# Wildfire Prediction Using Volatile Organic Compound Monitoring

Pascal Stevens, Aylin Cibik, Tom Gligorov

Final Report

ME 177K Freshman Introduction to Research in Engineering (FIRE)
The University of Texas at Austin

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# Chapter 1

## 1.1 Introduction

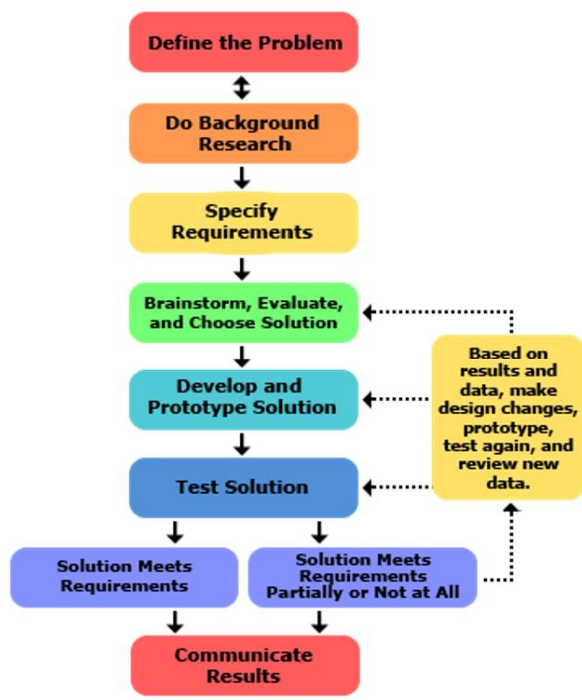
Last year, the Joint Economic Committee placed the total economic damage of wildfires between $394 and $893 billion, with 183 confirmed deaths in the calendar year. Not only are wildfires incredibly costly and dangerous, but they are also becoming more frequent as the world continues to heat up from the effects of Climate Change. Recent estimates predict an increase of up to 320% in the burn rate of wildfires globally over the next twenty-five years. Early detection and prediction are critical for minimizing this damage and implementing effective prevention strategies. This research proposes a novel approach for early wildfire detection by monitoring volatile organic compounds (VOCs) and other gasses released during the heating of biomasses by sunlight. By harnessing the sensitivity of advanced VOC sensors and the telltale chemical signatures of pyrolysis, we aim to develop a real-time monitoring system capable of predicting wildfires before they erupt.

## 1.2 Research Goals

Our objective throughout this semester is to collect and analyze VOC data released from forest fires, and comment on how this data could be used to create a solution for the proposed problem. Seeing that we are all freshman, we must first understand what professional research looks like at the University of Texas before beginning to assist in the lab environment. We have therefore broken this goal down into smaller, more achievable goals: (1) gain a familiarity and understanding of how graduate level research is conducted in an advanced education setting, (2) Familiarize ourselves with the concepts present within this research, including but not limited to; types of VOCs, combustion reactions that emit VOCs, existing wildfire detection systems, and existing information of VOC emittance from wildfires, (3) create a protype experiment that addresses the research problem and will provide solutions or insight into possible solutions (4) use the proposed experiment to gather such data, and (5) analyze and comment on the recorded data and how it helps address the problem.

Should each of these steps be completed, This research is expected to yield the following outcomes: (a) an understanding of the relationship between VOC signatures, environmental factors, and wildfire risk, (b) a robust and portable real-time VOC monitoring system capable of continuous data collection in wildfire-prone areas, (c) a reliable and accurate wildfire risk prediction model based on real-time VOC data and environmental parameters, (d) improved early warning systems and targeted prevention strategies for wildfires, leading to reduced damage and enhanced public safety.

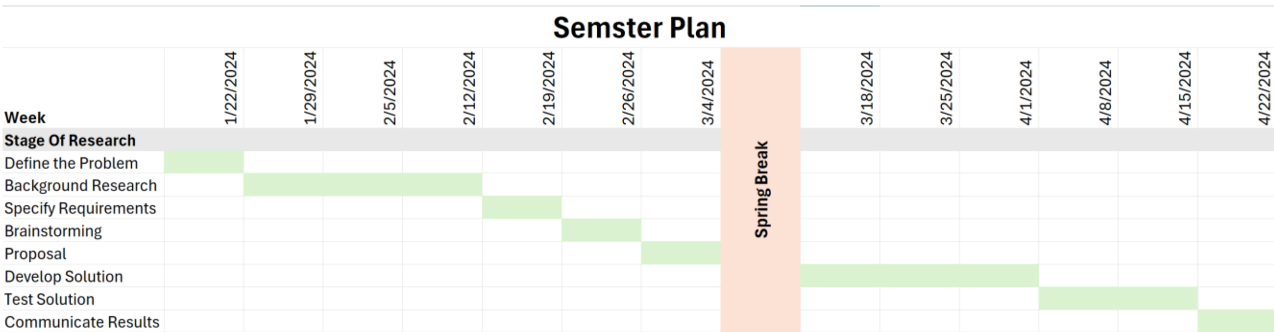
## 1.3 Research Plan




Above: Figure 1, A diagram of the engineering design process.

Our research plan revolved around the engineering design process, which we tethered our deliverables schedule and our semester plan to so we could ensure we had a proper direction and time schedule. We established a weekly Monday meeting to discuss progress. Our list of deliverables include: (i) a problem statement crafted among the team (due 1/22/2024), (ii) one annotated research paper per person per week (due each week through 2/12/2024), (iii) one proposal of a method to solve the problem statement per person (due 2/26/2024), (vi) one refined group proposal of said method (due 3/4/2024), (v) data and results from using said method (due 4/15/2024), a report analyzing the results of the method and how they compare and answer the initial research problem we discussed (due 4/23/2024).

Here is a Gantt chart for our planned progress throughout the semester, along with a list of each of our deliverables and when they're due.




| Deliverables: Expected Timeline | | | |
|---|---|---|---|
| Deliverable | Due | Format | Group/Individual |
| Problem Statement | 1/22/2024 | pdf | Group |
| Annotated Research Paper 1 | 1/29/2024 | pdf | Individual |
| Annotated Research Paper 2 | 2/5/2024 | pdf | Individual |
| Annotated Research Paper 3 | 2/12/2024 | pdf | Individual |
| Proposed Solution/Experiment | 2/26/2024 | pdf | Individual |
| Revised Solution/Experiment | 3/4/2024 | pdf | Group |
| Data and results | 4/15/2024 | xls | Group |
| Final Report | 4/23/2024 | pdf | Group |

Above: Figure 2, showing a Gantt charge of each week of the semester and how we intended to do each part of the design process.

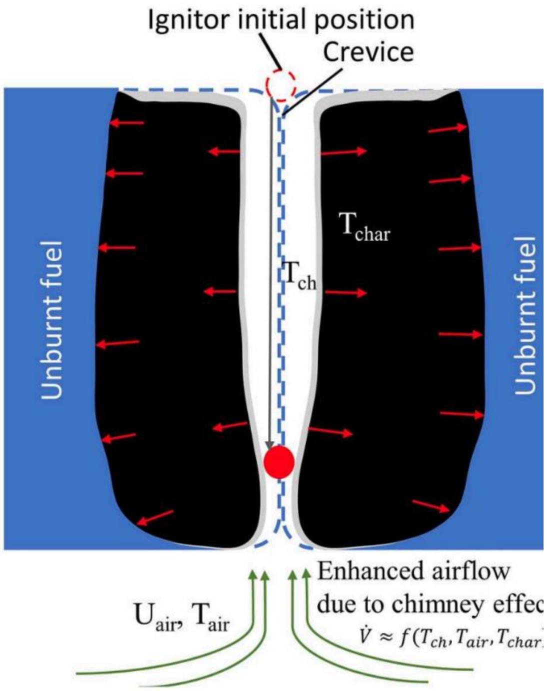
Left: Figure 3, showing a chart of each deliverable and when they would be due according to the Gantt chart.

As with any engineering project, we do expect to run into some unforeseen issues. Our hope is to work through them quickly and move forward with the limited time we have to design and implement an experiment that will address our problem statement.

# Chapter 2

## 2.1 Background Research & Literature Review

One area of particular interest is the idea of transitioning from a smoldering to flaming fire, in which a slow burn, often hard to detect wildfire that does minimal damage jumps to a ranging bonfire. This requires the presence of pyrolysis, a gas that helps facilitate this jump from smoldering to flaming fire and has a large content of VOCs. Smoldering fires often hide underground for months or years on end and are difficult to detect because they can hide from the naked eye, but they do emit trace amounts of VOCs and pyrolysis when jumping to flaming fires. For this jump to happen, a combination of things must occur, including the correct ratio of wind, moisture content, inorganic material, and non-consumed fuel. Once that is present, the smoldering fire often builds itself a chimney, pictured right. This chimney helps increase airflow from top to bottom, oxidizing the reaction while preventing a large amount of heat from escaping, creating the perfect atmosphere to fan the flames. The construction of these chimneys have to do with many factors of the material that is being burned, including it's permeability, (how easily fire passes through the material, think housing insulation vs solid wood logs), consolidation (whether the material collapses in on itself after burning, smothering the fire), and the material's overall flammability. Often after these fires transition from smoldering to flaming, the flaming fires release embers that are carried by the wind towards unburned areas and deposited creating "spot fires", which frequently escape containment areas and often entrap




Above: Figure 4, showing a chimney created by a smoldering fire. [7]

and kill response workers. These embers can also create more smoldering fires, which remain dormant and underground until the correct conditions are met again. A mathematical simulation of forest fuel pyrolysis done in Russia in 2019 describes the stages of wildfire combustion ( (1) heating, (2) moisture evaporation, (3) pyrolysis, (4) flame combustion, (5) carbonization, (6) afterburning of coke) and the environmental factors that cause these conditions for fires to be the highest. The study found that moisture evaporation is initially exponential and then stabilizes in exponential decay and is able to draw a connection between relative humidity and the remaining water content within forest material. In the pyrolysis process, the study notes that a large number of VOCs are pre-emptively released before flame combustion, but that these reactions are unpredictable in their activation energies and gasses released, making combustion both spontaneous and extremely hard to model. During heating and moisture evaporation, patterns of temperature showed the reverse of moisture, i.e., a very significant rise, followed by a gradual increase to pyrolysis.

Volatile Organic Compounds emitted from pyrolysis and wildfire combustion have significant impacts on both air quality and the climate. A key component of wildfire detection is identifying the specific VOCs released in the early stages of a fire. Identifying critical volatile organic compounds poses a challenge due to the variability and diversity of ecosystems and the biomass they contain. To address the obstacle, the research article *Fuel Type Independent Parameterization of Volatile Organic Compound Emissions from Western US Wildfires* argues that variability in VOC composition primarily stems from changes in combustion conditions rather than the specific fuel type burned. The article *High and Low Temperature Pyrolysis Profiles Describe Volatile Organic Compound Emissions from Western US Wildfire Fuels* further corroborates this perspective with data collected from an experiment measuring VOCs released from a myriad of biofuels. While comparing the emission profiles of natural fuel mixtures such as Ponderosa Pine, Douglas Fir, Engelmann Spruce, Bear Grass, Sage Brush, and Ceanothus, researchers observed commonality in VOC emissions across various fuel types. They concluded that differences in VOC emissions were linked to the pyrolysis processes, with high and low temperature factors accounting for nearly 70% of variability (Kanako Sekimoto et al.). Main sources of VOC emissions arise from the pyrolysis of polymers such as cellulose, hemicellulose, and lignin. Specifically, the depolymerization of cellulose and hemicellulose releases VOCs such as hydroxyacetone, acetaldehyde, acid. Environmental factors such as humidity, presence of oxygen, heating rate, residence time, and chemical composition of biomass determine the difference between high and low temperature pyrolysis. Since the three VOCs have relatively equal contributions from low and high temperature factors, they are most consistently recorded and utilized during experiments. However, specific VOCs released through high temperature and low temperature pyrolysis are also important to note—high temperature pyrolysis releases aliphatic unsaturated hydrocarbons, aromatic hydrocarbons, terpenes, HCN, HNCO, and HONO, while low temperature pyrolysis primarily releases aromatic oxygenates, furans, and NH3. VOCs as a whole need more data in order for the solutions that detect them to be effective.

Research papers from around the world have expanded on this knowledge, with data gathered that suggests a wealth of different prominent VOCs from the pyrolysis and combustion stages of fires. Research found that in the Mediterranean, the highest emitted gases from wildfires (measured in g/kg-1 of biomass burned) were carbon monoxide, ethylbenzene, isoprene, n-Hexane, and toluene. Over ten different wildfires tracked for months, the Portuguese found that the majority (78.3%) of the emissions were CO or CO2 emissions, and the remaining were split between Aromatic Hydrocarbons (responsible for 51% of the VOCs emitted), and a mixture of other types of gasses that comprised the other 49% of VOCs. In general, across each of these fires it was seen that each of the VOCs listed above proportionally followed the trend of total emission output, suggesting that they are frequent in each fire, not a disparity from a single trial. A similar study in the Western United States sampled the smoke from hundreds of wildfires over a 14 year period, and reported on both the reason of ignition, and the VOC breakdown of the pollutants from the fire. Fires tend to be larger in the east than the west, with over 70% of fires in the west starting naturally from thunderstorms and paralysis jumps, whereas only 27% of fires in the east start this way. Most are due to human interaction (see map on the right). This study found the top released gasses (measured in g/kg-1 of biomass burned) to be carbon monoxide, ethene, hydrogen cyanide, formaldehyde, ethane, methanol, propene, and acetaldehyde.

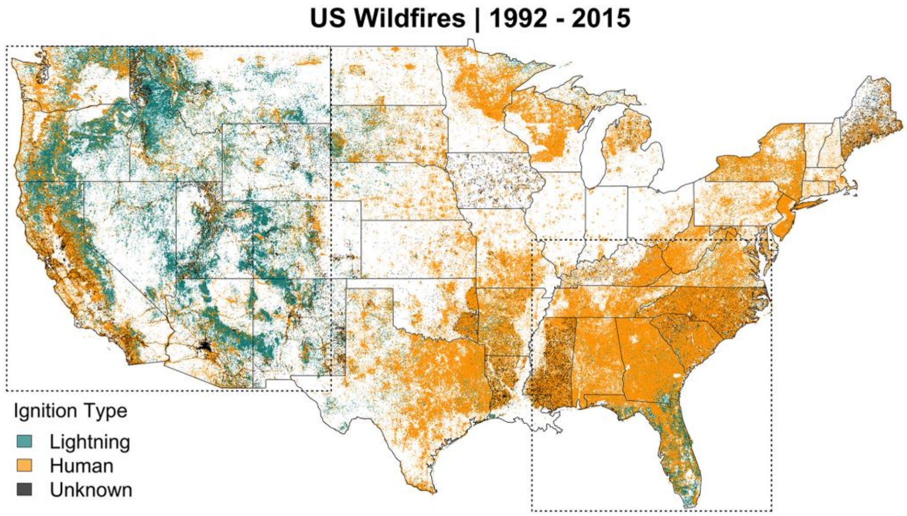



Figure 5: A map showing the source of wildfires around the United States. [5]

## 2.2 Requirements

From our background research, we cross referenced which VOCs were in the highest concentration from wildfires sampled around the world, providing a list of VOCs that would be high in concentration from the pyrolysis that took place before fire broke out regardless of the type of forest sampled. This data is cross-referenced from four samples of three different papers, namely [1], [3], and [4]. Seven VOCs were identified; Formaldehyde, Ethane, Isoprene, Methanol, Acetaldehyde, Toluene, and Hydrogen Cyanide, along with carbon monoxide and particular matter as gases of interest during the experiment.

Thinking about the practical implications of our research, we also thought of methods of implementation for these sensors to track real wildfires around the world. These tracking methods need to reliably transmit VOC monitoring data in real time for large areas of forests frequently, to allow for the best ability to move resources to prevent or mitigate wildfires.

### 2.3a Initial Proposals

**Independent Proposal 1 – Solar Powered Carbon Monoxide Sensor**

I propose using solar-aided battery-powered carbon monoxide sensors to monitor gas levels in forested areas and alert an organization if unnaturally high gas levels seem to be present. Carbon monoxide was chosen because, regardless of the type of natural environment present, it was the second most common gas released from the pyrolysis stage. Other VOCs could be explored and implemented, but there is already an extensive scale and production of carbon monoxide detectors that are commercially available. The use of solar-aided battery power in the system ensures a reliable and hassle-free operation. This practical feature eliminates the need for frequent battery replacements or complex wiring, making device distribution easy and cost-effective. Moreover, the batteries are designed to recharge naturally from the abundant solar radiation during the summer months, when most fires occur. The system will monitor the amount of CO emitted from the natural environment with sensors. This data will be taken, stored, and then routinely backed up to the internet via wireless transmission.

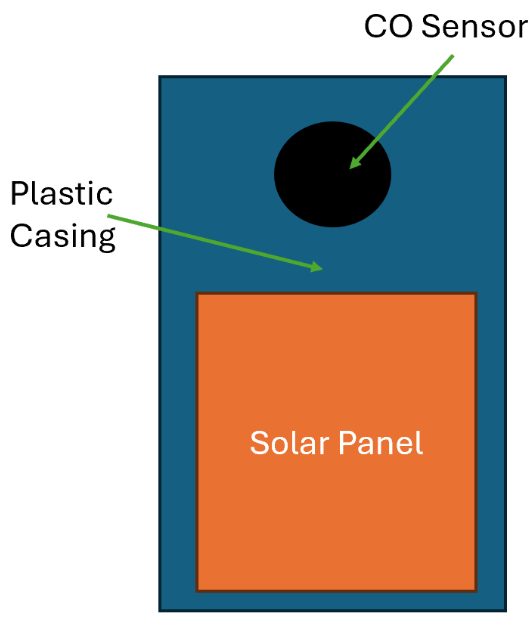



Figure 6: A diagram of independent proposal one.

**Independent Proposal 2 – Drone Data Collection**

For this proposal, we would use drones as our primary way of collecting data on VOCs around forests. The idea is as follows: You would have drones attached with VOC sensors that can measure certain ranges and have thresholds to be met. You would fly these drones into the forest on an autonomous path. The drones would then stop at a location, expose the sensors to gather data in the air. From here, two scenarios would occur. The VOCs sensors would detect a threshold of VOCs, which would promptly send a signal to a team to investigate the area further. On the other hand, if the threshold is not met, the drone would continue forward and repeat the process until an anomaly is found. If nothing if found, the drone will return to a home base and repeat the process. There would be multiple drones that optimally take paths to cover the most area, so it would cover lots of area effectively. In the research paper, "Analyzing VOCs using drones" they tested the implications of using sensors on drones and found that the drone itself does not change the data collected by more than 1%.

**Independent Proposal 3 – BVOC Tracker**

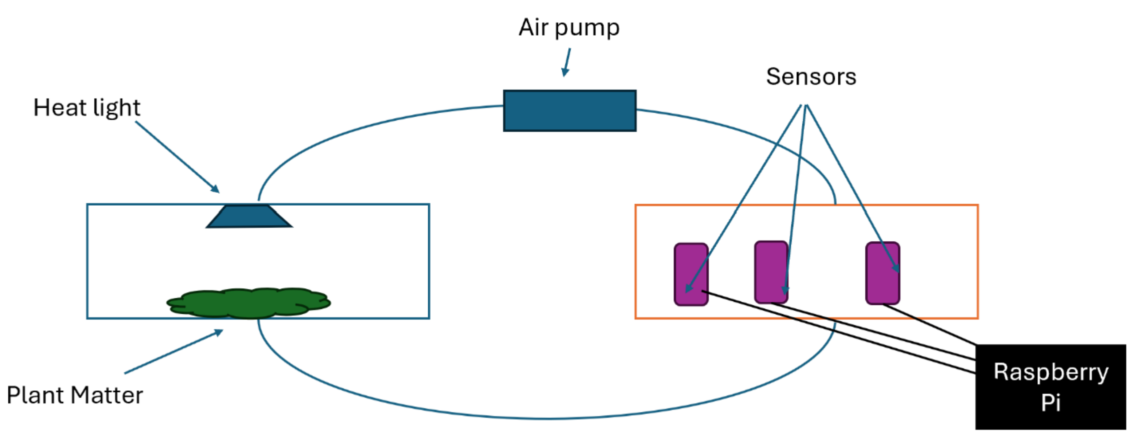
Biogenic Volatile Organic Compounds (BVOCs) are non-methane hydrocarbons and are commonly emitted by undisturbed forest trees. BVOCs include a wide range of chemicals such as isoprene, monoterpenes, sesquiterpenes, terpenes, aldehydes, and ketones. Together, they play a crucial role in helping vegetation enhance their heat tolerance and aid in protection against herbivores. In response to high temperatures, such as during wildfires, trees release copious amounts of isoprenoids as self-protection. For this proposal, we would first conduct experiments to determine a baseline for healthy isoprenoid emission and the primary BVOCs emitted to enhance heat tolerance. Then, we would create a boxlike structure to hold up to four primary BVOC sensors. Attaching the sensors to different trees, we would document and assess the changes in BVOCs in response to high temperatures. However, a pitfall of the proposal that we later realized is that trees also release copious amounts of isoprenoids in response to wounds inflicted by herbivores and human activity such as deforestation.

**Group Redesign**

After meeting with Dr. Hutter, we adjusted our plan to focus specifically on the collection of data samples for VOCs emitted from forest matter, not the system that would be used to implement this in the real world. This data could help others design more effective systems by providing which VOCs and sensors to use.

### 2.3b Final Proposal

Our final proposal was for a system that uses a heat lamp and forest matter in a closed environment to create a realistic scenario that occurs in a forest before a wildfire, and then use a variety of sensors to monitor and record the changes in VOCs overtime as the matter dried out. An air-pump attached to the heat box would circulate the air through the closed system to our Raspberry Pi and sensor reading box, ensuring a constant flow of air like that in a true forested environment.



Above: Figure 7, showing a diagram of our final proposal after Dr. Hutter's advice and adjustments.

Right: Figure 8, showing a chart of our list of chosen VOCs of interest and which sensor would be able to record their quantities.

| Gas Name | Sensor Used for Detection |
|---|---|
| Carbon Monoxide | CO Sensor |
| Methanol | Metaloxide broadband sensors |
| Toluene | Metaloxide broadband sensors |
| Acetaldehyde | No Sensor |
| Hydrogen Cyanide | No Sensor |
| Formaldehyde | PID |
| Ethane | PID |
| Isoprene | PID |
| Particular matter | PM Sensor |

Our choice of sensors was based off the list of nine gases of interest that we identified earlier, with an emphasis on carbon monoxide as that continued to show up as the largest predictor of wildfires of any gas, VOC or otherwise, on the list. A metal oxide broadband sensor was found to track Methanol and Toluene, and a PID sensor that was already present in the lab could be used to track Formaldehyde, Ethane, and Isoprene concentrations. Because of the importance of Carbon Monoxide and particular matter, independent sensors were bought for each of those gases. Each sensor was examined online to ensure that its minimum detection threshold was below the amount of gas we expected to be released within our system, ensuring proper detection instruments would be used. These sensors would be connected via Dupont Jumper cables to a breadboard and Raspberry Pi 4, which could upload our data directly to the internet after proper configuration. This would allow us to have real-time, round-the-clock data tracking of the VOC emissions within the box without us being present in the lab.

# Chapter 3

## 3.1 Experiment Set Up

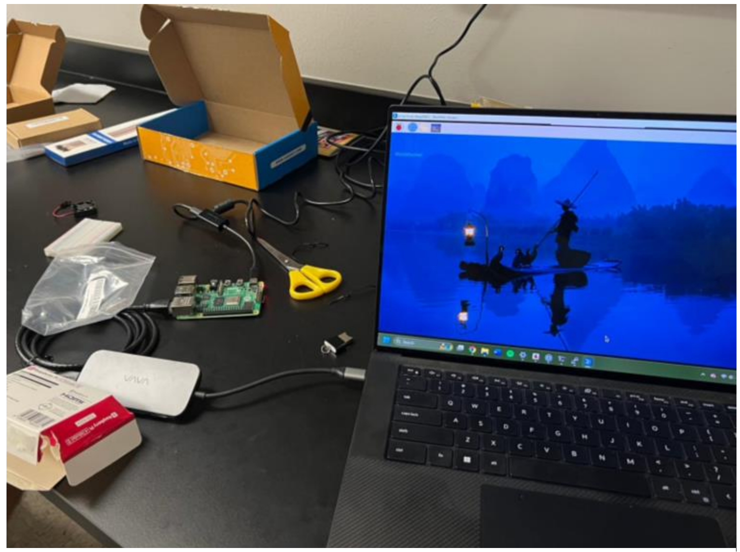


Figure 9, showing the Raspberry Pi connected to power and the computer, and its home screen.

Our experimental set-up took longer than expected, as none of us had previous experience with using Raspberry Pi systems. We began with attempting to wirelessly set up the Raspberry Pi, but quickly found that the University of Texas Wi-Fi setting does not allow for remote access models to be easily added, eliminating one of the main reasons we supported using the Raspberry Pi. In the picture above, you can see the home screen of the Raspberry Pi (on the computer screen on the right) and the Pi itself, plugged into ethernet and power.

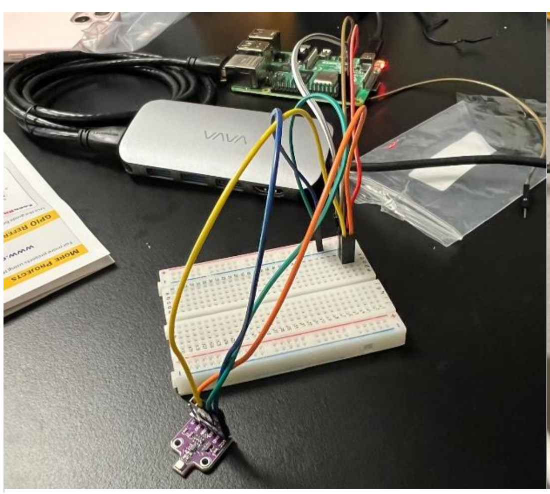
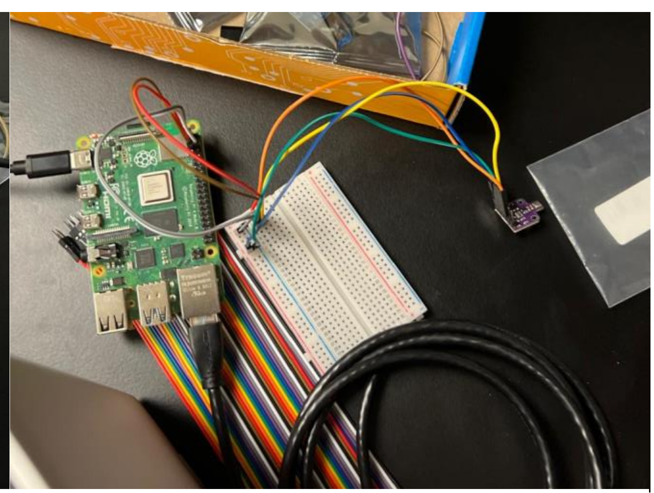



Figure 10 (left) & 11 (right) show the metal oxide sensor wired up to the Raspberry Pi through a breadboard. Connections included power, ground, and two data transmitter cables.

After accessing and setting up the Raspberry Pi as a remote machine, we began exploring how to connect the sensors to the breadboard. We began with the metal oxide broadband sensor, and hooked up power, ground, and the two data out ports to the breadboard, which was connected to the Raspberry Pi. We then soldered the pins of the wires to the sensor to ensure a constant connection and used an i2c standard connection program to find the sensor. In the bottom left of the command prompt window in the picture on the right there is a 77 visible, corresponding to the location of the VOC sensor that is plugged in with the yellow, orange, blue, and green wires. We then started working on how to locate the carbon monoxide sensor, seen in the bottom left of the same image, using the same standard i2c connection system.

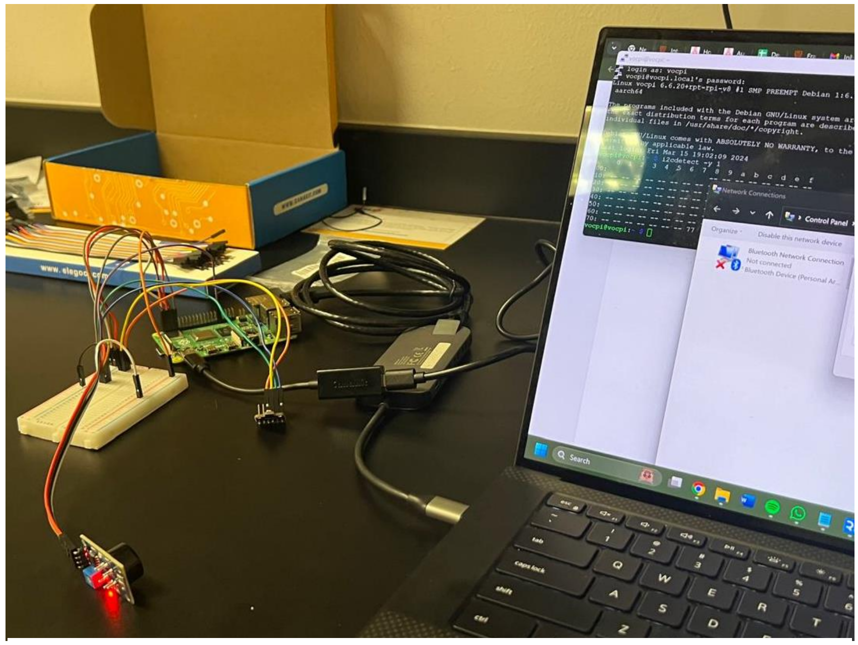
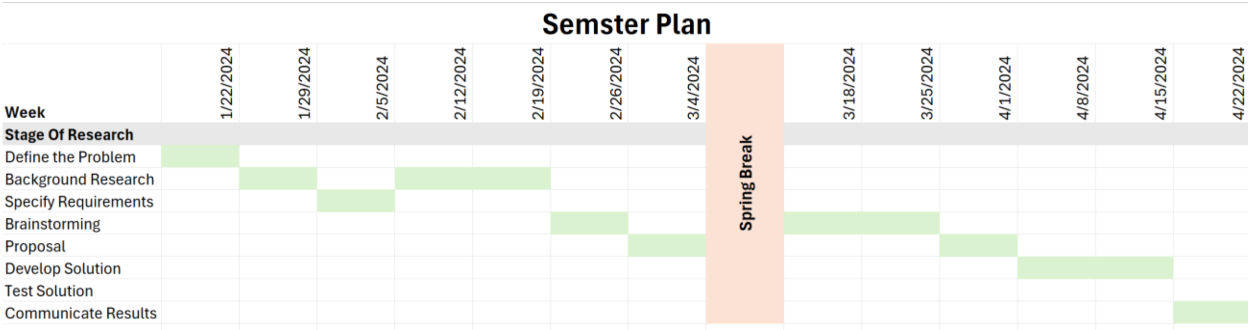


Figure 12: Shows the completed i2c link between the pi, computer, and metal oxide sensor, and the carbon monoxide sensor plugged in and responsive.

## 3.2 Results

Unfortunately, before we found a way to connect the carbon monoxide sensor to the Raspberry Pi, time forced us to move onto our research paper and conclusion of the project, which leaves the project in this current state as of right now. Over the course of the semester, we ran into more issues than we expected that set our plan back multiple weeks, preventing us from having ample time to finish developing and testing the experiment we created.




| Deliverables: Actual timeline | | | |
|---|---|---|---|
| Deliverable | Expected | Actual | Group/Individual |
| Problem Statement | 1/22/2024 | **1/22/2024** | Group |
| Annotated Research Paper 1 | 1/29/2024 | **1/29/2024** | Individual |
| Annotated Research Paper 2 | 2/5/2024 | **2/12/2024** | Individual |
| Annotated Research Paper 3 | 2/12/2024 | **2/29/2024** | Individual |
| Proposed Solution/Experiment | 2/26/2024 | **3/4/2024** | Individual |
| Revised Solution/Experiment | 3/4/2024 | **4/1/2024** | Group |
| Data and results | 4/15/2024 | **N/A** | Group |
| Final Report | 4/23/2024 | **4/22/2024** | Group |

Above: Figure 13, Showing the actual progress we made on a Gantt chart.

Left: Figure 14, showing the actual status of each deliverable relative to it's predicted finish date.

Although we started off on the right foot, we quickly fell behind attempting to propose an experiment to answer our problem statement. Much of this came from confusion and experience in working with undergraduate research. As a new team, we did not know the proper policies of requesting equipment and were unaware of what we had at our disposal within the lab already, which made developing a solution to our problem difficult. Another factor is that our initial proposals revolved around creating solutions to address this problem in the real world with devices that could be successful in the forests, rather than designing experiments that would return VOC data in the lab. This confusion meant that we spent nearly three weeks redesigning our proposal and data recording method, delaying us from setting up and gaining results on our Raspberry Pi. Furthermore, our level of inexperience with the Raspberry Pi interface and physical sensor development meant that even when we did design our experiment and receive the necessary components, progress towards setting up the sensors to retrieve data was slow.

# Chapter 4

## 4.1 Future Work

The next steps for this project are to continue with the raspberry pi and research process and set up the sensors to record the data outlined above. After ideally taking multiple samples of similar and different types of forest matter within the enclosure, the data should be analyzed for patterns within the VOC content that help show a predictive pattern before combustion of the material is imminent.In the future beyond this experiment, the data found using these tests can be used in industrial and commercial grade equipment to manufacture devices similar to those in our initial proposals that can act as early-warning devices, helping countries and agencies move resources to areas that are prone to wildfire breakouts before they occur.

## 4.2 Conclusion

Throughout the process, we learned about VOCs and their implications to preventing wildfires. We researched, proposed, and began implementing a system to gather valuable data. We also learned a great deal about how to conduct research at large institutions such as the University of Texas, and some of the benefits and downsides of doing so. Looking at our goals outlined in the beginning, we successfully achieved goals one and two, and made substantial progress on goal three. Goals four and five are within reach, but unfortunately unforeseen issues, mainly tethered to our inexperience in a research lab such as this and our unfamiliarity with a Raspberry Pi meant we came up short. Because we failed at recording data within the time allotted, we were not able to achieve any of the secondary goals stated. This lab provided us with a great deal of information, both about wildfires, the problems we face, and a professional lab environment, and we hope that someone can continue this research in the future with promising results.

# Appendix

A. References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