristics, it was necessary to search for the smallest possible sensor that is lightweight and also easy to transport. Our next task was to find the most suitable method for transporting the sensor to desired measurement locations. Most methods included some form of remote controlled transportation such as using an aerial drone that could gather concentration measurements at various locations above the surface of a reservoir. Another option could be a remote controlled boat that would travel on the surface of the reservoir and take measurements in a more stable setting accounts for air movement and sensor stability. From here, we will move forward in researching different types of methane sensors and determine which one would be the most appropriate and feasible for this research.

2

Methods

2.1 Types of Methane Detectors

A methane gas sensor is a key instrument in determining the amount of methane in a specific region or the amount of methane that is being emitted by that same region. There are several types of methane gas sensors that exist and there are pros and cons associated with each of them. The two main types of technologies used in methane sensors are infrared sensors and catalytic bead sensors.

2.1.1 Infrared Gas Sensors

The following information on infrared gas sensors has been gathered from *Hazardous Gas Monitors: A Practical Guide to Selection, Operation and Applications* by Jack Chou.

An infrared gas sensor uses an infrared light source to measure the concentration of a desired gas. One of the main benefits of using an infrared sensor is its longevity. This is because the gases being detected never come in direct contact with the detector itself due to the optical equipment protecting it.

There are a few key components of an infrared gas sensor that can be arranged in various ways in order to give you a sensor with desired characteristics. The first component of any infrared sensor is the detector itself. These detectors will take electromagnetic radiation energy or temperature changes and convert them into electrical signals. The second component is an infrared source. There is some flexibility when it comes to this source but any light that can provide enough radiation at the correct wavelength of interest for targeting a certain gas will be sufficient. Another component necessary for an infrared gas sensor is an optical filter and these filters can be split into two categories. The first type is a dispersive filter which utilizes a grating or prism in order to spread the reflected light out over an area, allowing for the sensor to analyze specific portions of that reflected spectrum. The second type of optical filter is nondispersive infrared (NDIR). This type of filter is similar to sunglasses in that it filters out unwanted UV radiation, only allowing for the desired wavelengths to reach the detector. The final required component of an infrared gas sensor is a gas cell/light path which is shown in Figure 2.1.1:

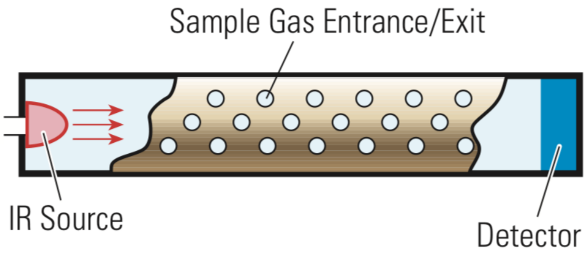

Figure 2.1.1. Gas Cell/Light Path[11]

In this cell, an infrared light source is placed at one end and a detector is placed at the other. The gas being sampled is allowed to flow freely through the cell, coming in contact with the infrared beam. The length between the light source and the detector is known as the path length and this length is directly proportional to the amount of radiation absorbed by the detector. That is, as the path length increases, the area where the gas interacts with the light source also increases, allowing the light source to absorb more radiation and in return, produce a larger signal.

The basic principle of operation for an infrared sensor mainly deals with the infrared spectrum and frequencies. The sensor uses a beam of infrared light containing a range of spectral wavelengths which interacts with the sample gas molecules. When this infrared radiation interacts with the gas molecules, part of the radiation energy has the same frequency as the gas molecule's natural frequency. In this case, the radiation will be absorbed into those molecules. If the molecules do not a have the same natural frequency as the infrared source then the light will be transmitted through the gas. In the case where the energy is absorbed by the molecules, the molecules will begin to vibrate and increase in temperature, therefore producing a larger signal for the detector to read.

There are multiple ways to configure an infrared gas sensor and the simplicity of these designs will vary depending on the application. Cases requiring a limited accuracy will only need a simple configuration consisting of essential elements. In cases that require greater sensitivity and accuracy, the developed sensors will need to be more complex.

Although infrared gas sensors seem like the logical choice when choosing between various sensors, they do come at a cost, both in weight and price. A combination of these factors might be enough to deter one from purchasing this type of sensor especially if it is for a low budget project which involves moving the sensor with potentially small remote controlled vehicles.

2.1.2 Catalytic Bead Gas Sensors

Catalytic bead gas sensors have been used for many years before infrared gas sensors were developed. This type of sensor contains a micro aluminum oxide (Al_2O_3) ceramic tube which is coated with tin oxide (SnO_2), where the tin oxide layer is the region of the sensor that is exposed to surrounding gases. For now, we will refer to this tin oxide coated ceramic tube as the bridge. Tin oxide was chosen to coat the ceramic tube because of its semiconductor properties. Before going further into how the sensor operates we will take a step back and discuss the properties of semiconductors.

Electrons occupy specific energy levels in an atom. When two atoms interact, these energy levels begin to shift around. When many atoms interact, like in a solid metal, individual energy levels smear into energy bands. In order for a material to conduct, electrons must be able to jump from lower energy bands to higher energy bands. The spacing between these energy bands is what determines whether a material is a conductor, insulator or a superconductor. When energy bands are close enough together where electrons can jump between bands, current is able to flow and these materials are classified as conductors. Metals have no gap between energy bands and therefore it is very easy for electrons to travel freely throughout the material, making them great conductors. If energy bands are too far apart and electrons cannot make the jump, no current flows and these materials are known as insulators. Semiconductors fall in the middle, having a medium size band gap. While under standard conditions semiconductors may act as insulators, with a little push, electrons can gain enough energy to make the jump to a higher energy band. Some methods used to change the conductivity of semiconductors are applying heat and electric currents.

In a catalytic bead sensor, a resistor is placed closely to the bridge in order to heat the tin oxide to the required temperature. A current is then passed through the bridge, giving the bridge a calculable resistance. This resistance is then affected by the interaction between the tin oxide layer and surrounding gases. To describe this process we will use the interaction between the sensor and methane as an example.

When methane in the air comes in contact with the tin oxide layer of the bridge, the following chemical reaction occurs:

$$\mathrm{SnO_2} + 2\,\mathrm{CH_4} \longrightarrow \mathrm{Sn} + 4\,\mathrm{H_2} + 2\,\mathrm{CO} \tag{2.1.1}$$

Here we can see that the methane provides the tin oxide with electrons, therefore changing the resistivity of the bridge. From here, a Wheatstone bridge is used to determine this resistance.

A Wheatstone bridge, as shown in Figure 2.1.2, allows us to find the resistance of an unknown resistor which in our case is the bridge in a catalytic bead sensor.

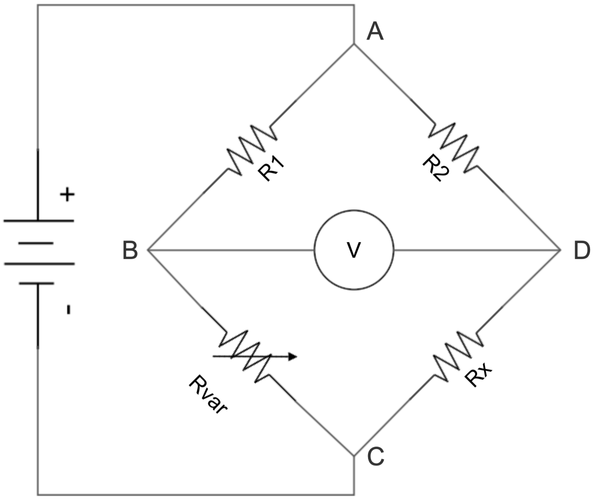

Figure 2.1.2. Wheatstone Bridge

In this circuit, R_1 and R_2 are resistors with well known resistances, R_{var} is a variable resistor, and R_x is a resistor with an unknown resistance. A Wheatstone bridge operates as a balance that "weighs" the resistances of each of the two paths of its circuit. It uses a voltage reading between points B and D to quantify this "balance".

Now we will attempt to solve for R_x by utilizing Ohm's Law:

$$V = I \cdot R \tag{2.1.2}$$

Next we will solve for voltage drop over R_1 and R_{var}:

$$V_1 = I_{ABC} \cdot R_1 \tag{2.1.3}$$

$$V_{var} = I_{ABC} \cdot R_{var} \tag{2.1.4}$$

Here, V_1 and V_{var} are the voltage drops over R_1 and R_{var}, respectively, and I_{ABC} is the current passing through each of these resistors. Now if we divide Equation 2.1.3 by Equation 2.1.4 we get:

$$\frac{V_{var}}{V_1} = \frac{R_{var}}{R_1} \tag{2.1.5}$$

And if we do the same for the resistors on path ADC we get the following:

$$\frac{V_x}{V_2} = \frac{R_x}{R_2} \tag{2.1.6}$$

Equations 2.1.5 and 2.1.6 show that the voltage at points B and D are only dependent of the ratio between the upper and lower resistors on each path. The objective of a Wheatstone bridge is to have a voltage measurement of zero between points B and D, meaning there is no difference in potential between the two points. If this were the case, we can conclude the following:

$$\frac{R_x}{R_2} = \frac{R_{var}}{R_1} \quad \implies \quad R_x = R_{var} \cdot \frac{R_2}{R_1}\ . \tag{2.1.7}$$

In other words, if the voltage between points B and D is zero, then the ratio of the upper and lower resistors on each side of the circuit are equal. This fact will be used to calculate the unknown resistance.

Within a catalytic bead sensor, the variable resistor in the Wheatstone bridge sweeps over a range of resistances until the voltage between points B and D from Figure 2.1.2 becomes zero. This means both sides of the resistance ratio in Equation 2.1.7 are equal. At this point, the values of R_1, R_2, and R_{var} are known and R_x can be calculated using

Equation 2.1.7. This resistance, R_x, is the unknown resistance of the bridge in a catalytic bead sensor and will later be used to calculate the concentration of methane in the surrounding air.

Although catalytic bead sensors frequently require calibration and are sometimes poisoned by exposure to high concentrations of gas, some prefer this type of sensor because of its low cost and ability to sense multiple various combustible gases.

2.2 Feasible Detectors for this Study

There were many considerations that went into deciding on the sensor used in this study. Some of the main requirements for the chosen sensor are it needs to be lightweight in order to be transported via remote control vehicle efficiently and it must be budget friendly. For these reasons, a catalytic bead gas sensor was chosen. Although these sensors must be frequently calibrated, we believe their budget friendly cost and lightweight build will be very beneficial, especially in the early stages of testing where accidents are prone to occur. One sensor which seemed to be a good fit is the MQ-4 gas sensor.

2.3 MQ-4 Gas Sensor

The following calculations are based on those found in *Understanding a Gas Sensor*, published by Jaycon Systems.

There are many applications for the MQ-4 gas sensor which was chosen to be used during this experiment. This sensor can be used to sense multiple gases such as Methane (CH_4), Carbon Monoxide (CO), Hydrogen (H_2), Liquefied Petroleum Gas (LPG), alcohol, and smoke concentrations.

This type of sensor has a variable resistor built in which is at the heart of the methane sensing. This resistor varies in resistance according to the concentration of gas in the surrounding air, therefore, we will call it the concentration dependent resistor. As the concentration of gas increases, the resistance value will decrease, providing a larger voltage reading which is correlated to the concentration value calculated. In areas with lower concentrations of certain gases, the resistance will increase, effectively lowering the voltage reading and outputting a smaller concentration value. A load resistor is also required in the sensor in order to adjust the accuracy and sensitivity of the methane sensor. The value of this load resistor can vary anywhere between 2000 Ohms and 47000 Ohms whereas the resistivity increases, so does the sensitivity of the sensor. Adjusting this resistor depends on what concentration of gas you plan on measuring. If you are preparing to expose the sensor to a large concentration of gas then it is best to lower the sensitivity of the sensor. This will allow you to measure with more accuracy for larger numbers. If you plan on sensing small concentrations of gas then increasing the sensitivity will provide you with more accurate results. For example, using the sensor in a gas with a concentration of 1000 parts per million (PPM) with an accuracy of ±10 ppm would mean having a percent error of ±1%. If you were to use this same accuracy but this time in a gas concentration of 100 ppm, you would have a percent error of ±10%. In order to decrease this percent error you would increase the sensitivity of the sensor by increasing the resistance of the load resistor. In this case, increasing the accuracy to ±1 ppm would decrease the percent error back down to ±1%. The final resistor involved in the gas sensor is built in and used for the heater. A heater is required by the sensor in order to provide the necessary temperature the sensor needs to work effectively. In Figure 2.3.1 we can see the circuit that creates the gas sensor with some of the previously listed components:

The central component of this circuit is the gas sensor itself. There are six pins on the physical sensor but two of them are labelled A and two are labelled B so that leaves us with four distinct pins as shown above. The built-in resistor that varies resistance based on the concentration of gas exists between pins A and B while the resister that supplies heat sits between both H pins.

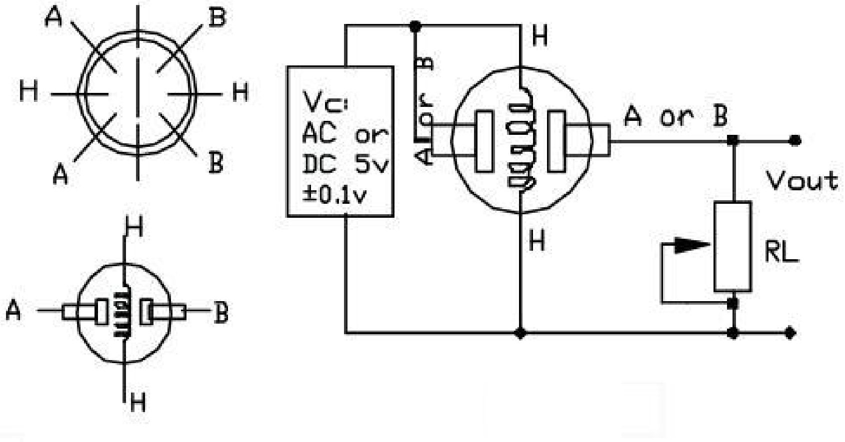

Figure 2.3.1. Sensor Circuit[14]

From here we can move on to how we calculate the concentration of the gases we are exposing the sensor to. These calculations stem from the MQ-4 sensitivity characteristic chart that is provided by the sensor data sheet.

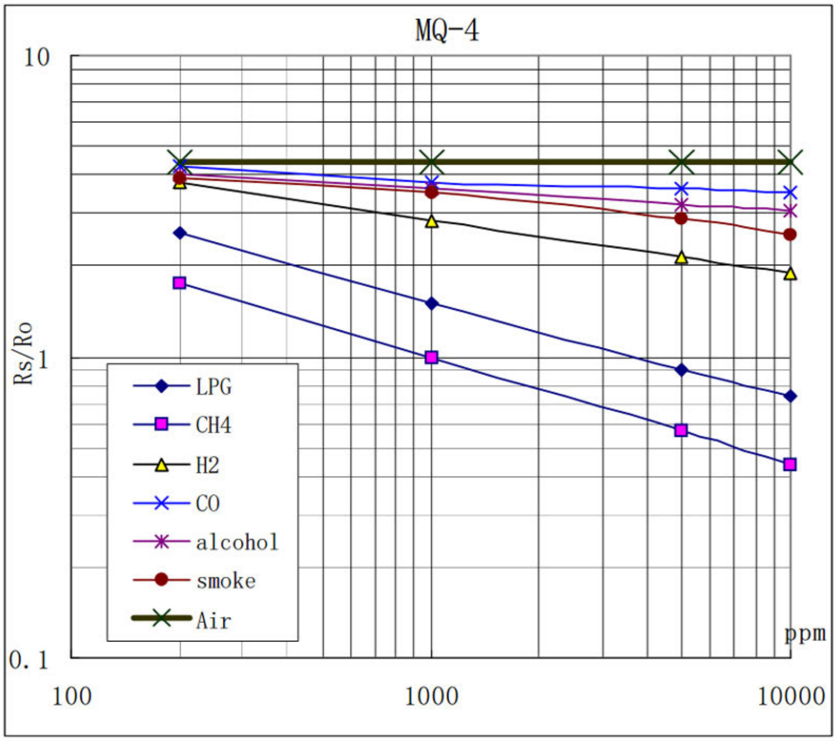

Figure 2.3.2. Sensitivity Characteristics[14]

From this graph we are given the concentration of gas ranging from 100 PPM to 10000 PPM on the x-axis and the ratio between two resistance values ($\frac{R_S}{R_0}$) on the y-axis. In this ratio, R_S represents the resistance of the concentration dependent resistor and R_0 is that resistance of that same resistor but when it is exposed to fresh air or a known concentration of gas. First, it is important to reference Figure 2.3.3 in order to have a clear understanding of the path we will take to calculate concentration:

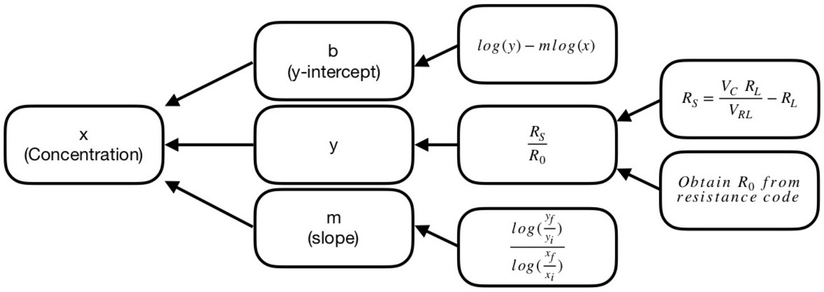

Figure 2.3.3. Calculation Flowchart

Now we should simplify the circuit shown in Figure 2.1.1 in order to more clearly make use of Ohm's Law:

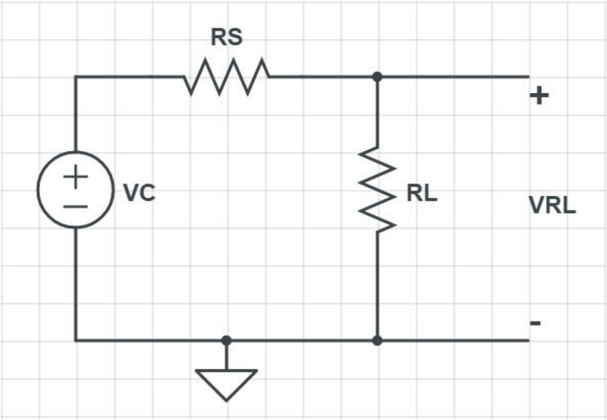

Figure 2.3.4. Sensor Circuit Simplified[14]

Here, R_L is the resistance of the load resistor, V_C is the input voltage powering the gas sensor, and V_{RL} is the voltage over the load resistor. Ohm's Law gives us:

$$V = I \cdot R \tag{2.3.1}$$

where V is the voltage, I is the current, and R is the resistance. We can then combine R_S and R_0 since they are in series with each other and derive the current to be:

$$I = \frac{V_C}{R_S + R_L} \tag{2.3.2}$$

Now we can attempt to solve for the output voltage at the load resistor by again using Ohm's Law. If we have:

$$V_{R_L} = I \cdot R_L \tag{2.3.3}$$

We can plug in the current we previously solved for to obtain:

$$V_{R_L} = \frac{V_C}{R_S + R_L} \cdot R_L = \frac{V_C \cdot R_L}{R_S + R_L} \tag{2.3.4}$$

Then solve for R_S:

$$V_{R_L} \cdot (R_S + R_L) = V_C \cdot R_L \tag{2.3.5}$$

$$R_S + R_L = \frac{V_C \cdot R_L}{V_{R_L}} \tag{2.3.6}$$

$$R_S = \frac{V_C \cdot R_L}{V_{R_L}} - R_L \tag{2.3.7}$$

At this point, the values of V_C and R_L are known and the values of V_{RL} are being outputted from the gas sensor in order for Arduino to calculate R_S. Next we can use the provided Arduino code in Appendix A.2 to calculate R_0, the resistance of the concentration dependent resistor when exposed the fresh air. Within this code, R_0 is calculated by calculating R_S in fresh air using the same method as above then relating R_S to R_0 using the ratio:

$$\frac{R_S}{R_0} = 4.4\ ppm \tag{2.3.8}$$

We know this because the fresh air curve on the MQ-4 sensitivity characteristic chart has a constant y value of 4.4 ppm.

Now we are prepared to analyze the sensitivity chart in Figure 2.3.2. The first thing we must notice is that the graph scale is logarithmic. This means that when put into a linear scale, gas concentration will change exponentially with the resistance ratio. First, it is best to treat the curve for each gas as linear so we can use a formula that linearly relates the concentration and resistance ratio. Once we have a linear equation relating these two values we will be able to determine concentration from the resistance values gathered from the Arduino board and the gas sensor. We will start with the equation of a line:

$$y = mx + b \tag{2.3.9}$$

where y is the resistance ratio value, m is the slope of the line, x is the concentration value, and b is the y-intercept. The logarithmic interpretation of this linear equation is as follows:

$$log(y) = mlog(x) + b \tag{2.3.10}$$

Our next step is to calculate the slope. To do this we will need to choose two points on the same line, take the ratio of the change in y position to the change in x position, then use the logarithmic quotient rule to simplify the expression as follows:

$$m = \frac{log(y_f) - log(y_i)}{log(x_f) - log(x_i)} = \frac{log(\frac{y_f}{y_i})}{log(\frac{x_f}{x_i})} \tag{2.3.11}$$

Now that we can calculate the slope of our desired line, we can also find the y-intercept. We can do this by rearranging Equation 2.3.10:

$$b = log(y) - mlog(x) \tag{2.3.12}$$

These two calculations were repeated for each gas on the MQ-4 sensitivity characteristic chart and are listed in the Table 2.3.1.

	Fresh Air	CO	Alcohol	Smoke	H_2	LPG	CH_4
x_f	10000	10000	10000	10000	10000	10000	10000
x_i	200	200	200	200	200	200	200
y_f	4.4	3.4	3	2.4	1.9	0.73	0.42
y_i	4.4	4.2	4	3.9	3.7	2.5	1.8
m	0	-0.054	-0.073	-0.124	-0.170	-0.315	-0.3720
b	0.6434	0.748	0.771	0.877	0.9602	1.122	1.111

Table 2.3.1. Characteristic Sensitivity Values

Now that we have this information, we can once again rearrange Equation 2.3.10 so that we can solve for x, the concentration of a particular gas:

$$log(y) = mlog(x) + b \tag{2.3.13}$$

$$mlog(x) = log(y) - b \tag{2.3.14}$$

$$log(x) = \frac{log(y) - b}{m} \tag{2.3.15}$$

$$x = 10^{\frac{log(y)-b}{m}} \tag{2.3.16}$$

where y is the resistance ratio that was previously calculated.

3

Creating the Sensor

The system that was built was designed with a few necessities in mind. In order to make use of the equations discussed in the previous chapter, a platform was needed that could compute the solutions to these equations repeatedly and efficiently based on the input of some methane sensor. The system also needed to include a global positioning system (GPS) in order to track where the measurements were taken, a real time clock (RTC) which would keep accurate time stamps as measurements were being taken, and a microSD card logger and reader which would allow for the system to log all data to an SD card without a computer connection being requirement. The chosen platform was Arduino which allowed for the possibilities of all these options.

3.1 Arduino

Arduino is an easy to use, open software and open hardware platform. The company designs and manufactures single-board microcontrollers and kits for building digital devices and interactive objects that can sense and control both physically and digitally[10]. With nearly unlimited applications for Arduino, using it to create a methane gas sensor is very feasible. There are various types of Arduino boards with different amounts of memory, and inputs and outputs (both digital and analog). Arduino was chosen because Arduino boards seemed to be compatible with a wide variety of possible methane sensors, making them an easy fit and easily tailored to any sensors requirements. Arduino also seemed like it would happily accept interactions with other instruments required during testing. Arduino boards are generally programmed by connecting them to a computer then writing and uploading the desired code to the board via an integrated development environment. The next step was to determine which board to use during testing. The most easily accessible board was the Arduino Uno which is a pretty basic and well rounded board. This board did everything it needed to do in terms of its lightweight build and processing power although the code which was used, located in Appendix A.1, was beginning to reach the board's maximum global variable storage space. In a case where more storage space is required one could easily move to an Arduino Mega as only a few code modifications would be necessary to do so.

3.2 Detector Components

The first component required for this system was an Arduino Uno board. This board and similar models can be purchased online from various electronics websites. You can also often purchase these boards in an electronics kit which would provide you with many other electronic circuitry components that could be incorporated into your project. The next component acquired for this homemade methane sensor was the methane sensor itself. The sensor used was the MQ-4 Gas Sensor shown below:

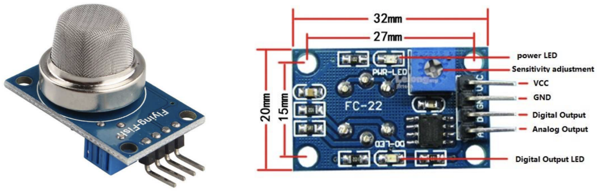

Figure 3.2.1. MQ-4 Gas Sensor [12]

This sensor was purchased already connected to an Arduino compatible board which made it easy to interface with the Arduino Uno used during testing. Next, an Adafruit Ultimate GPS Logger Shield was purchased because it contained many of the key components required for this project. This shield incorporated a GPS for tracking where measurements were taken, a real time clock for keeping accurate time stamps of when measurements were taken, and an SD card logger for storing measurements, GPS, and RTC information. The Adafruit shield is shown below:

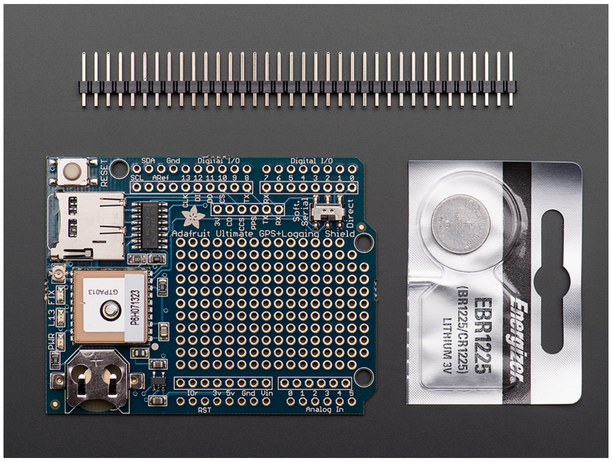

Figure 3.2.2. Adafruit Ultimate GPS Logger Shield[13]

Metal headers are provided with the shield and they allow you to connect the shield to the Arduino board. If you want to stack multiple shields on a board then you can purchase a set of stacking headers like the ones attached to the shield in Figure 3.3.1. A stack header has been soldered to the shield so the methane sensor can be easily attached and removed. Other necessary components include some breadboarding wire (∼22 Gauge), a microSD card if you plan on remotely recording data, and a battery holder with a 2.1 millimeter by 5.5 millimeter connector that can supply a 9V output to the board. A complete materials list with places where each item was purchased is included in Appendix B.

3.3 Building the Sensor

Constructing the sensor itself was pretty straight forward. The first step was to solder stack headers to the Adafruit shield. Although stacking a second shield on the system was not part of the plan, installing the stack headers allowed us to retain access to the digital and analog pins for potential connections. Next, a stack header was soldered to the center of the shield which was designed for creative space. This stack header allowed the methane sensor to be easily attached and removed from the rest of the system. From here, wire was used to connect one leg of the header to the Analog 0 pin, one leg to ground, and one leg to the 5V pin. These pins were connected to specific header legs based on the sensor's orientation when inserted into the stack header. Each leg on the sensor is labeled, allowing you to identify where each connection should be made. Once you have all stack headers and wires soldered to the shield you can align the header legs with the Arduino Uno board's pins and push them together. The final product should look something like Figure 3.3.1 and Figure 3.3.2.

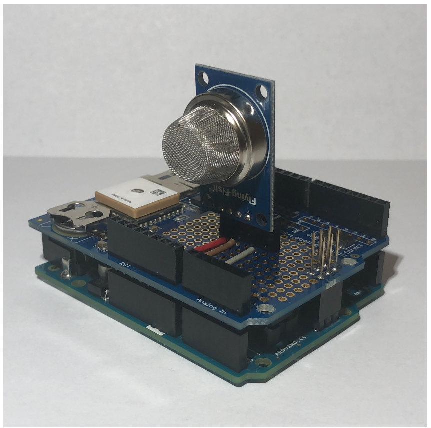

Figure 3.3.1. Constructed Sensor

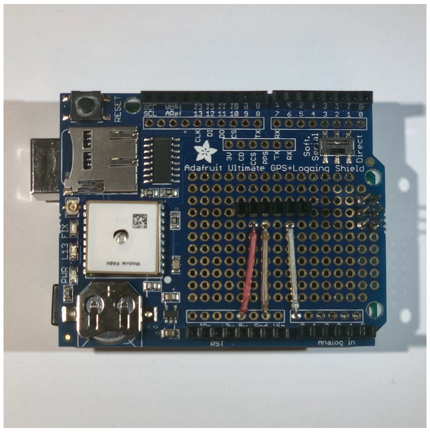

Figure 3.3.2. Shield Wiring

Figure 3.3.2 gives a better look at the wiring used to connect the MQ-4 sensor to the Adafruit shield. On the underside of the shield, solder is used to connect each wire to the correct header leg.

3.4 Programming the Sensor

The code for this sensor was developed by combining multiple pieces of code pertaining to each part of the Adafruit shield and methane gas sensor and can be found in Appendix A for reference. The starting point for constructing this code was with the *parsing* example in the Adafruit GPS Library which can be found and downloaded on GitHub in a ZIP format[15]. Without the *parsing* example, the GPS will output the following repeatedly:

```
$GPRMC,194509.000,A,4042.6142,N,07400.4168,W,2.03,221.11,160412,,,A*77
```

This information is known as the recommended minimum data for a GPS. It provides information such as the time, date, location, etc. The *parsing* example allows us to break down this information and only call to the serial monitor the information we request. Within this example there are specific instructions which tell you which commands and pins to use depending on the Arduino board you are using. Once we were able to access the required GPS data, an edited version of the *parsing* example was saved for us to add to later.

Next, we acquired code for the MQ-4 gas sensor which was then added to the *parsing* code[16]. This code included the methane concentration calculations and also outputted them to the serial monitor. In this portion of the code, the linear equation values will have to be slightly modified depending on which gas you plan on measuring.

The last section of the code that must be added is the microSD card logging portion. This code can be found in the *sdshield_logging* example in the Adafruit GPS Library. This code provides you with a method to access your microSD card, create files, write in those files, and store them on the microSD card. This is crucial if you plan on recording data without your sensor being directly connected to a computer.

When these three sections of code are combined, you will have a running code that outputs the following to the serial monitor and also records it to your microSD card:

```
0.00,0.00%,16:6:50,4/9/2019,1,1,4201.2841N,7354.3872W,42.0214,-73.9065,60.50,4

0.00,0.00%,16:6:50,4/9/2019,1,1,4201.2841N,7354.3872W,42.0214,-73.9065,60.50,4

0.00,0.00%,16:6:51,4/9/2019,1,1,4201.2841N,7354.3872W,42.0214,-73.9065,60.50,4

0.00,0.00%,16:6:51,4/9/2019,1,1,4201.2841N,7354.3872W,42.0214,-73.9065,60.50,4

...
```

These comma separated strings tell us the concentration of methane in parts per million, the percentage of methane in the air, time, date, GPS fix (1 or 0), the fix quality (1 or 0), latitude, longitude, a Google Maps compatible latitude and longitude, altitude, and the amount of satellites the GPS is connected to. This information can then be transferred to a spreadsheet and separated into columns for convenience.

4

Testing the Sensor

4.1 Tests Completed

In order to ensure that your sensor is working correctly it is important to put it through a series of tests. The most basic tests would include exposing your sensor to a known concentration of gas and comparing that to your sensor's measured concentration. From here you would incrementally increase the concentration which the sensor was exposed to and again observe how the sensors measurements respond. This test theory was attempted in a few ways.

Initially it was planned to test the methane sensor under the conditions of a vacuum in an evaporator. By placing the sensor in a vacuum, this would assure us that no gases were present at the beginning of each test. Once we achieved a low vacuum, we would then bleed small amounts of 99% pure methane into the evaporator and allow the methane sensor to take its measurements. These concentration measurements would then be compared with the actual concentrations of methane in the evaporator. The actual concentration of methane in the evaporator would be determined by using the ideal gas law:

$$PV = nRT \tag{4.1.1}$$

In this equation we would use the change in pressure when the methane was released into the evaporator, the volume of the area under vacuum, the number of calculated moles, the ideal gas constant, and the absolute temperature. One complication for this testing situation was a combination of the time it took to produce a low vacuum in the evaporator and the inability to read live measurements from the sensor while it was in the evaporator. The sensor that was built was designed to function while being powered by an external battery, therefore, operation within the evaporator would have been possible. The real concern was the time it would have taken to produce a vacuum, take measurements, release the vacuum, and retrieve the microSD card repeatedly in order to view the data. Our solution to this problem was to feed a USB extension cable through one of the evaporator adapter plugs which are screwed into the bottom of the evaporator. This was done by milling a slot into the side of the plug, placing the USB extension cable in the slot, then filling the slot with Torr Seal so a low vacuum could still be achieved. This made it possible for the sensor measurements to be outputted and displayed on a laptop while testing was occurring.

It was quickly realized that there would be some problems with testing the sensor in a vacuum. The first issue we encountered was the actual concept of measuring concentration. The methane sensor was designed to calculate the concentration of methane in air in parts per million, then convert this number to a percentage. Since almost all of the air was removed from inside the vacuum, wouldn't the concentration with one methane molecule inside be 100%? But clearly this cannot be the same concentration as if there were thousands of methane molecules in the vacuum. This would lead us to wonder what a part per million means when taking measurements in a vacuum. There were also concerns about how accurately we could provide a constant flow of methane to the evaporator. This would be required since the vacuum would be constantly removing the methane we let into the system. We soon decided that the sensor testing should take place in a closed environment at atmospheric pressure.

In order to test the methane sensor in an air tight environment at atmospheric pressure, we decided to use a vacuum oven. In an attempt to measure the pressure of the oven accurately, a pressure gauge with a smaller maximum value was installed on the oven. Blocks of aluminum were placed inside the oven in order to reduce its internal volume and and therefore decrease the amount of methane which was required to reach a certain pressure. Next we placed the methane sensor in the oven and latched the door closed. From here, 99% pure methane was slowly released into the oven. In this situation, we still planned on comparing the sensor's concentration measurements to the calculated concentrations, but in this case the concentrations were to be calculated using the partial pressures of air and methane. In other words, the ratio between the change in pressure due to methane and the initial pressure of the oven (atmospheric) would allow us to calculate the current concentration of methane.

When testing began, it became clear that we needed a significant amount of methane in order to raise the pressure of the oven enough to see a reading on the pressure gauge. Measurements near zero on any gauge are highly inaccurate so higher pressures are required in order to accurately calculate the concentration of methane in the oven using partial pressures. After using our methane supply in multiple instances throughout testing, we quickly ran low when these higher pressures were required.

4.2 Results

Below is a sample set of the type of data that was being recorded from the Adafruit shield and methane sensor using Arduino after it has been entered into a spreadsheet and separated into columns.

PPM	Percentage (%)	Time (HH:MM:SS)	Date (MM/DD/YYYY)	Fix	Quality	Google Lat (DD.MMMMM)	Google Lon (DD.MMMMM)	Altitude (meters)	Satellites
28.75	0.00	17:47:56	4/11/2019	1	1	42.0215	-73.9059	100.5	5
37.76	0.00	17:47:56	4/11/2019	1	1	42.0215	-73.9059	100.5	5
47	0.00	17:47:56	4/11/2019	1	1	42.0215	-73.9059	100.5	5
61.82	0.01	17:47:58	4/11/2019	1	1	42.0215	-73.9059	100.5	5
77.44	0.01	17:47:58	4/11/2019	1	1	42.0215	-73.9059	100.5	5
93.03	0.01	17:47:58	4/11/2019	1	1	42.0215	-73.9059	100.5	5
127.67	0.01	17:47:59	4/11/2019	1	1	42.0215	-73.9059	100.5	5
154.34	0.02	17:47:59	4/11/2019	1	1	42.0215	-73.9059	100.5	5
180.42	0.02	17:47:59	4/11/2019	1	1	42.0215	-73.9059	100.5	5
215.01	0.02	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.5	5
254.54	0.03	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.5	5
292.73	0.03	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.5	5
342.81	0.03	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.8	5
408.06	0.04	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.8	5
472.9	0.05	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.8	5
545.69	0.05	17:48:00	4/11/2019	1	1	42.0215	-73.9059	100.8	5
652.19	0.07	17:48:02	4/11/2019	1	1	42.0215	-73.9059	100.8	5
732.07	0.07	17:48:02	4/11/2019	1	1	42.0215	-73.9059	100.8	5
819.7	0.08	17:48:02	4/11/2019	1	1	42.0215	-73.9059	100.8	5
967.02	0.10	17:48:03	4/11/2019	1	1	42.0215	-73.9059	100.8	5

Table 4.2.1. 99% CH_4 Released into a Vacuum

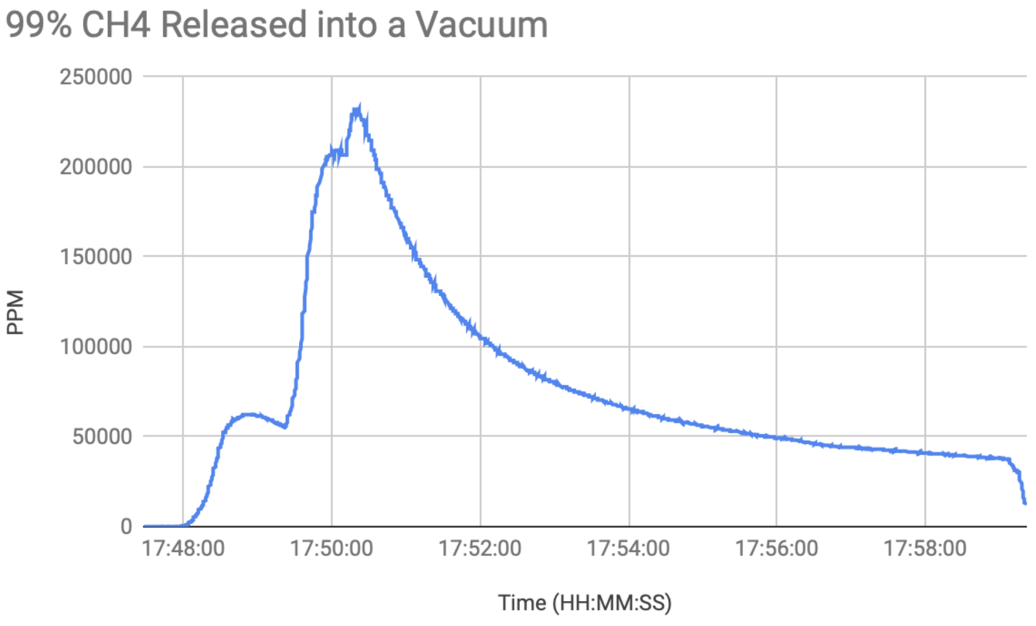

Figure 4.2.1. Concentration of CH_4 Over Time in a Vacuum

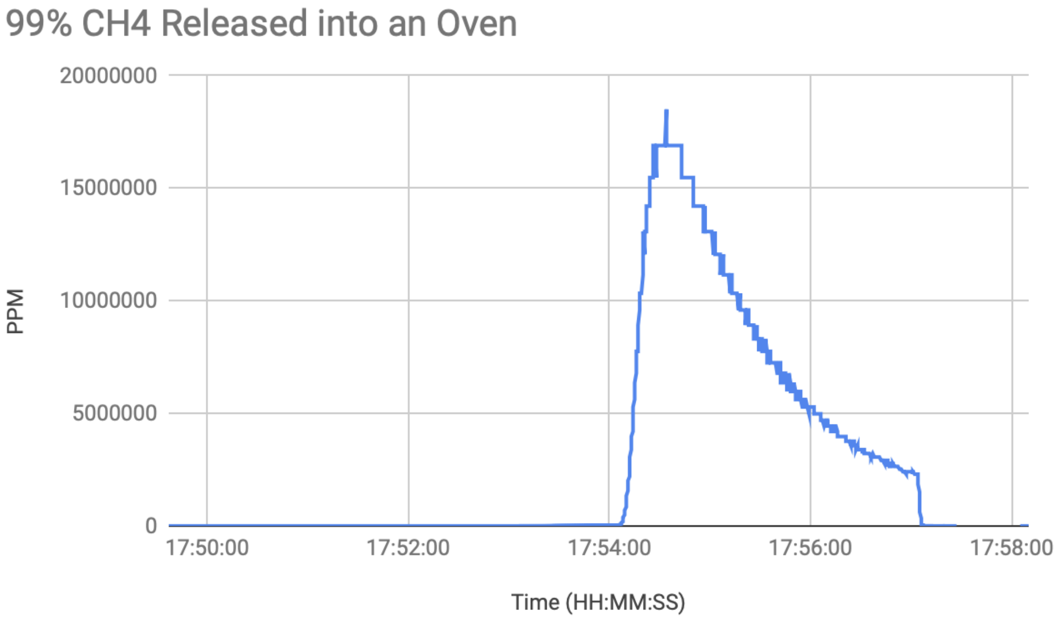

Figure 4.2.2. Concentration of CH_4 Over Time in an Oven

4.3 Discussion

While testing the methane sensor, thousands of measurements were taken during each experiment. Table 4.2.1 shows a sample set of what this data looks like after it is retrieved from the microSD card in the methane sensor. The calculated concentrations were then plotted against time in Figure 4.2.1. We can clearly see as methane was released into the vacuum, the concentration of methane dramatically increased. As time went on and the vacuum removed that methane from the system, the concentration slowly decayed. Very similar results were gathered from the same experiment but at atmospheric pressure. In Figure 4.2.2, you can see the concentration of methane increase when methane was pumped into the oven. The concentration quickly decreases when the methane was left to slowly exit the oven and ultimately returns to zero when the oven door is opened. One concern we had is the catalytic bead sensor within our system was possibly over saturated after being repeatedly exposed to such high concentrations of methane. We believe the graphs and data are of the correct form but further investigation is required to accurately calibrate the sensor.

5

Summary

At the beginning of this project, we identified the emission of methane as an unfortunate side effect of hydropower implementation. Moving forward, it seemed clear that identifying a method which could help us study this side effect could prove to be beneficial to researchers around the world and to our world itself. From here it seemed that the real difficulty of gathering this emission data was the time and resources it would take to map out large, remote regions. It only seemed fitting that we used some form of remote controlled vehicle to bring a measurement device to these remote regions. This would allow us to access areas which were previously very difficult to reach, at a must faster speed. In order to obtain this goal, it was necessary to design a methane sensor that was lightweight, accurate, and for the sake of this project, budget friendly. Constructing a sensor using an Arduino board and a compatible sensor seemed like a logical decision given the amount of freedom Arduino gives you in terms of customization. Next, we implemented an Adafruit shield which gave us methods of recording measurement locations via GPS, keeping an accurate time stamp for each measurement, and storing this data on a microSD card. By combining these components, we were able to construct a lightweight and budget friendly methane sensor that calculated and recorded methane concentrations from the surrounding air.

6

Looking Forward

Moving forward it is important to be able to accurately calibrate the catalytic bead sensor you are using. Since the MQ-4 gas sensor we used is a reasonable price, it would be beneficial to have extra sensors in case you are suspicious of your sensor being over saturated. In order to test the sensor's accuracy, performing a test using an air tight environment at atmospheric pressure should be the preferred method. Having a large supply of methane gas for this testing would be ideal in order to reach the necessary pressures you would need to accurately calculate methane concentrations for comparison. Once you are convinced your sensor is working properly, the next step would include mounting your sensor to a remote controlled vehicle and surveying a larger area while taking similar measurements.

There are also many other applications for a gas sensor such as this one. One of the simplest applications would be placing your sensor in a region where you wish to test for methane. This would be if you were only concerned about gas in a very specific area. This type of sensor could also be used as a warning system that alerted you if there was a combustible gas in a room or building.

Appendix A

Arduino Code

A.1 Methane Sensor + Adafruit Ultimate GPS Logger Shield

```
#include <Adafruit_GPS.h> //Library for GPS
#include <SoftwareSerial.h>

#include <Adafruit_GFX.h>
#include <gfxfont.h>

#include <SD.h> //Library for SD card reader
#include <SPI.h> //Library for SPI interface
#include <Wire.h> //Library for I2C interface

#define OLED_RESET 11 //Reset pin
//Adafruit_SSD1306 display(OLED_RESET); //Set Reset pin for OLED display

// If you're using the Adafruit GPS shield, change
// SoftwareSerial mySerial(3, 2); -> SoftwareSerial mySerial(8, 7);
// and make sure the switch is set to SoftSerial.
SoftwareSerial mySerial(8, 7);

```

```
Adafruit_GPS GPS(&mySerial);

//GPSECHO true sends the raw GPS data to the serial monitor.
//GPSECHO false refrains from sending this data.
#define GPSECHO false

//Keeps track of if we are using the interrupt - is off (false) by default
bool usingInterrupt = false;

// Func prototype keeps Arduino 0023 happy
void useInterrupt(bool);

//Methane Sensor
int gas_sensor = A0; //Sensor pin
float m = -0.372; //Slope
float b = 1.111; //Y-Intercept
float R0 = 11.820; //Sensor Resistance in fresh air from resistance calculation code

//SD Card Reader
File myFile;
int pinChipSelect = 10; //SD logging pin for Arduino Uno
//int pinChipSelect = 53; //SD logging pin for Arduino Mega

void setup() {
  Serial.begin(115200);   //115200 baud is fast enough to echo the raw GPS data
  GPS.begin(9600);        //9600 baud is the default baud rate for Adafruit MTK GPS's

  GPS.sendCommand(PMTK_SET_NMEA_OUTPUT_RMCGGA); //Turns on RMC (recommended minimum) and GGA (fix data) including altitude

  //GPS.sendCommand(PMTK_SET_NMEA_OUTPUT_RMCONLY); //This line only turns on RMC

```

```
  GPS.sendCommand(PMTK_SET_NMEA_UPDATE_1HZ); //Set the update rate to 1Hz
                                             //To allow for enough time to sort through the data and print it,
                                             //don't use an update rate higher than 1Hz

  GPS.sendCommand(PGCMD_ANTENNA); //Request updates on antenna status.
                                  //Comment out to keep quiet

  useInterrupt(true); //Set a timer interupt that goes off and reads data from the GPS
  delay(1000);        //every 1 millisecond

  mySerial.println(PMTK_Q_RELEASE);//Ask for firmware version\

  pinMode(gas_sensor, INPUT); //Set gas sensor as input
  pinMode(pinChipSelect, OUTPUT); //Set SD card pin as output
  digitalWrite(10, HIGH);

  // SD Card Initialization
  if (SD.begin())
  {
    Serial.println(F(”SD card is ready to use.”));
  } else
  {
    Serial.println(F(”SD card initialization failed”));
    return;
  }

}

// Interrupt is called once a millisecond to look for any new GPS data and store it
SIGNAL(TIMER0_COMPA_vect) {
  char c = GPS.read();
```

```
  // if you want to debug, this is a good time to do it!
#ifdef UDR0
  if (GPSECHO)
    if (c) UDR0 = c;
    // writing direct to UDR0 is much much faster than Serial.print
    // but only one character can be written at a time.
#endif
}

void useInterrupt(boolean v) {
  if (v) {
    // Timer0 is already used for millis() - we'll just interrupt somewhere
    // in the middle and call the "Compare A" function above
    OCR0A = 0xAF;
    TIMSK0 |= _BV(OCIE0A);
    usingInterrupt = true;
  } else {
    // do not call the interrupt function COMPA anymore
    TIMSK0 &= ~_BV(OCIE0A);
    usingInterrupt = false;
  }
}

uint32_t timer = millis();

void loop() {

//Methane Sensor Code

  float sensor_volt; //Define variable for sensor voltage
  float RS_gas; //Define variable for sensor resistance
  float ratio; //Define variable for ratio
```

```
  float sensorValue = analogRead(gas_sensor); //Read analog values of sensor
  sensor_volt = sensorValue * (5.0 / 1023.0); //Convert analog values to voltage
  RS_gas = ((5.0 * 10.0) / sensor_volt) - 10.0; //Get value of RS in a gas
  ratio = RS_gas / R0;   // Get ratio RS_gas/RS_air

  double ppm_log = (log10(ratio) - b) / m; //Get ppm value in linear scale according to
    the the ratio value
  double ppm = pow(10, ppm_log); //pow(base, exponent) Convert ppm value to log scale
  double percentage = ppm / 10000; //Convert to percentage

//Shield Code

  // in case you are not using the interrupt above, you'll
  // need to 'hand query' the GPS, not suggested :(
  if (! usingInterrupt) {
    // read data from the GPS in the 'main loop'
    char c = GPS.read();
    // if you want to debug, this is a good time to do it!
    if (GPSECHO)
      if (c) Serial.print(c);
  }

  // if a sentence is received, we can check the checksum, parse it...
  if (GPS.newNMEAreceived()) {
    // a tricky thing here is if we print the NMEA sentence, or data
    // we end up not listening and catching other sentences!
    // so be very wary if using OUTPUT_ALLDATA and trytng to print out data
    //Serial.println(GPS.lastNMEA());   // this also sets the newNMEAreceived() flag to
    false

    if (!GPS.parse(GPS.lastNMEA()))   // this also sets the newNMEAreceived() flag to
    false
```

```
      return;  // we can fail to parse a sentence in which case we should just wait for another
  }

//Write to SD card code

  // Create/Open file
  myFile = SD.open(”oven.txt”, FILE_WRITE);

  // if the file opened okay, write to it:
  if (myFile) {
    //Serial.println(F(”Writing to file...”));

    //Write to file
//The following lines print values to the serial monitor
    Serial.print(ppm);
    Serial.print(”,”);
    Serial.print(percentage);
    Serial.print(”%”);
    Serial.print(”,   ”);
    Serial.print(GPS.hour, DEC); Serial.print(':');
    Serial.print(GPS.minute, DEC); Serial.print(':');
    Serial.print(GPS.seconds, DEC);
//The following lines write values on your microSD card
    myFile.print(ppm);
    myFile.print(”,”);
    myFile.print(percentage);
    myFile.print(”%”);
    myFile.print(”,”);

    myFile.print(GPS.hour, DEC); myFile.print(':');
    myFile.print(GPS.minute, DEC); myFile.print(':');
```

```
    myFile.print(GPS.seconds, DEC);
    //Serial.println(GPS.milliseconds);
    myFile.print(",");
    myFile.print(GPS.month, DEC);
    myFile.print('/');
    myFile.print(GPS.day, DEC);
    myFile.print("/20");
    myFile.print(GPS.year, DEC);
    myFile.print(",");
    myFile.print((int)GPS.fix);
    myFile.print(",");
    myFile.print((int)GPS.fixquality);
    if (GPS.fix) {
      myFile.print(",");
      myFile.print(GPS.latitude, 4); myFile.print(GPS.lat);
      myFile.print(",");
      myFile.print(GPS.longitude, 4); myFile.print(GPS.lon);
      myFile.print(",");
      myFile.print(GPS.latitudeDegrees, 4);    //Google compatible latitude
      myFile.print(",");
      myFile.print(GPS.longitudeDegrees, 4);   //Google compatible longitude
      myFile.print(",");
      //myFile.print("Speed (knots): "); Serial.println(GPS.speed);
      //myFile.print(",");
      //myFile.print("Angle: "); Serial.println(GPS.angle);
      //myFile.print(",");
      myFile.print(GPS.altitude);
      myFile.print(",");
      myFile.print((int)GPS.satellites);
    }

    myFile.println();
```

```

    myFile.close(); // close the file
    Serial.println();
  }
  // if the file didn't open, print an error:
  else {
    Serial.println(F("error opening file"));
  }
  // Reading the file
/*
  myFile = SD.open("data.txt");
  if (myFile) {
    Serial.println(F("Read:"));
    // Reading the whole file
    while (myFile.available()) {
      Serial.write(myFile.read());
   }
    Serial.println();
    myFile.close();
  }
  else {
    Serial.println(F("error opening test.txt"));
  }
*/
delay(250); //take a measurement every 0.250 seconds

}
```

A.2 Methane Sensor Resistance

```
/*
 Arduino MQ4 gas sensor - Geekstips.com
 This example is for calculating R0 which is
```

```
 the resistance of the sensor at a known concentration
 without the presence of other gases, or in fresh air
*/
void setup() {
  Serial.begin(9600); //Baud rate
}

void loop() {
  float sensor_volt; //Define variable for sensor voltage
  float RS_air; //Define variable for sensor resistance
  float R0; //Define variable for R0
  float sensorValue; //Define variable for analog readings
  float sensorValue1;
  float sensorValueAVG;
  for (int i = 0 ; i < 500 ; i++) //Start for loop
  {
    sensorValue = sensorValue + analogRead(A0); //Add analog values of sensor 500 times
  }
  sensorValueAVG = sensorValue / 500.0; //Take average of readings
  sensor_volt = sensorValue * (5.0 / 1023.0); //Convert average to voltage
  RS_air = ((5.0 * 10.0) / sensor_volt) - 10.0; //Calculate RS in fresh air
  R0 = RS_air / 4.4; //Calculate R0

  Serial.println(sensorValueAVG);
  //Serial.print("R0 = "); //Display "R0"
  //Serial.println(R0); //Display value of R0
  delay(500); //Wait 1 second
}
```

Appendix B

Sensor Materials List

- Arduino Uno R3 Development Board
    - Website: `https://www.amazon.com/Development-Microcontroller-ATmega328-ATMEGA16`
      `dp/B07MMMSNYH/ref=sr_1_6?keywords=arduino+uno&qid=1556405112&s=electronics&sr=1-6`
- Adafruit Ultimate GPS Logger Shield
    - Website: `https://www.amazon.com/Adafruit-Ultimate-GPS-Logger-Shield/dp/B00E4WEX76/ref=sr_1_fkmrnull_1?keywords=Adafruit+Ultimate+GPS+Logger+Shield+-+Includes+GPS+Module&qid=1556406242&s=gateway&sr=8-1-fkmrnull`
- CJRSLRB Gas Detection Module Kit
    - Website: `https://www.amazon.com/gp/product/B016KABTDK/ref=as_li_tl?ie=UTF8&camp=1789&creative=9325&creativeASIN=B016KABTDK&linkCode=as2&tag=geek07f-20&linkId=8756cb93ffa317e13d2bf83ea16d2370`
- Arduino Software (IDE)
    - Website: `https://www.arduino.cc/en/Main/Software`

- SanDisk Mobile Class4 MicroSDHC Flash Memory Card
    - Website: `https://www.amazon.com/SanDisk-Mobile-MicroSDHC-SDSDQM-B35A-Adapter/dp/B004ZIENBA/ref=sr_1_12?crid=GTC2P0I4REV7&keywords=micro+sd+card&qid=1556463452&s=electronics&sprefix=micro%2Celectronics%2C146&sr=1-12`
- 6 AA Battery Holder With 2.1mm x 5.5mm Connector 9V Output
    - Website: `https://www.amazon.com/gp/product/B01IRX4DOU/ref=ppx_yo_dt_b_asin_title_o00_s00?ie=UTF8&psc=1`

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