Preventing Underground Vault Electrical Explosions

Final Report

Senior Design

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Abstract

Underground vault electrical explosions have become a major issue for power utilities. As they begin to improve their technology and analytics to prevent failures, utilities such as Southern California Edison, our sponsor, are evaluating further investments in data acquisition and sensors. In this project, we are required to develop a monitoring and broadcasting tool for vault conditions. We have chosen a semiconductor metal oxide gas sensor array device, as this low-cost method is improving while other methods remain expensive. A low-cost gas sensor device has never been developed for quantitative or safety applications, but the goal is getting nearer with modern research. We have developed and tested a gas monitoring and warning device that can operate in changing environmental conditions.

1.1 Problem/Background

Figure 1.1. Electrical Vault Explosion

Southern California Edison owns underground structures for electrical equipment that collect explosive gases. Figure 1.1 shows a vault explosion. These gases can provide a fuel source for explosions that threaten human safety and occur in milliseconds. The vast majority of visible vault events only involve smoke production, but explosions are happening more and more. A vault is a confined space, so the energy is dissipated outside the vault. Explosions require fuel and a spark. The fuel in vault explosions is gas buildup in the cable duct or vault. Gas values are often given in volume percent or ppm, parts per million. The gas concentration must reach the lower explosive limit percent and not exceed the upper explosive limit percent. The spark is usually from a cable fault but can be from many other sources. In terms of heat source, cables and transformers generate a great deal of heat. It is the thermal-oxidative properties of materials that are outcome-determinant, such as cable insulation, ductwork, splices and terminations, transformer material, etc. The gases in vault explosions mostly come from cable deterioration in the duct. Heat comes from the cables, transformers, environment, etc. Cable insulation and gasoline are made of the same basic substance, methylene. Thermal decomposition, also known as pyrolysis, produces CO and char, the main culprits in explosions. Other chemical processes that are part of explosions are oxidative decomposition and polymer plasmatization which comes from high temperature faults. Concentric neutrals get corroded due to seawater. The air environment for the device is challenging to its sensors. Crews describe a rotten egg smell (methane, sewer gas), which was described in the vault visit. An unlimited variety of substances that may impact sensor functionality. We attempted to anticipate the most probable explosive scenarios. Figure 1.2 shows the components of atmospheric air as a reference. Oxygen can be used up in as burning proceesses develop in a cable duct and vault.

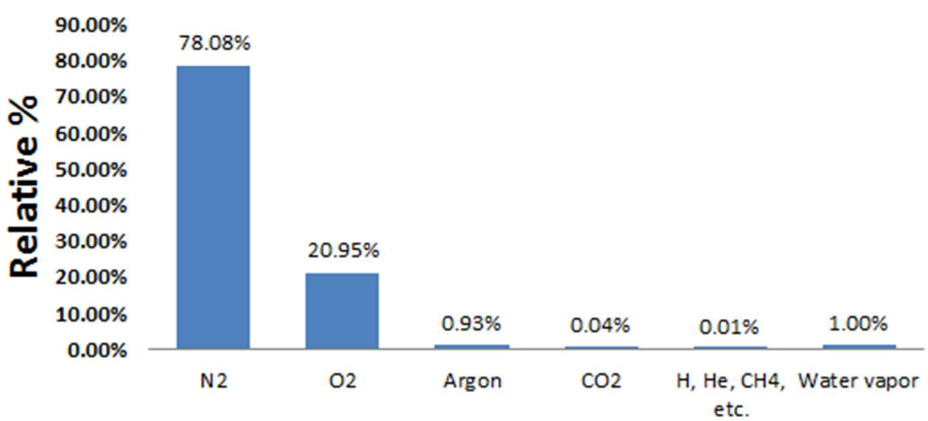


Figure 1.2. Gaseous components of atmospheric air

After an explosion, Edison engineers must be forensic analysts in their task to figure out why the explosion occurred. The sparse data they have to work with primarily includes current sensors on overhead lines called Current Transformers (CT). The current in the secondary winding is proportional to the current flowing in the primary winding:

$$I_{secondary} = CT_{turnsRatio} \times I_{primary} \quad (1)$$

$$CT_{turnsRatio} = Turns_{primary} / Turns_{secondary} \quad (2)$$

where I is current, CT is current transformer, and Turns is winding turns. These sensors scale down the high voltage signal for sampling every minute. This sampling period is too low to provide adequate information to analyze an explosion. Furthermore, gas exposure can be dangerous to regular vault crews. Table 1.1 shows exposure limits to carbon monoxide from the Occupational Health and Safety Administration.

Table 1.11. Carbon monoxide exposure limits [1]

PPM CO in Air	**Air Quality, Workplace and Residential CO Exposure Limits**
9 ppm	EPA National Ambient Air Quality Standard (NAAQS) over 8 hour TWA
25 ppm	ACGIH Threshold Limit Value (TLV) and Cal/OSHA PEL over 8 hour TWA
35 ppm	EPA NAAQS over 1 hour and NIOSH Recommended Exposure Limit (REL) over 8 hour TWA
50 ppm	OSHA Permissible Exposure Limit (PEL) over 8 hour TWA
70 ppm	NFPA 720 and UL 2034 Residential CO Alarm Activation within 1 to 4 hours TWA
150 ppm	NFPA 720 and UL 2034 Residential CO Alarm Activation within 10-50 minutes TWA
200 ppm	Cal/OSHA and NIOSH Ceiling Limit (C)
400 ppm	NFPA 720 and UL 2034 Residential CO Alarm Activation within 4-15 minutes TWA
1200 ppm	NIOSH Immediately Dangerous to Life or Health value (IDLH)

Our chosen solution for measuring gas concentration is a semiconductor metal oxide sensor array. In terms of solutions, many methods are shown in Table 1.2.

Table 1.2. Evaluated explosion prevention methods

Prevention method	**Conclusion**
Optical	Expensive, needs microelectromechanical advances
Pressure sensor	Too slow
Current transformer/sensor	Expensive
Filler (sand)	Removal
Residential CO alarm	No data, challenging environment
Replace cable	Expensive
More airflow	Expensive, already exists
Vented cover	Still explodes, already exists
Seal ducts	Seals fail
Restrain cover	Still explodes

Explosions happen in milliseconds, so overhead current sensors show regular current for 1 minute and zero the next minute, which does not provide information for diagnosis. Our option is a sensor array that could potentially warn of incipient conditions and provide data for inspection programs. Inexpensive gas sensor arrays are called electronic nose. Metal oxide are the most studied due to low cost, simplicity, large number of detectable gases, but they have never been used for quantitative or safety applications because of performance degradation due to resistance drift and surface poisoning. The sensor signal is from a resistance change due to chemical bonding on the surface. Poisoning occurs when a gas compound irreversibly interacts with the surface. In gas sensor design there are contradictory constraints because precision implies strong interactions, and reversibility implies weak ones.

Because faults that lead to explosions happen primarily in the duct, power line insulation decay is important. A power cable fails when the local electrical stresses (E) are greater than the local dielectric strength (alpha) of a given dielectric. The reliability and thus the rate of failure of the cable system depends on the difference between the local stress and local strength. Measures such as the Weibull scale (Beta) are used to estimate cable failure probability:

$$P_f = 1 - e^{\frac{E^B}{a}} \tag{3}$$

where P is probability of failure, E is local electric stress, B is the Weibull scale parameter, and alpha is the local dielectric strength [2]. Figure 1.3 shows a typical vault.

Figure 1.3. Model of underground electrical vault [3]

Environmental leakage of gas is a problem as well, including from natural gas lines, gas stations built before 1980 as shown in Figure 1.4, organic decomposition, sewer gas, farmland, etc.

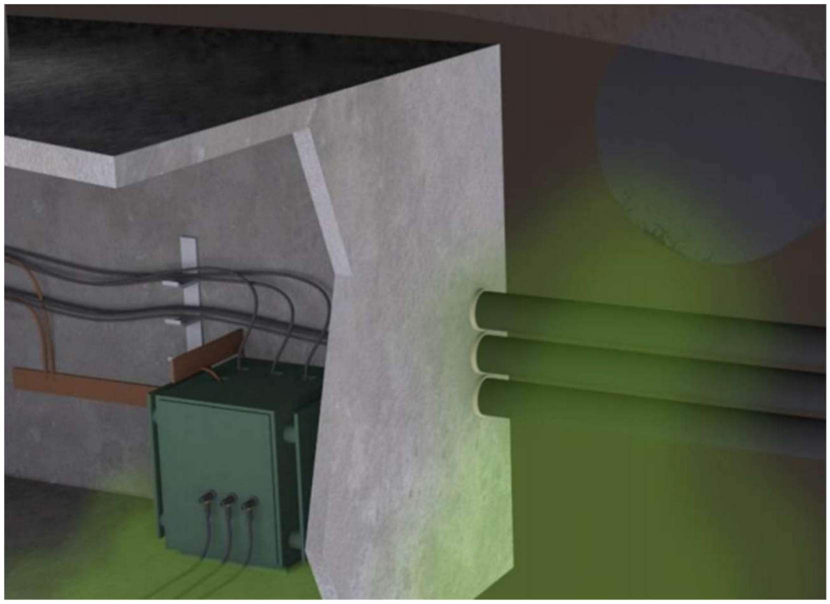


Figure 1.4. Sewer gas leakage into vault [3]

Insulation can burn in a duct for a long time without producing a flame and then quickly erupt into flame. This oxidation process is illustrated in Figure 1.5.

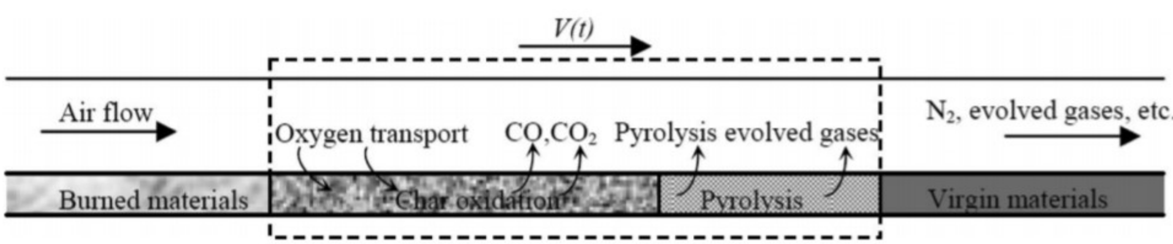


Figure 1.5. Electrical duct showing evolved gases [4]

1.2 Project Objective/Scope

A monitoring device is needed to provide a warning and data about potentially dangerous gas conditions. Society must receive a warning, and inspection crews must know about vault conditions. The data could be used to inspect at-risk structures and record conditions leading up to events for later analysis. Gas sensing devices fall under a broader category of devices called electronic nose as demonstrated by Figure 1.6. Therefore, the task was to create an electronic nose for explosive gas sensing in underground structures.

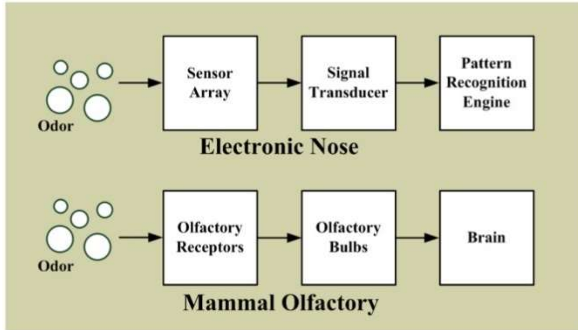


Figure 1.6. Electronic nose system compared to biological system

1.3 Society Impact/Factors

Figure 1.7. Power distribution vault for street lights and other structures in Costa Mesa, CA

According to IEEE (Institute of Electrical and Electronics Engineering), it is estimated that there will be 2000 manhole events per year or 5.5 events per day in the U.S. In addition, there is a risk rate of 1 event per 1000 manholes per year [20]. Figure 1.7 shows a vault with current sensors being installed. Sidewalk vaults pose a threat to pedestrians, and street vaults pose a threat to cars.

2.0 Approach

2.1 Design Process

The design process began by meeting with Edison and reviewing background research that engineers had collected about the problem of vault explosions. Schedule, Work Breakdown Structure, and Scope of Work documents were created. An initial prototype using lower cost sensors was tested to verify initial hypotheses. Following this, detailed design work began on an integrated system to sense and warn about vault gas conditions and an enclosure to house the device. An iterative test process was followed to produce a working sensor electrical subsystem.

The project was divided into three phases as of early December 2018. The plan showed three phases with their specific tasks and estimated duration days to complete. It was estimated that the project would take 182 days to complete and deliver its prototype.

Phase 1: Research and Initial testing

- Started on September 3, 2018 and expected to be completed February 13, 2018.
- There are 6 tasks assigned in this phase that are necessary components for detailed design and assembly.
- It is estimated that it will take 118 days to complete.
- 3 tasks are completed and 3 tasks are undergoing that will be completed by the end of January 2019.

Phase 2: Design and Assembly

- Started on October 8, 2018 and expected to be completed April 26, 2019.
- It is estimated that it will take 145 days to complete.
- 4 tasks are assigned and 2 tasks are above 50% completion while the rest 2 are undergoing.

Phase 3: Test and Evaluation

- Started on November 12, 2018 and expected to be completed May 8, 2019.
- It is estimated that it will take 128 days to complete.
- 4 tasks are assigned and 2 tasks are 25% and above completion. 2 tasks are not started yet and scheduled to be started after March 25, 2019.
- Prototype testing iteration and safety measures for testing gases will be areas of effort.

2.2 Organization/WBS

The organization chart in Figure 2.1 includes liaisons, faculty advisor, and the team.

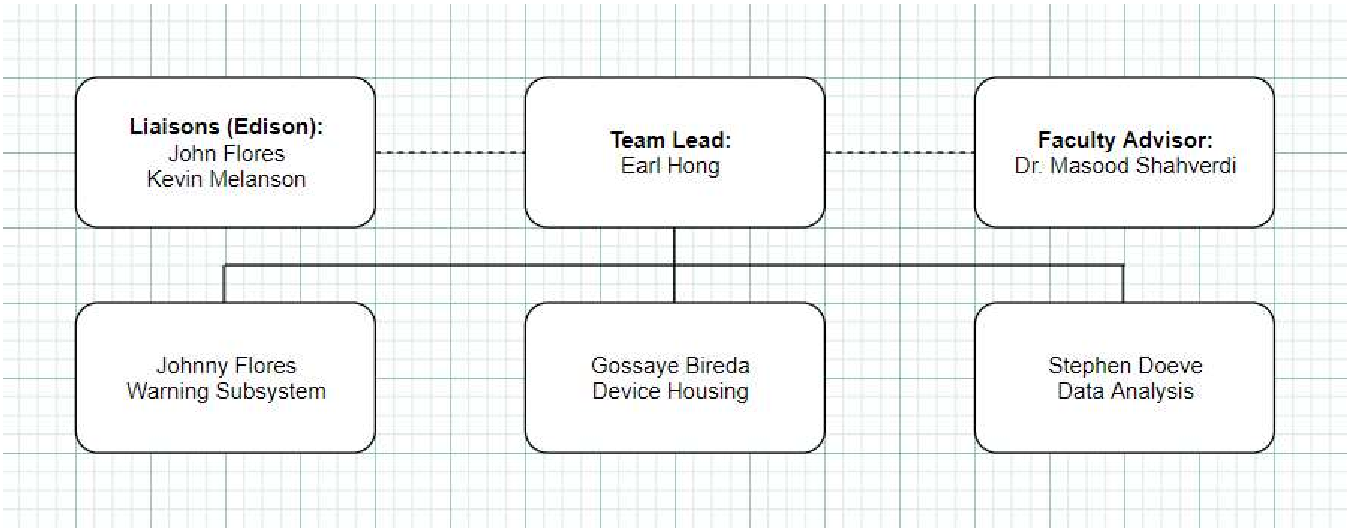


Figure 2.1 Organization chart

The Work Breakdown Structure assigns work to each team member in Table 2.1.

Table 2.1. Work Breakdown Structure

WBS Number	Task	Lead
1.0	**Phase 1 – Research and Initial Testing**	
1.1	XLPE byproduct research	Johnny
1.2	Gases Research	Gossaye
1.3	Sensor Research	Stephen
1.4	Prototype Specifications/Concept Design	Earl
2.0	**Phase 2- Detail Design and Assembly**	
2.1	Software Implementation/Testing	Stephen
2.2	Component Acquisition/Research	Johnny
2.3	Component Testing/Troubleshooting	Gossaye
2.4	Prototype design/build	Earl
3.0	**Phase 3- Test and Evaluation**	
3.1	Prototype Testing	Stephen
3.2	Prototype Specifications Review	Johnny
3.3	Prototype Calibration	Earl
3.4	Prototype Retesting	Gossaye
4.0	**Project Management**	
4.1	Finance and Business	Evelyn Li
4.2	Weekly Agendas	Stephen
4.3	Minutes	Earl
4.4	Design Review packages	Johnny
4.5	Research reports	Gossaye

2.3 Schedule

A schedule was updated weekly with progress for each WBS component as shown in Figure 2.2.

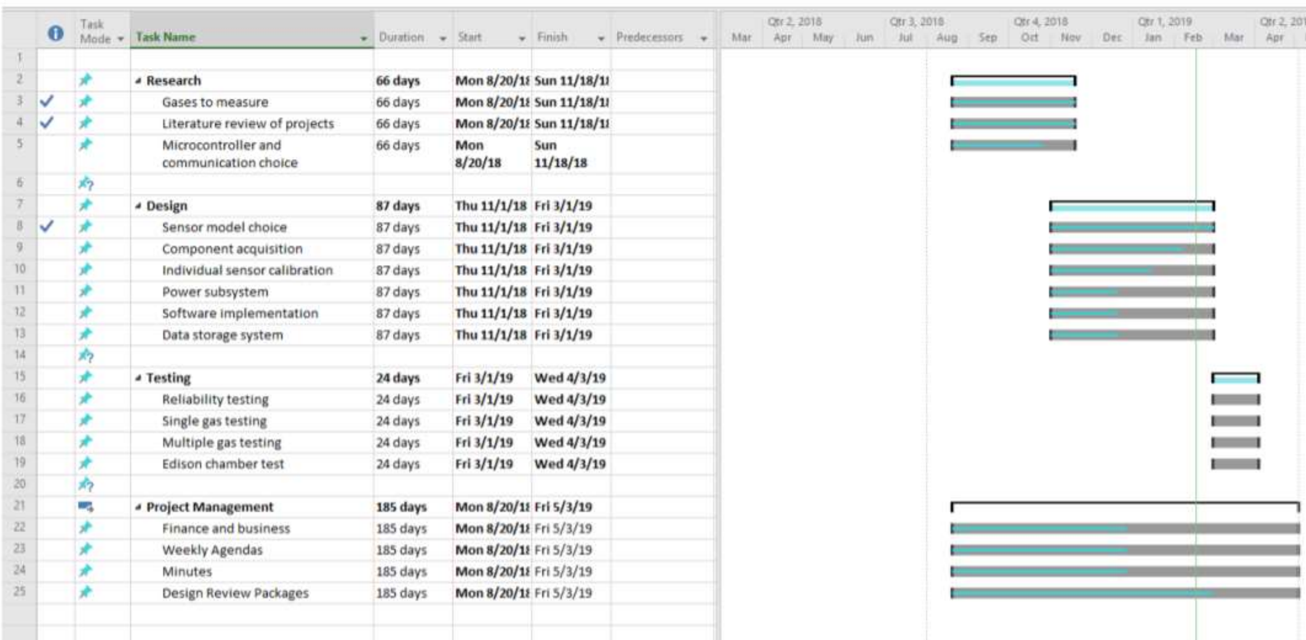


Figure 2.2. Schedule in February 2019

2.4 Deliverables

The project deliverables included the device, operation manual, and reports as shown in Table 2.2.

Table 2.2. Project Deliverables

Item	Quantity	Description	Due Date
1*	4	Report of gas sensors (Carbon Monoxide, Carbon Dioxide, Methane, Hydrogen)	13 May 2019
2	2	Report of temperature sensor	13 May 2019
3	1	Report of humidity sensor	13 May 2019
4*	1	Report of Configuring Arduino Uno Microcontroller	13 May 2019
5	1	Housing/Packaging design and assembly report	13 May 2019
6	1	Final paper	13 May 2019
7	1	Operation Manual	13 May 2019

3.0 System Overview

3.1 Requirements

Research was necessary to determine the gases that needed to be measured in . The gases primarily implicated in explosions can be measured, and other gases that provide data about explosive conditions can be important to measure as well. Carbon monoxide and carbon dust are by far the primary fuels for explosions. [6] Pyrolysis, which is burning without oxygen that degrades cable insulation, generates carbon monoxide, which is is highly toxic and explosive at concentrations between 12 and 75% in air. Carbon dioxide is a product of pyrolysis as well [3]. Combustible zones in vaults contain an amount of oxygen in a specific range where if a spark occurs, then ignition occurs. [3] Temperature and humidity are required for meaningful sensor values and knowledge of vault conditions. Figure 3.1 shows what can happen when sensor readings are not updated.

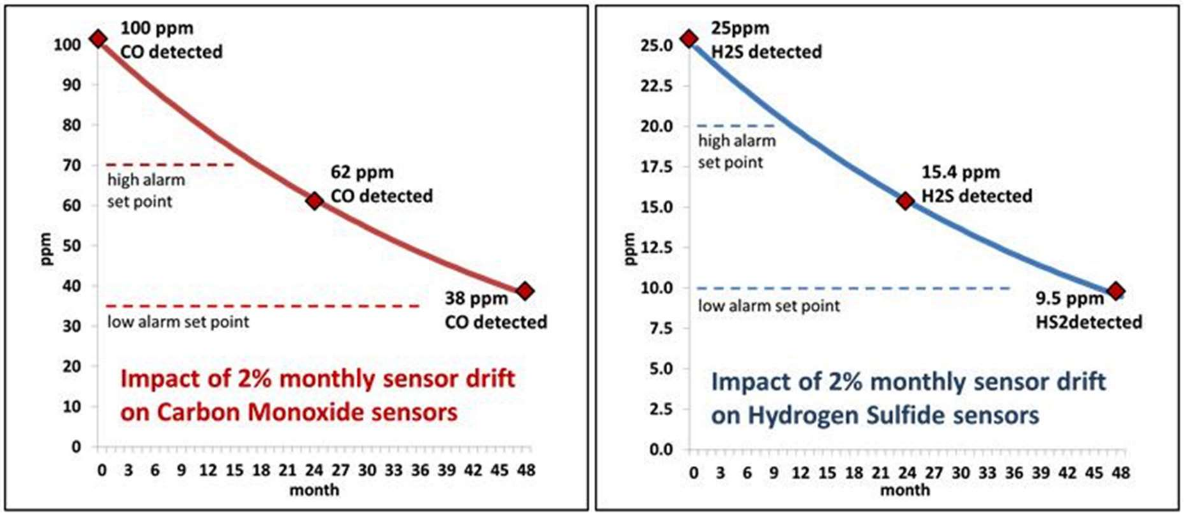


Figure 3.1. Example of sensor drift due to environmental humidity and temperature [7]

Methane and other explosive hydrocarbons occur in large quantities in vaults as shown in Figure 3.2.

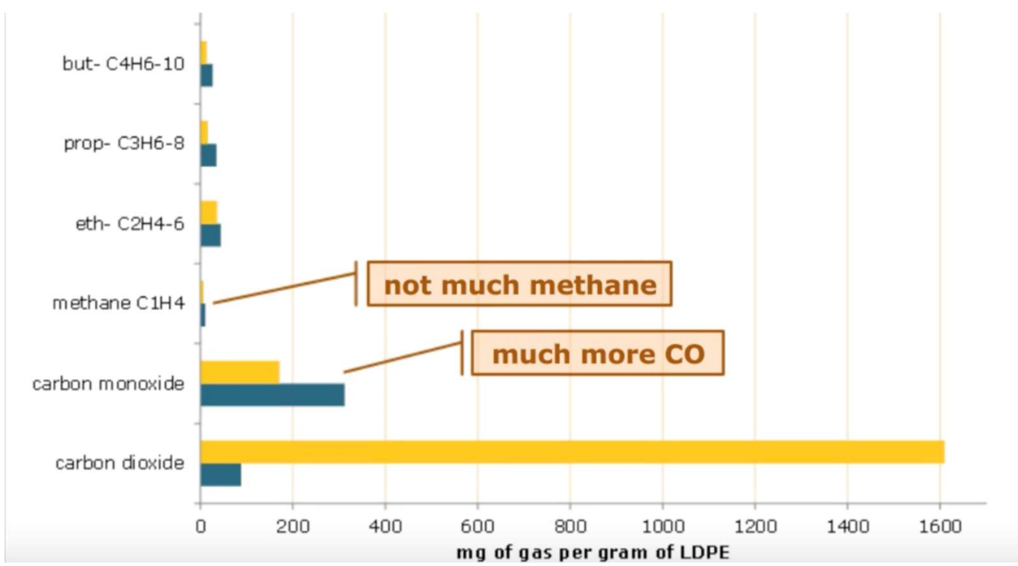


Figure 3.2 Several gases found in vaults [3]

Volatile organic compounds (VOC's) are implicated in explosions as well and can be toxic. [3] If there is enough water vapor (humidity) in the vault, an explosion cannot occur. Heat is a major contributing factor to insulation degradation and combustion chemistry. Table 3.1 shows the quantities we chosen to measure in the final prototype

Table 3.1. Measured quantities in final device

Name	CO	C	CO_2	CH_4	VOC's (C_4H_6, C_5H_8, etc.)	H_2O	Light	Temperature
	carbon monoxide	carbon dust / char	carbon dioxide	methane	(propane/ butane/ LPG, etc)	water vapor / humidity	N/A	N/A
LEL -UEL (%)	12.5 74.2	dust	non-flammable	4.4 17	various	non-flammable		
Density vs. air	⇡	⇣	---	⇡	⇣	---		
Explosive	Yes	Yes	No	Yes	Yes	No		
Flammable	Yes	Yes	No	Yes	Yes	No		
Odor	none	none	none	added rotten egg smell	various	none		
Source	cable insulation	cable insulation	burning reactions	nursuries, farmland	gas lines, cable insulation	environmental		

The requirements for the prototype and varying vault conditions are shown in Table 3.2 below.

Table 3.2. Device Requirements

No.	Title	Requirement	Capability
1	Material	Stainless Steel	Stainless Steel
2	Reliability	>5 Years	>3 Years
3	Power Source	110-120VAC/12VDC	110-120VAC/12VDC
4	Size	8 x 8 x 5 in	7.85 x 7.95 x 4.38 in
5	Gas Sensing	Monitor CO, CO2, Methane Levels in PPM	Complies
6	Temperature	-20 < T < 50 C	Complies

The material chosen was stainless steel due to its capability of withstanding heat and durability. The device needs to be able to survive vault explosions and fire as well as have an enclosure that can last throughout humid or water conditions.

There are current programs sponsored by Southern California Edison that check and maintain conditions in underground vaults. These vault visits are costly and occur every 5 years hence why the prototype device is required to fully operate within this time frame to reduce maintenance cost. The device is powered using an outlet source which will then be connected to an adapter specifically made for the PSoC microcontroller that will convert the AC voltage to the microcontroller's operating DC voltage. An 8x8x5 enclosure to secure the device components as well as create manageable air flow. The gas sensors chosen must detect gasses within the vault and programmed to convert sensor readings to parts per million. Underground vaults also tend to experience extreme temperature conditions, which is why the components for the device must stay operable within or close to the temperature range of –20 to 50 degree Celsius.

3.2 Architecture Overview

System-on-chip (SoC) technologies have had a major impact on portable system integration. [8] Our microcontroller includes technology to understand analog signals from sensors and convert them to digital before performing post-processing. PSoC 5LP includes Analog Front End, which performs the analog signal processing steps of amplifying and filtering the sensor signals. An analog-to-digital converter (ADC) quantizes and samples the data to be sent to the microcontroller (MCU). Figure 3.3 illustrates this process:

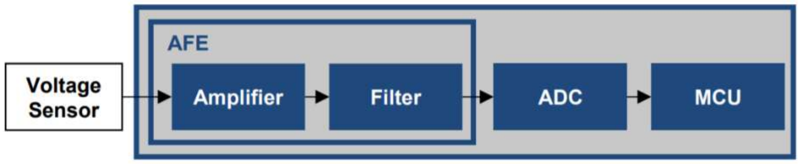


Figure 3.3. Analog Front End in PsoC 5LP [9]

A CAD design of the porotype inside a vault is shown in Figure 3.4. The device will be placed along the wall of the vault and attached to the wall. Due to accumulation of water on rainy days or water that run off into the vault, we chose to implement a rail in this design which could serve as protection when water level increases within the vault. The microcontroller will have a water level sensor that is capable of detecting water level and a motor within the enclosure that is attached to the rail will adjust the height of the device based on water levels. We also have our enclosure with an opening for the LED and LCD to display vault conditions, as well as a buzzer located inside the enclosure for an auditory warning

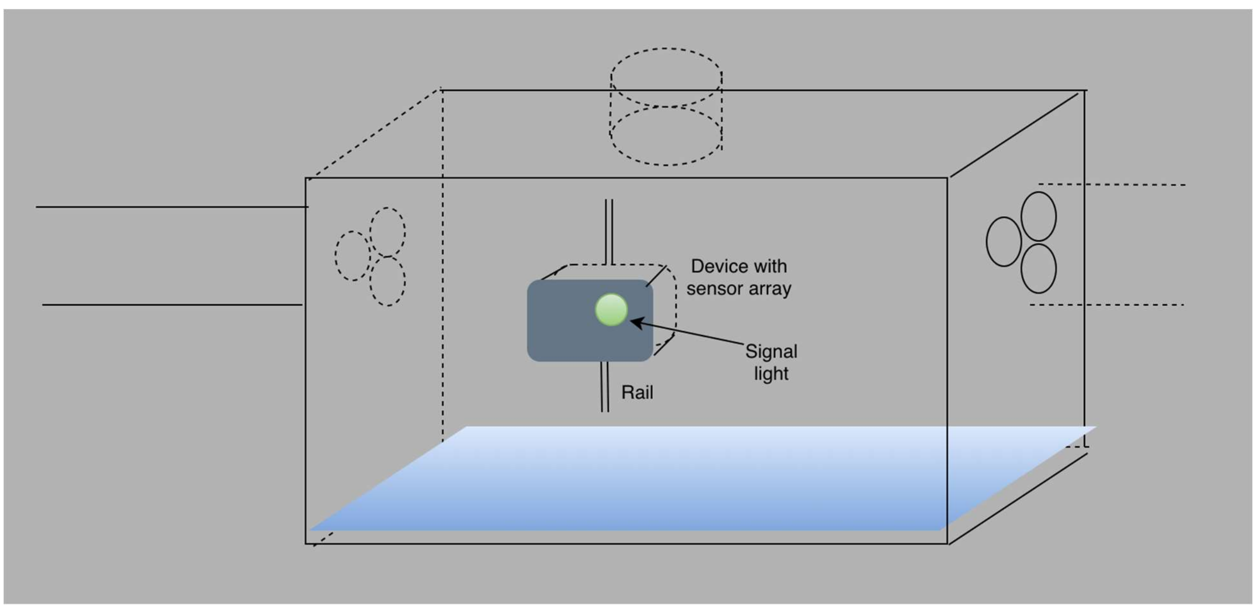


Figure 3.4. Mechanical conceptual overview of device in underground vault

Figure 3.5 shows each component inside the enclosure.

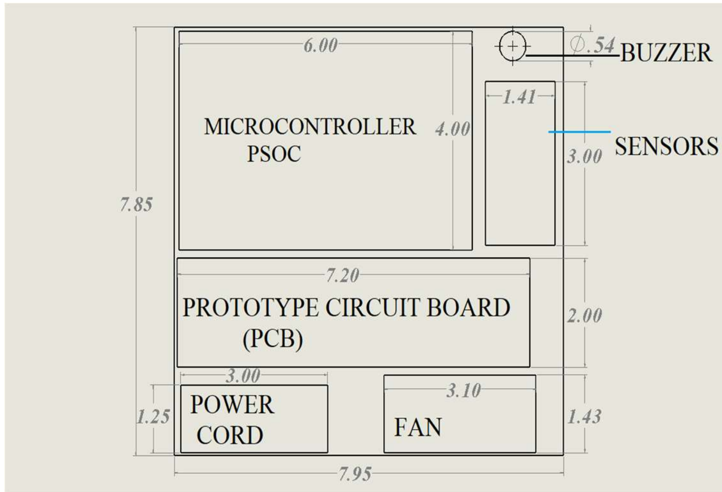


Figure 3.4. Schematic of components inside enclosure

The electrical schematic in Figure 3.5 shows the overall architecutre.

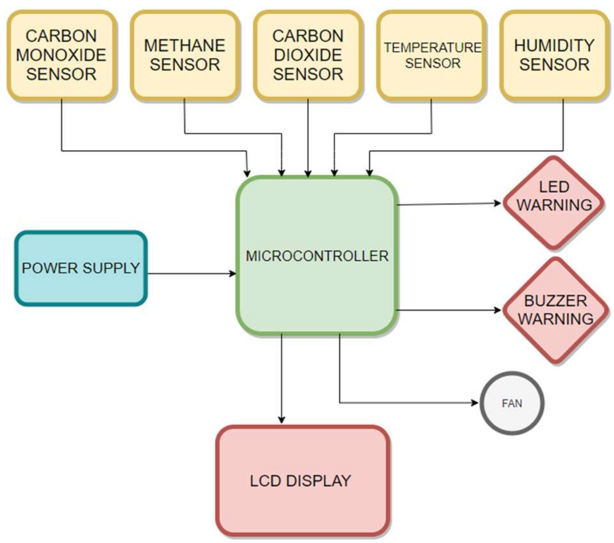


Figure 3.5. Electrical schematic of final device

3.3 Design Budgets

In terms of general architecture, our chosen sensor array could be connected to further hardware in several configurations with trade-offs in cost, portability, etc. Table 3.3 lists architectures that have been used previously in gas sensing devices.

Table 3.3. Architectures for a gas sensing device [10]

Architecture	Typical Configuration (bit/speed/RAM)	Pros/Cons	Typical Programming Language	Available Processing
Sensor Array + µC (PIC)	8 bit/10 MHz/k bytes	Easy, small, low power, portable, cheaper	ASM/C	Easy algorithms with few data, KNN, easy NN, mostly trained off-system, linear classifiers, quadratic classifiers.
SA + high perf. MC	8–16 bit/ 10–33 MHz/k bytes	Small, low power, portable, cheap	ASM/C	Some small matrix manipulation available, linear (PCA, LDA, PCR), KNN, easy fuzzy interface Systems.
SA +µP or DSP	16–32 bit/ 20–100 MHz/Mb	Very fast, medium size, portable, high power consumption	ASM/C/C++	Linear (PCA, LDA, PCR, PLS), KNN, easy neural and fuzzy system, standard feature extraction/selection (PCA, LDA).
SA + Embedded PC	32 bit/ 80–233 MHz/Mb	Fast, medium size, portable, huge data capacity, high consume expensive	Any	Linear, complex learning algorithms (GA, NeuroFuzzy Systems, mixture models, APR, FIS Optimization Algorithms), advanced feature extraction/selection (SFS, SFFS).
SA + Desktop PC	32–64 bit/ 700 MHz/Mb	Fast, medium size, portable, huge data capacity, consume not critical, expensive, not portable	Any / Visual	Linear, complex learning algorithms (GA, NeuroFuzzy Systems, mixture models, FIS Optimization Algorithms), advanced feature extraction/selection (SFS, SFFS), *etc.*

µC, microcontroller; µP, microprocessor; PIC, peripheral interface controller; SA, sensor array; NN, nearest neighbor algorithm; DSP, digital signal processing; KNN, k-nearest neighbor algorithm; PCA, principal component analysis; LDA, linear discriminant analysis; PCR, price coupling of regions; PLS, projection to latent

structures; GA, genetic algorithm; APR, annual percentage rate; FIS, fuzzy inference system; SFS, shape from shading; SFFS, sequential forward floating selection.

Furthermore, several off-the-shelf solutions are available. However, these options are cost-prohibitive for installing in many vaults and are not configured for the specific explosive gas conditions of an underground vault.

Gas sensors are available with a wide variety of operating principles. Microelectromechanical sensors can provide high sensitivity and selectivity as demonstrated in Figure 3.6. They can also operate with extremely low power and use small batteries. While these sensors have experience large reductions in cost, they still cost $1,000 and more, making them impracticable for purchase in large scale by utilities.

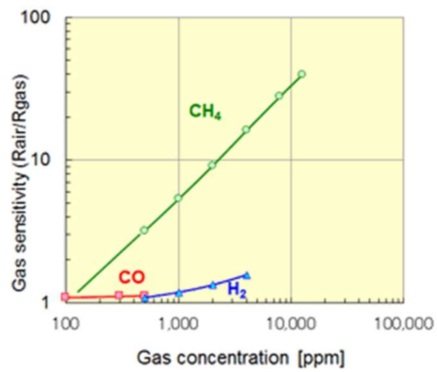


Figure 3.6. Microelectromechanical sensor sensitivity [11]

A popular sensor type for low-cost gas sensing is metal oxide semiconductor (MOS). Figure 3.7 shows a schematic of a MOS sensor.

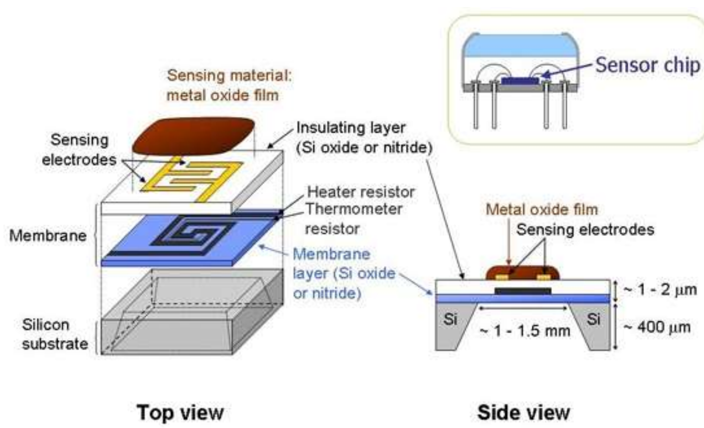


Figure 3.7. Top and side views of metal oxide semiconductor (MOS) sensor type [12]

These sensors are commonly used in low-cost gas detection systems with their main limitation being durability because of surface poisoning in high exposure conditions. With the MOS strategy defined, the need for sensitivity to each gas was evaluated. Table 3.1 in Section 3.1 provides the upper and lower explosion limits for each gas. Sensitivity to higher ranges of gas requires more expensive sensors, so cost-effective choices were made that could still provide information necessary to warn about explosions and unsafe conditions. Ranges in Parts Per Million are provided for many commercial gas sensors in Figure 3.8.

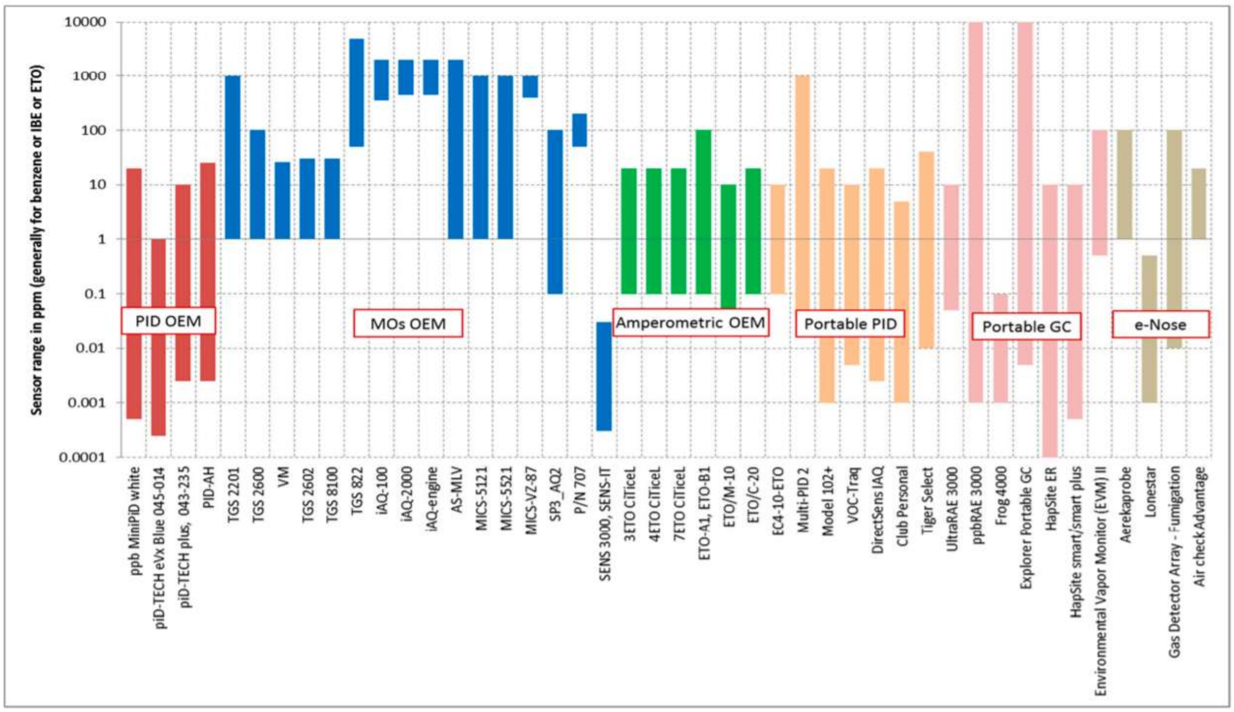


Figure 3.8. Rated range in parts per million for Volatile Organic Compound sensors [13]

The Figaro 5042 Carbon Monoxide sensor was chosen for its longevity, low cost, and sensing range. A cutaway view of the sensor is shown in Figure 3.9.

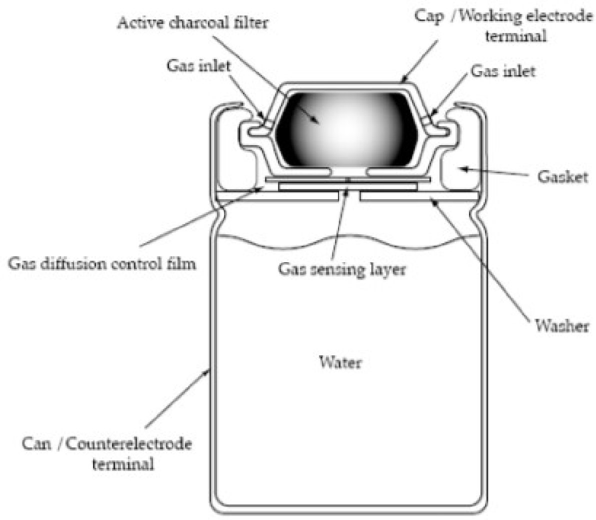


Figure 3.9. Figaro TGS 5042 Carbon Monoxide sensor with sensing layer shown [21]

Figaro sensor response is typically given as concentration versus logarithmic axis of R_s/R0 which can be represented by the equations:

$$\log_{10}\frac{R_S}{R_0} = a + b\log_{10} p \quad (5)$$

$$p = (\frac{R_S}{R_0}10^{-a})^{\frac{1}{b}} \quad (6)$$

where R_s is the sensor resistance in displayed gases at the measured concentration p and R0 is the sensor resistance in clean air. These equations provide sensor response in a linear relationship with measured gas.

Oxygen and carbon dioxide sensors from Figaro and other manufacturers cost over $100 each. Therefore, we sough to achieve similar results from a lower cost sensor. The Amphenol MiCS-VZ-89TE provides measures of both CO_2 and Volatile Organic Compounds. A comparison chart for CO_2 performance against an expensive and highly accurate Nondispersive Infrared sensor is shown Figure 3.10.

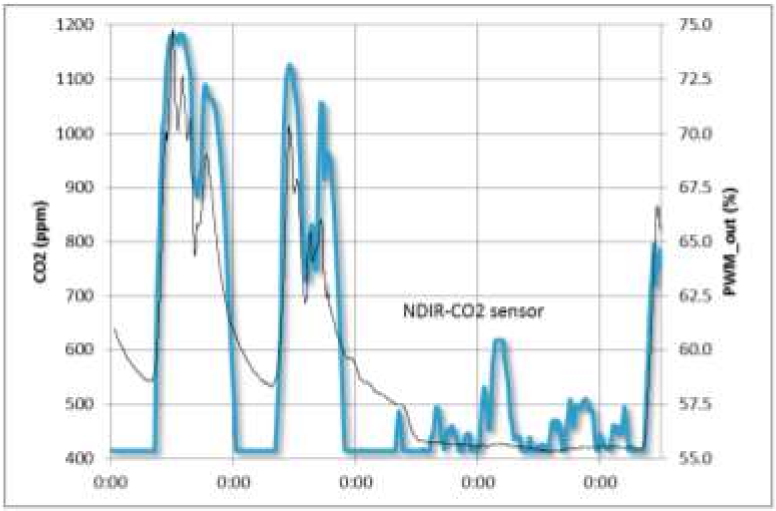


Figure 3.10. Amphenol CO_2 and Volatile Organic Compounds sensor [14]

In addition to measuring gases, we sought to provide information about light and darkness levels in the vault. Many environmental monitoring studies have demonstrated the efficacy of combining very different sensors. For instance, it has been found that combining a photoresistor with a carbon monoxide detector can more effectively classify fire and smolder events. A light dependent resistor can reduce its resistance with increased light intensity. Figure 3.11 shows the operating principle of the light sensor.

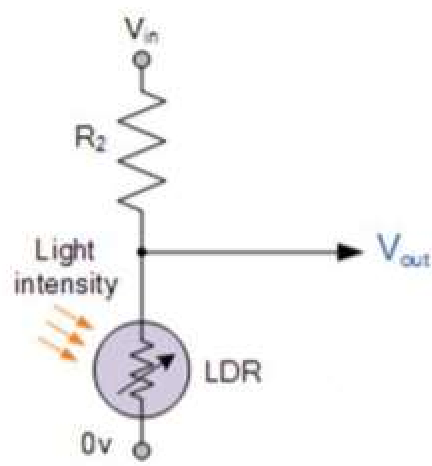


Figure 3.11. Photoresistor [15]

Components for the device were chosen based on the project’s requirements as well as component capabilities. Table 3.4 shows the trade study taken to decide the proper microcontroller for the device. The Programable System On Chip (PSoC 5LP) was chosen for its abundant amount of general input/output pins, and processing speed. The only downside was the price.

Table 3.4. Microcontrollers trade study

Microcontroller	**Arduino Uno REV 3** 	**Arduino Mega 2560 REV3** 	**Raspberry Pi 3** 	**Beaglebone Black** 	**PSOC 5 LP** 
Recommended Power Supply	9-12V DC 0.5-2A barrel, or 5V 500mA USB or 9-12V on VIN pin	7-12V rec. input voltage, 6-20 input voltage limit	5V 2.5A micro USB port	5V 1.2A -2A barrel	1.7-5.5V
GPIO pins	6 analog in 14 Digital- 6 PWM	54 digital input/output pins, 16 analog inputs, 4 UARTS	40 I/O pins, including 29 Digital **No analog pins**	65 Digital- 8PWM 7 analog in	72 I/O pins
Processor & Processor Speed	ATMega328P U (16KHz)	ATmega2560 (16MHz)	ARM Cortex A53 (1.2GHz)	AM335X ARM Cortex A8 (1GHz)	ARM Cortex M3 (80MHz)
Memory	32KB flash, 1 KB EEPROM	256 KB (8KB used by bootloader)	1GB	4GB	256KB Flash, 64KB RAM
Operating Temperature Range	-40< T < 85 degree C	-40< T < 85 degree C	-40< T < 85 degree C	-40< T < 85 degree C	-40<T< 85 degree C
MSRP	$22.00	$38.50	$35.00	$49.00	$99.00

Our methane sensor uses the metal oxide sensing principle. In this scenario, by heating a semiconductor element, oxygen is adsorbed on the sensor surface and attracts free electrons. When explosive reducing gases are present, the surface density of oxygen is reduced and current can flow freely through the sensor. Figure 3.12 shows this approach.

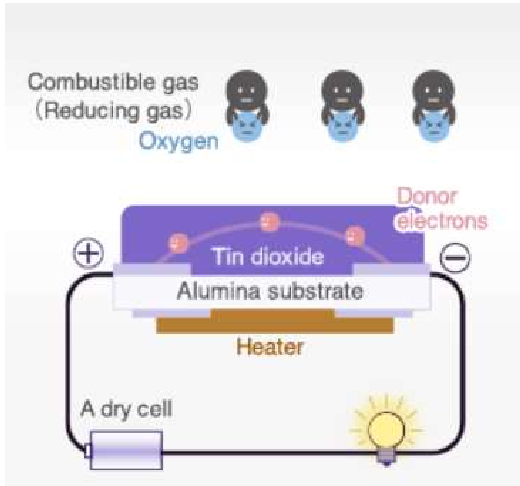


Figure 3.12. Metal oxide semiconductor sensor operating principle [16]

Gas sensors were chosen based on characteristics such as gas detection range, preheat time, gasses that could affect the sensor, and power consumption. Methane sensors considered are shown in Table 3.5. As seen from Table 3.5 the best choice to methane sensor is the TGS-2611, which was chosen for the project. Table 3.6 shows carbon monoxide sensors and from the table it can be seen that the TGS-5042 is the best sensor and so the TGS-5042 was used. Table 3.6 shows temperature and humidity sensor.

Due to high concentration of combustible gasses accumulate inside underground vaults, gas sensors with high detection range were chosen. Preheat time is defined as the time for sensors to be in full operation, therefore, faster or nonexistent heating time were considered. Also, sensors must be able to accurately read the gas concentration while other gasses are present in the environment to prevent interference. Lower power consumption for the sensors were desired for their capability to last longer.

Table 3.5. Methane sensor trade study

Methane	MQ-2	MQ-4	TGS-2611
			
Detection Range	5,000-20,000 PPM	300-10,000 PPM	500-10,000 PPM
Preheat time	Over 24 hours	Over 48 hours	7 days
Operating range	20-50 °C	20-50 °C	-40-70 °C
Gases Affecting Sensibility	H2, Alcohol, smoke, LPG, Propane, butane	Propane, Alcohol	Hydrogen
Power Consumption	900 mW	775 mW	295 mW

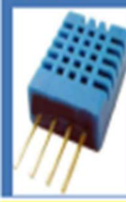
Table 3.6 contains the evaluated CO sensors.

Table 3.6. CO sensor trade study

Carbon Monoxide	MQ-7 	3SP_CO_1000 	TGS- 5042 
Detection Range	20-2,000 PPM	0-1,000 PPM	0- 10,000 PPM
Preheat time	Over 48 hours	None	None
Operating Range	-20-50 °C	-33-55 °C	-40-70 °C
Gases Affecting Sensibility	Methane, H2, LPG	H2, Isopropyl Alcohol	Hydrogen
Power Consumption	775 mW	10-50 micro Watts	265 mW

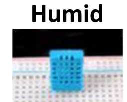
The temperature and humidity sensor were chosen based on range and accuracy. HDC2010 and DHT 11 were the only sensors that were desirable with only a small margin of difference. The DHT 11 was chosen based on its price and availability, however after building of first prototype the DHT-11 prove to be a very slow response sensor. A different temperature sensor (TMP36) was chosen for the project as it had a temperature range of –40 to 125 degrees Celsius. The DHT-11 was keep to be used as a humidity sensor. Table 3.7 shows the trades.

Table 3.7. Humidity sensor trade study

Temperature/Humidity	HDC2010 	DHT11 	DS18B20 
Humidity Range (RH)	0-100%	20-90%	None
Temperature Range	-40-85°C	0-50°C	-55-125°C
Temperature Accuracy	Within 0.2°C	Within 2°C	Within 0.5 °C
Humidity Accuracy	Within 2%	Within 5%	None

The sensors chosen for the prototype are shown in Table 3.8. These sensors will be connected to our microcontroller and will be used to set the warning system.

Table 3.8. Final device sensor overview

Sensor	**CO** 	**C** 	**O2** 	**CO2** 	**CH4** 	**(C4H6, C5H8)**	**Temp** 	**Humid** 
Model	Figaro TGS 5042	10102001 2	KE-25F3	Figaro TGS4161	Figaro TGS 2611		DS18B20+	DHT11
Price	$25.27	$11.73	$70.49	$27.20	$30.36		$4.54	$5.00

4.0 Risk Analysis

The largest risk comes from the sensor surface poisoning and the ability to adjust data for this. Vaults are inspected roughly once every five years, and MOS sensors have been adjusted to last for up to 7 years. A typical system of gas classification consists of a sensor array and a pattern recognition system as shown in Figure 4.1.

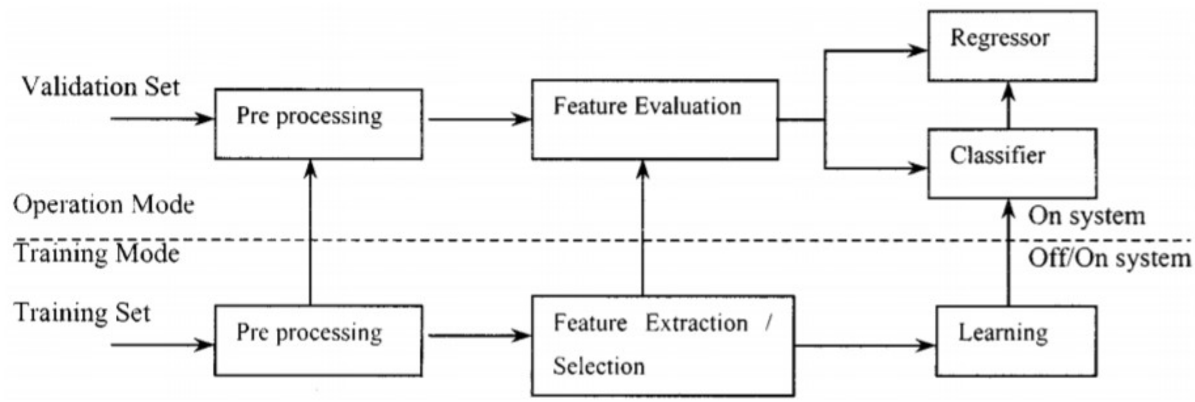


Figure 4.1. Typical gas classification system [17]

A simple alternative for testing was to implement rules that classified the gases as dangerous or explosive as shown in Figure 4.2.

If: $CO_2 > 210$ ppm **or** $T > 105$ F: **Flaming fire**.
Elseif: $V_{TGS822} > 0.9$ V **and** $V_{TGS880} > 0.15$ V: **Nuisance**.
Elseif: $CO > 17$ ppm **and** $CO_2 > 22$ ppm **and** $V_{TGS822} > 0.27$ V: **Smoldering fire**.
Else: **Background**.

Figure 4.2. Code to prevent alarm activation in event of nuisance scenario [18]

Risks were evaluated before developing the final prototype. The design included a rail along the vault wall so that the device could keep the same relative position as water accumulated in the vault and displaced the time-changing gas striations upward. Our risks are shown in Table 4.1.

Table 4.1 Risk analysis

Risk no.	Risk item	Mitigation approach	Consequence	Probability
1	Compensation for sensor degradation over 5 years	Reaction chamber data generation, analysis	4	5
2	Housing actuation failure (poisons sensors) and rail system failure (submerged in water)	Install prototype versions in Edison test chamber	3	3
3	Failure of circuit components causing out of reference signal	System testbed verification/validation	4	2
4	Improper power and heat delivered to sensors	System testbed verification/validation	3	2
5	Explosion- and water-proofing	Submersion test	3	3

The consequences of these risks were evaluated, with sensor data degradation over time as the highest risk, as shown in Figures 4.3 and 4.4.

Legend		
High		**Major disruption likely**
Med-High		**Some disruption likely**
Medium		**Some disruption possible**
Med-Low		**Minor disruption possible**
Low		**Minimal disruption**

Figure 4.3 Risk analysis legend

			Consequence of Risk				
			Low 1	Minor 2	Moderate 3	Substantial 4	Severe 5
Probability of Occurrence	Very Likely 5	>70%				(1)	
	Likely 4	30-70%					
	Possible 3	10-30%			(2), (5)		
	Unlikely 2	1-10%			(4)	(3)	
	Very Unlikely 1	<1%					

Figure 4.4 Risk analysis initial

With appropriate statistical compensation measures and proper protection measures for circuit components in place, risks were re-evaluated in Figure 4.5.

			Consequence of Risk				
			Low 1	**Minor 2**	**Moderate 3**	**Substantial 4**	**Severe 5**
Probability of Occurrence	**Very Likely 5**	**>70%**					
	Likely 4	**30-70%**			**(1)**		
	Possible 3	**10-30%**		**(2), (5)**			
	Unlikely 2	**1-10%**	**(4)**		**(3)**		
	Very Unlikely 1	**<1%**					

Figure 4.5. Risk analysis with adjustment

5.0 Final Design

The final design is to create a monitoring system of the underground electrical vault, a device consisting of a microcontroller, sensors, buzzer, multi-color light emitting diode (LED), liquid crystal display (LCD), and fan was constructed. The microcontroller takes care of the signal processing from the sensors. The microcontroller also does calculations, and stores important information, as well as activate external hardware, such as the LED, LCD, buzzer and fan. A housing for all the components was designed, with the conditions of the underground electrical vault in mind.

5.1 Work element 1: First Prototype

In the first semester of class, the first prototype was built. This prototype, as seen in Figure 5.1, consisted of an Arduino microcontroller, a temperature and humidity sensor (DHT 11), methane sensor (MQ-4), and a carbon monoxide sensor (MQ-7). After doing research the most dangerous gasses due to the decomposition of cross-link polyethene in an electrical vault were found to be carbon monoxide and methane, which why the first prototype consisted of the most crucial sensing elements.

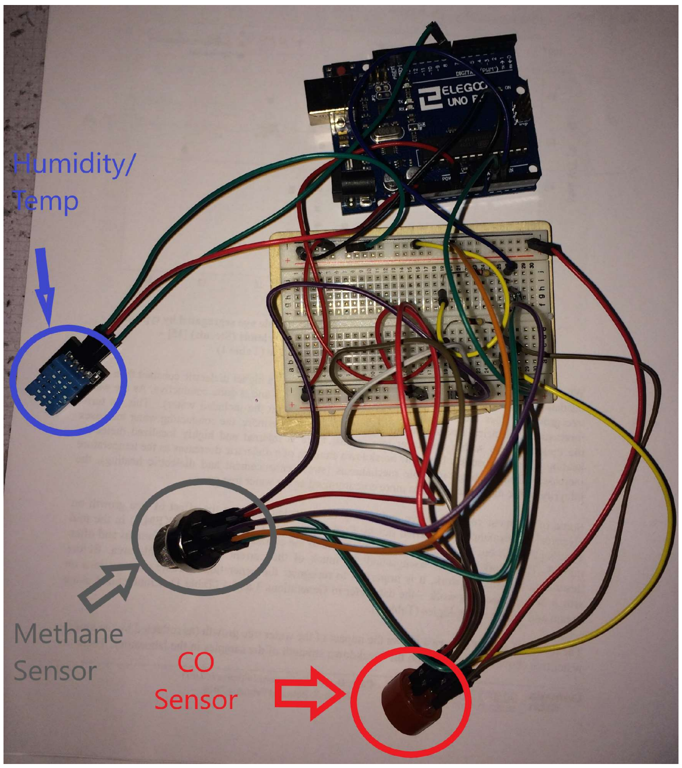


Figure 5.1. Prototype with sensors attached

As seen in Figure 5.1 there is no warning system in the first prototype. This prototype was built as a proof of concept design, as well as a guide/ practice for a second prototype that would have upgraded equipment.

All the sensors used in the first and final prototype consist of sensors that have datasheets with either a graph or an equation relating the measured quantity (such as temperature, humidity, gas concentration in parts per million, etc.) with the voltage output the microcontroller is reading. For sensors which used graphs to relate the measured quantity with voltage, Excel was used to generate an equation. The equation would be put into the program to give measured quantities. For example the methane sensor (MQ-4) came with the graph shown in Figure 5.1. Sample points where taken from the graph in Figure 5.2 and plotted on excel to generate to generate an equation. Figure 5.3 shows the points plotted and the graph generated as well as the equation generated on the right top corner. This process was also used in the final prototype build.

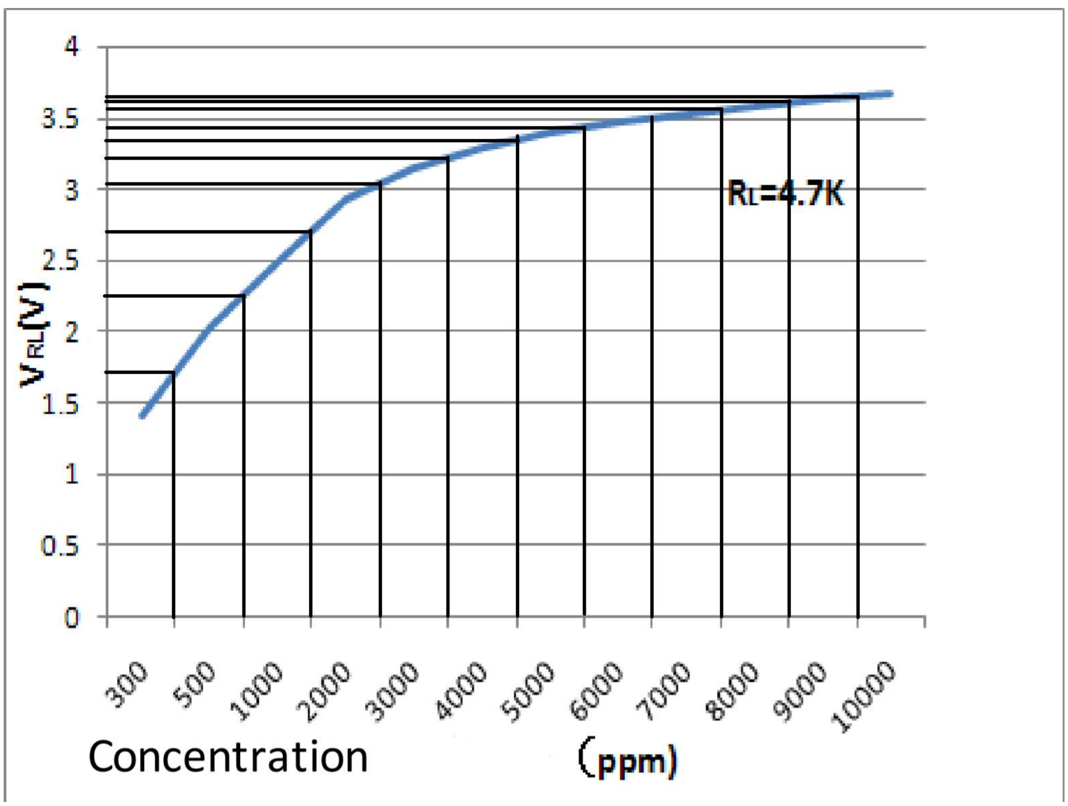


Figure 5.2 Prototype test of gas concentration

The First prototype, which was built as proof of concept, was able to detect changes in carbon monoxide, methane, temperature and humidity. One of the limitations of the first prototype was that the sensors did not meet the required temperature operating range. This is huge problem and underground vaults sometimes experience harsh weather conditions. Other limitation include no warning system as well as low concentration reading for carbon monoxide and slow response time of temperature and humidity sensor.

PPM	Volts
300	1.65
500	2.3
1000	2.65
2000	3.07
3000	3.25
4000	3.35
5000	3.45
6000	3.5
7000	3.58
8000	3.6
9000	3.65

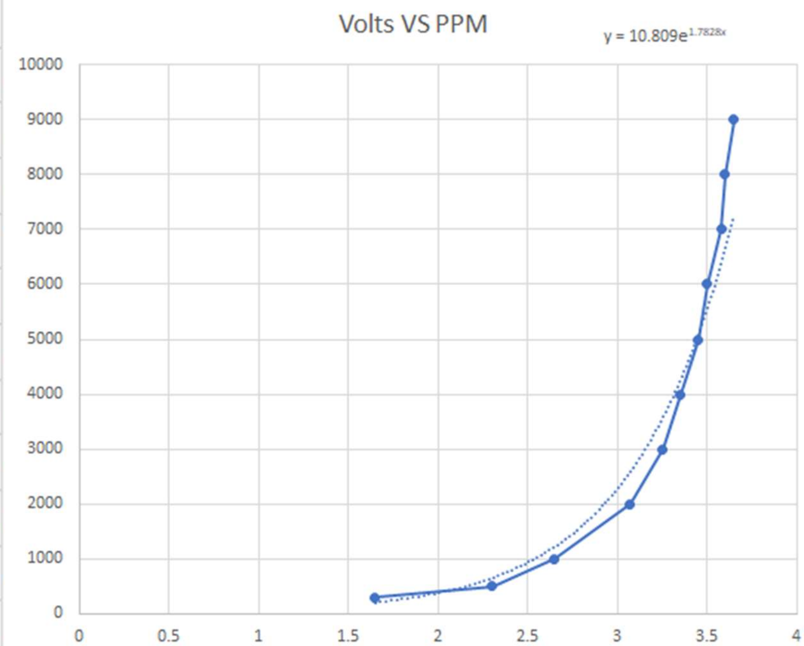


Figure 5.3 Parts per million measurement

5.2 Work element 2: The Current Device

For the final prototype the microcontroller used was the Programable System On Chip 5LP (PSOC 5LP). The reason being is that it had a lot more processing speed than the Arduino microcontroller, as well as many more general input/output pins (GPIOs). As work began on the final prototype it was unclear how many input/output pins would have been required so a microcontroller with sufficient pins and processing speed was chosen, hence the PSoC 5LP was chosen. For sensing carbon monoxide the TGS-5042 sensor was chosen as it had a very wide range of sensing capabilities compared to the MQ-7 sensor, as well as wider temperature operating range. The methane sensor used was the TGS-2611 because it had a wider operating range compared to the MQ-2 sensor. For temperature the TMP36 sensor was chosen as it also had a wider operating range than the DHT-11 sensor. Reading from the sensors where displayed on the LCD. For the warning system a buzzer and multicolor light emitting diode where used. The LED was used as a visual warning and the buzzer served as an audio warning. Each would come on depending on what the sensors were reading. A fan was also installed to help purge the sensors, and help airflow through the housing in order to keep the sensors reading as accurate as possible. Sensors that were installed on the microcontroller but where not programmed to the PSoC was the temperature sensor (DHT-11), and the carbon dioxide sensor, this was due to insufficient time. Figure 5.4 shows the final prototype.

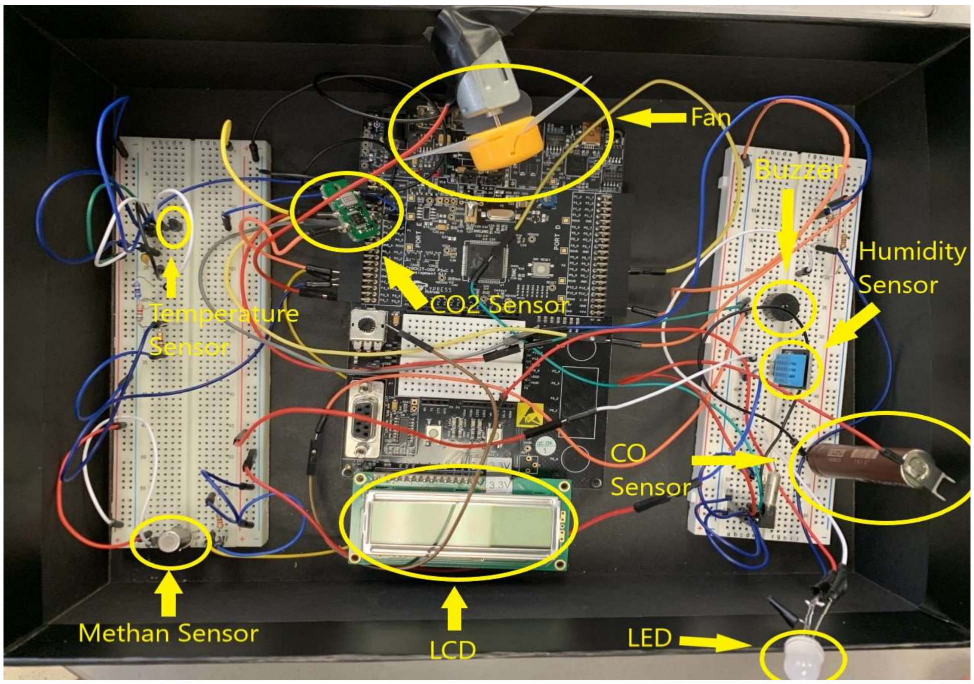


Figure 5.4 Final prototype

The electrical subsystem in Figure 5.5 uses the PsoC's power adapter to connect to the Partial Transformer available in many vaults.

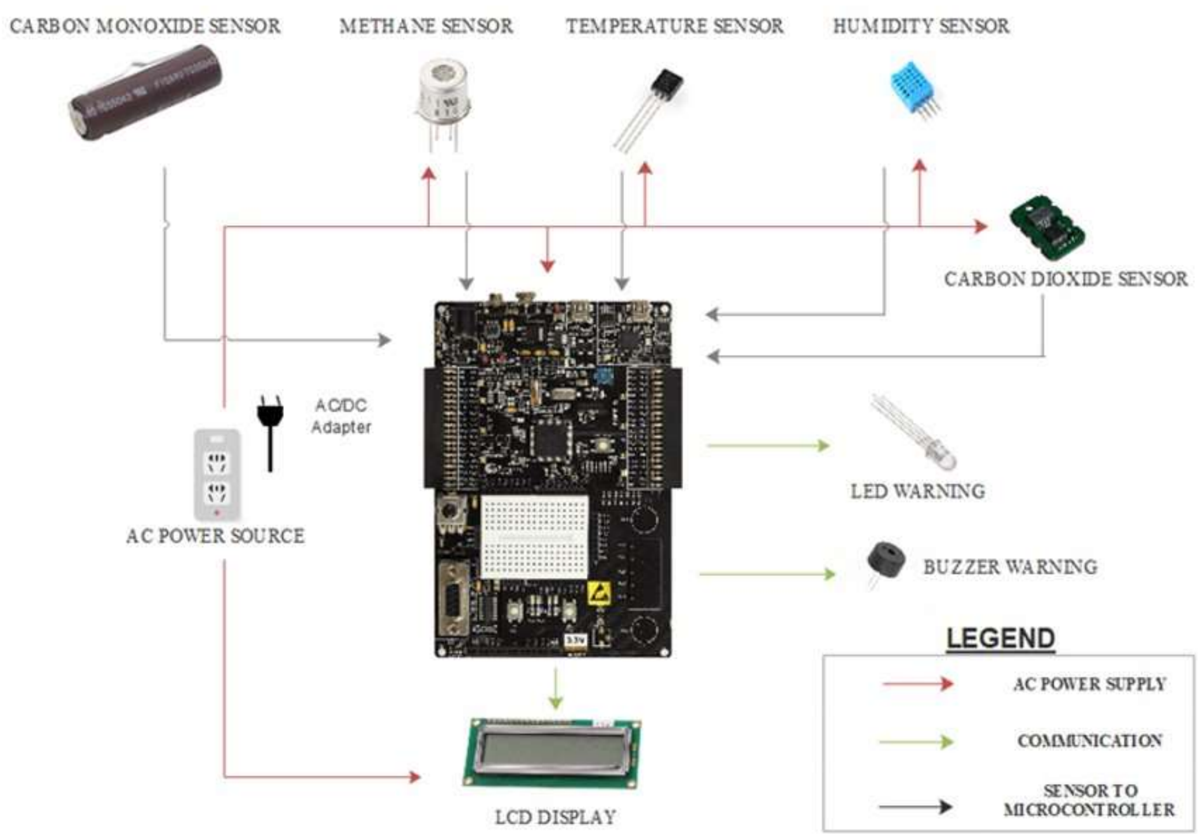


Figure 5.5. Electrical subsystem

Data was primarily provided to the microcontroller through the Analog Front End (AFE), but the carbon dioxide and VOC’s sensor used the I2C communication protocol as this could deliver both gas values.

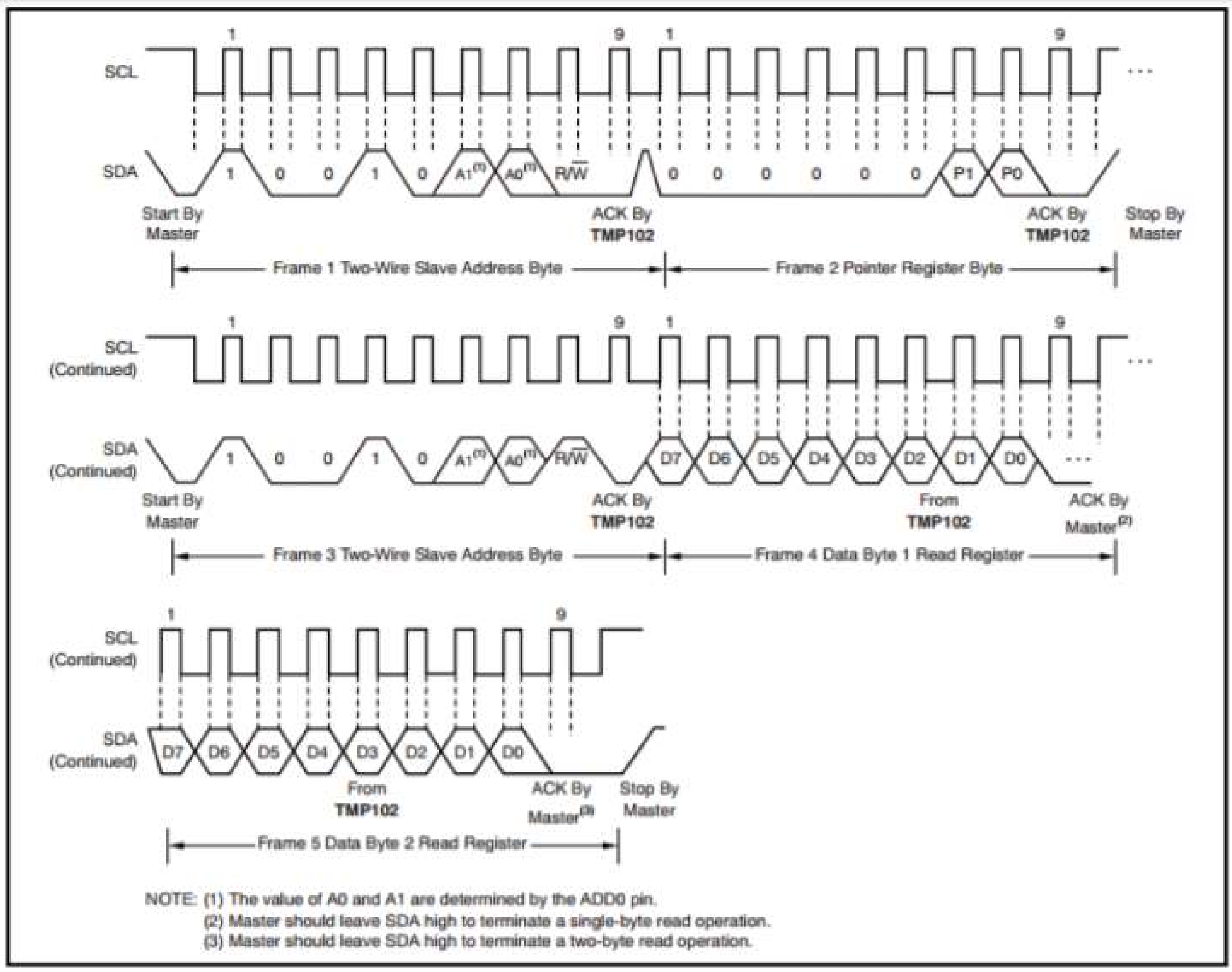


Figure 5.6 I2C Communication for VOC's sensor

The Inter-integrated Circuit (I2C) Protocol in Figure 5.6 allows bidirectional communication between devices. Our PSoC 5LP was configured as an I2C master with 100 Kbps data rate. The master device must know the I2C address of the slave in order to communicate.

5.3 Work element 3: Housing

The housing design was carried out by using solid works software. The actual dimensions of the prototype components, air ventilation mechanism and the power source type were taken into considerations. A stainless steel was selected as an excellent material for housing since it can withstand the harsh underground environment such as higher temperature and pressure level.

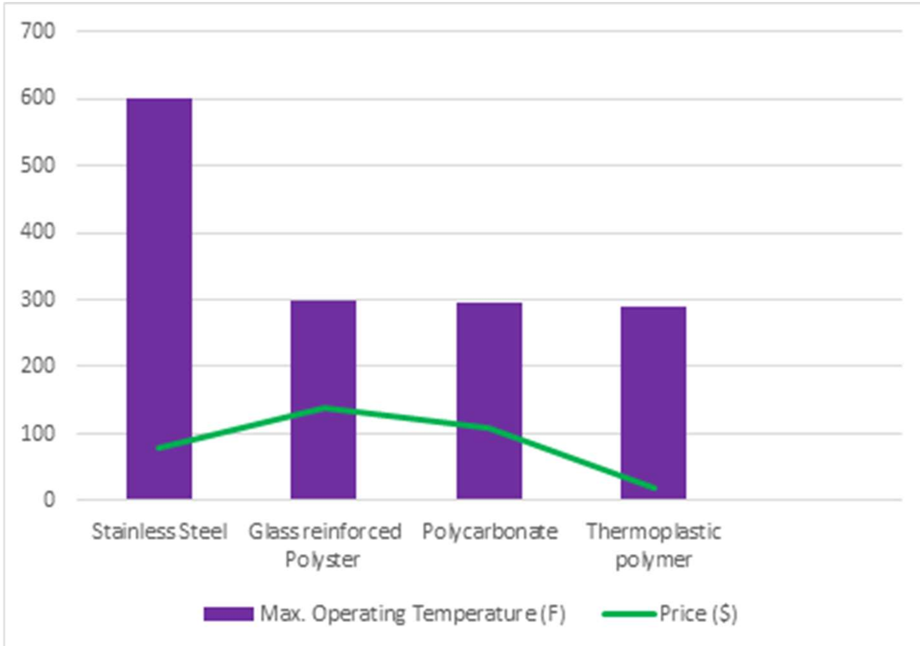


Figure 5.7. Maximum Operating Temperature and Price of Materials

Figure 5.7 shows the relative cost of housing based on material. Figure 5.8 is an overview with the CAD model enclosure and labels.

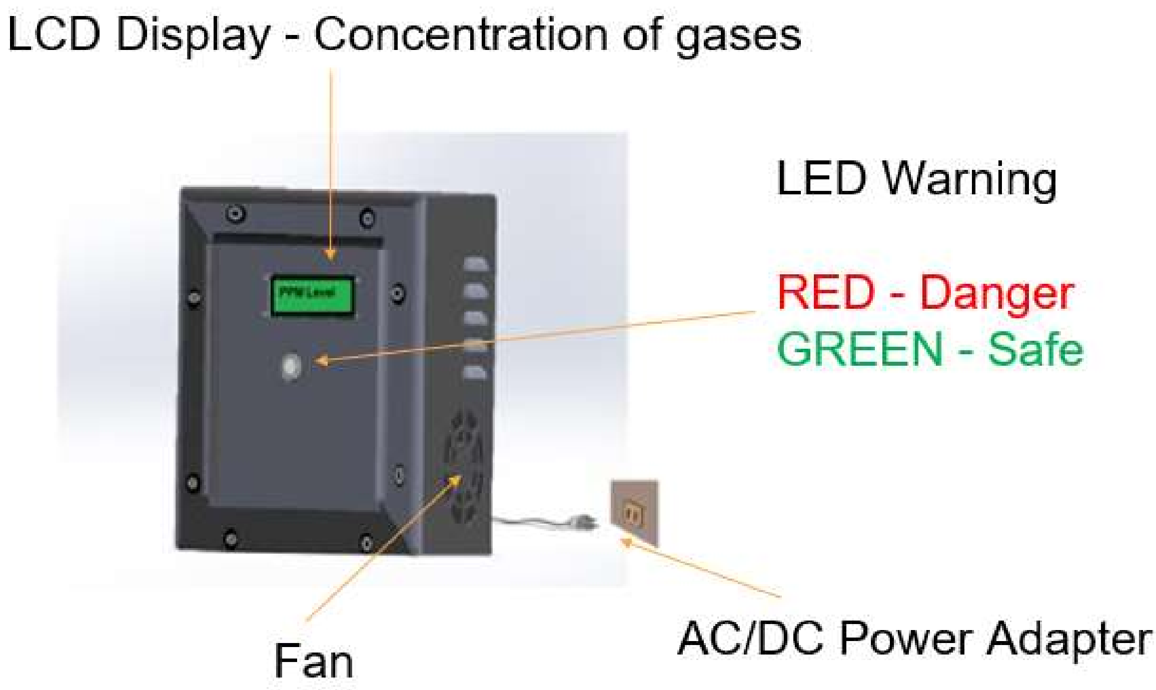


Figure 5.8. Mechanical overview

Figure 5.9 shows the mechanical schematic with dimensions.

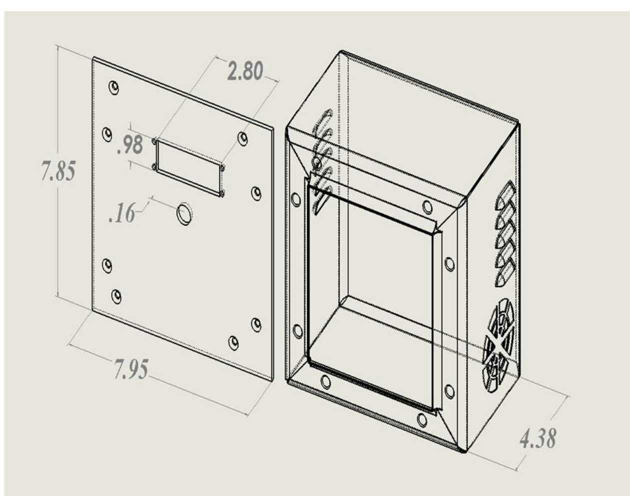


Figure 5.9. Mechanical schematic

5.4 Work element 4: Programming

In order to make all these components work together a program was written and developed. This program would processes the electrical signals of the sensor to give meaningful measurements, and based on those measurements decide what action to take. The action needed was to give a warning. Figure 5.10 shows a simplified flow chart for how the warning system works.

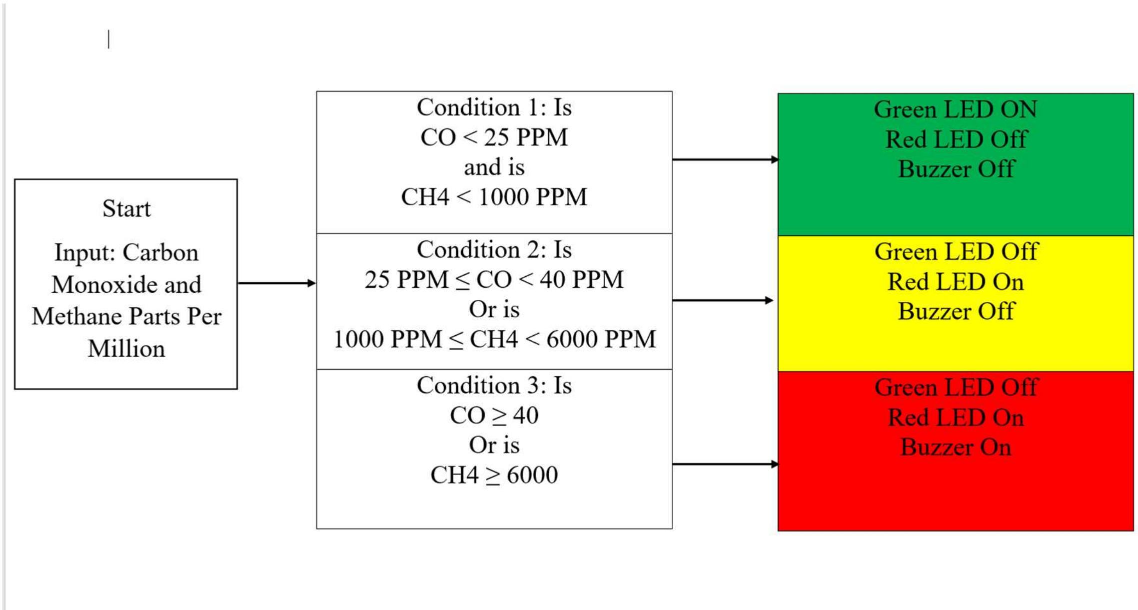


Figure 5.10. Warning System Flow chart

As seen in Figure 5.10 the warning system is split into three condition. The conditions are determined by the carbon monoxide and methane readings, as these are the most dangerous gasses to have in an underground electrical vault. If carbon monoxide is below 25 parts per million and at the same time methane is below 100 parts per million then the green light emitting diode will be on and the buzzer will be off. This means that everything is fine within the vault, there is no danger to anyone in or around the vault. At those concentrations neither carbon monoxide nor methane is harmful. If one gas goes above that threshold then the system will move into condition two. In condition two carbon monoxide is between 25 and 40 parts per million, and methane is between 1,000 and 6,000 parts per million At this point the gasses are still not harmful, but it would be abnormal to be reading those concentrations. Methane becomes explosive at 120,000 parts per million, but someone can be experiencing carbon monoxide poisoning at around 50 parts per million, while methane becomes explosive at 50,000 parts per million. Under condition two the light emitting diode will be red and the buzzer will be off. Personnel might want to investigate why the sensors are picking up abnormal readings. In the last condition carbon monoxide reading is above 40 parts per million and methane is above 6,000 parts per million. Someone in or around the vault can experience carbon monoxide poisoning above those concentrations. Due to the limitation of the methane sensor the threshold was set at 6,000 parts per million, however if a sensor that could sense up to 50,000 parts per million were being used the threshold would be set at about 35,000 parts per million. At that concentration methane is getting very close to its explosive limit, and hence no person should be in or around the vault. Under condition three the light emitting diode would be red and the buzzer, acting as an audio alarm would sound.

5.5 Work element 5: Warning components

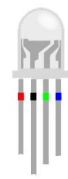


Figure 5.11

Warning components included an Tri-color RGB (Red Green and Blue) LED and buzzer. An RGB LED has one anode for each color and a single cathode for ground as shown in Figure 5.11. This order can be switched.

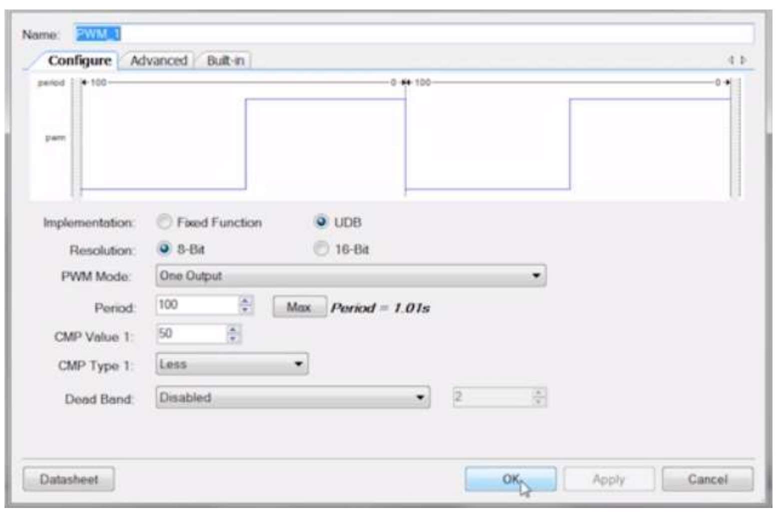


Figure 5.12 PWM in PsoC Creator [19]

Pulse Width Modulation (PWM) is used in a wide variety of applications, including LED intensity control. Brightness is set by the duty cycle of the microcontroller output signal in Figure 5.12. For instance, if PWM component output is at 5V for 90% of the time, then the load will receive 90% of the power. Figure 5.13 shows a configurable PWM module.

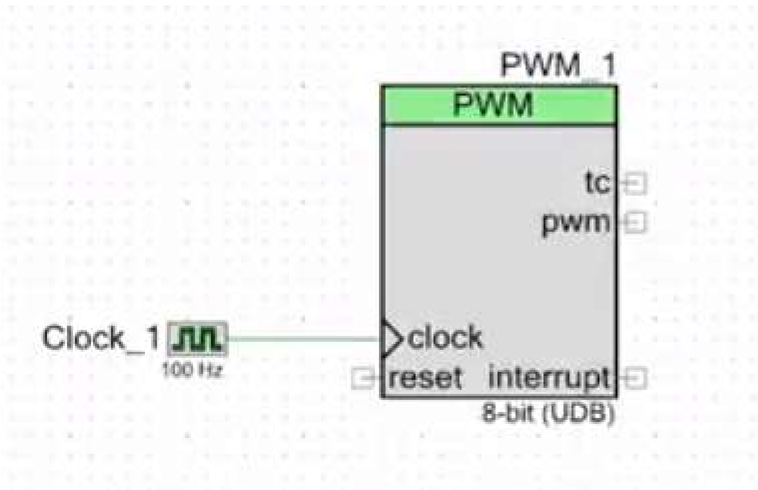


Figure 5.13. PWM Module [19]

For greater visibility, we implemented a breathing effect in our warning LED. This was done by routing two PWM's through a XOR gate as shown in Figure 5.14.

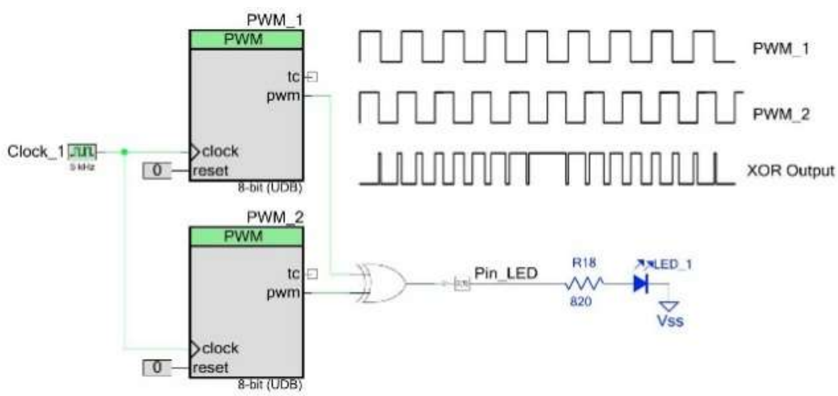


Figure 5.14 PWM and XOR gate [19]

5.6 Work element 6: Reaction chamber

Several reaction chamber types were considered over the course of the project. A chemistry lab was made available that could provide mass flow controllers as shown in Figure 5.15 to deliver precise amounts of gas to our sensors.

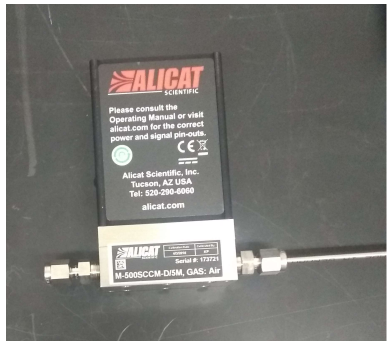


Figure 5.15 Mass flow controller

In Figure 5.16, the lab hood could be configured with a tube containing our sensor and the gas mixture.

Figure 5.16 Reaction chamber tube (right)

Gas tanks could provide a mixture of gases (Figure 5.17).

Figure 5.17 Gas tank area

Southern California Edison also made a gas chamber available out of a used fuse box in Figure 5.18.

Figure 5.18 Edison test chamber

Ultimately, a mason jar and tupperware container were used in lab tests as these could allow quicker testing and the use of other lab equipment.

5.7 Work element 6: Data analysis

The first step in the data analysis is to verify correct sensor operation, in which a gas testing environment is needed, including the chamber and test gas. The carbon monoxide and methane sensors were verified to operate accurately within the bounds of the testing apparatus, which included a methane stove and a burning paper test in which oxygen was burned up before placing the sensor in the chamber. The methane test in Figure 5.19 shows the sensor response to methane gas released by the stove.

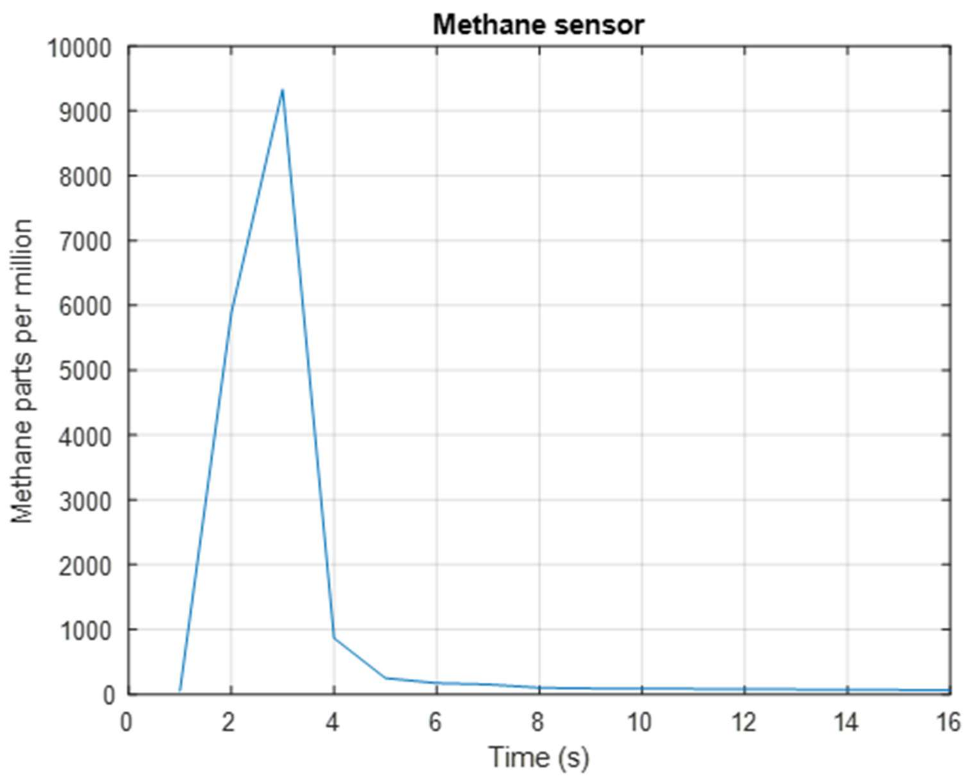


Figure 5.19. Methane sensor circuit demonstration

The carbon monoxide test in Figure 5.20 shows an appropriate increase in carbon monoxide over the test.

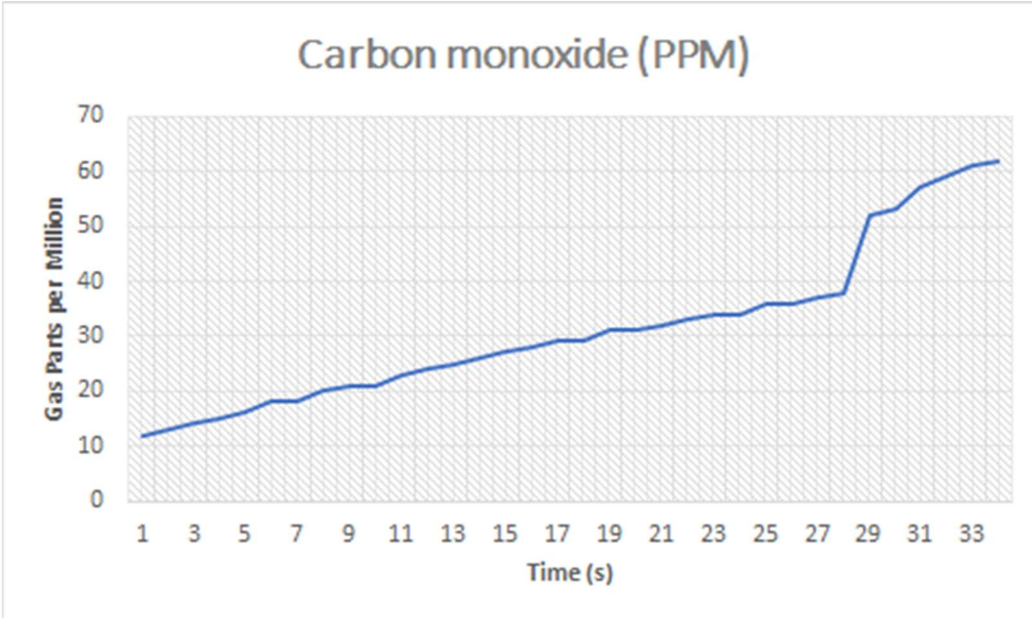


Figure 5.20. Carbon monoxide sensor circuit demonstration

6.0 Summary and Conclusions

With the rate of vault explosions increasing, and sensing and computing technologies advancing, there are excellent new ways to help prevent threats to human safety from explosive power distribution structures. Through the Preventing Underground Vault Electrical Explosions project, the team gained further understanding of the requirements of sensor circuit operation, power utility engineering and its concerns, sensor data analysis, and the combination of engineering and chemistry.

All components necessary for implementation of the device design have begun to be installed, and demonstrations of effective carbon monoxide and methane sensing were performed. The device could be installed in a vault to provide visual and auditory signals to Edison crews for these explosive and toxic gases. Utilities and the public can benefit from development of remote sensing capability.

7.0 References

[1] "Carbon Monoxide Safety Standards and Exposure Limits." Defender Detectors.10 May 2019. https://www.defenderdetectors.com/aboutco/standards.pdf

[2] Hampton, Nigel. Medium Voltage Cable System Issues. 10 May 2019. https://www.neetrac.gatech.edu/publications/CDFI/2-MV-Issues_25_with-Copyright.pdf

[3] Manhole Events: Why They Occur. KENT. 10 May 2019. https://www.youtube.com/watch?v=KM_bZbl_IxM

[4] Zhang, L., Boggs, S., & Murray, G. (2011). Effect of limiting airflow in mitigating combustion-driven manhole events. IEEE Electrical Insulation Magazine, 27(6), 37–44. doi:10.1109/mei.2011.6059983

[5] Chiu SW, Tang KT. Towards a chemiresistive sensor-integrated electronic nose: a review. Sensors (Basel). 2013;13(10):14214–14247. Published 2013 Oct 22. doi:10.3390/s131014214

[6] “Effect of limiting airflow in mitigating combustion-driven manhole events” https://ieeexplore.ieee.org/document/6059983

[7] Industrial Scientific. No Calibration Required? Jan 27, 2017 http://www.indsci.com/the-monitor-blog/no-calibration-required/

[8] Wang WS, Huang HY, Chen SC, et al. Real-time telemetry system for amperometric and potentiometric electrochemical sensors. Sensors (Basel). 2011;11(9):8593–8610. doi:10.3390/s110908593

[9] AFE Implementation using PSOC 4. [https://www.cypress.com/file/445196/download]

[10] Chiu SW, Tang KT. Towards a chemiresistive sensor-integrated electronic nose: a review. Sensors (Basel). 2013;13(10):14214–14247. Published 2013 Oct 22. doi:10.3390/s131014214

[11] MEMS Gas Sensors Utilizing the World's First Battery-Powered Gas Alarm. Fuji Electric. https://www.fujielectric.com/company/research_development/theme/mems_sensor.html

[12] "Electronic gas sensors and detectors – clasification and operating principles." Electronics-Base. 10 May 2019. http://www.electronics-base.com/general-description/gas-sensors/171-electronic-gas-sensors-and-detectors-clasification-and-operating-principles

[13] Spinelle L et al. Review of Portable and Low-Cost Sensors for the Ambient Air Monitoring of Benzene and Other Volatile Organic Compounds. https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5539520/pdf/sensors-17-01520.pdf

[14] Data Sheet. "The MiCS-VZ-89TE is an integrated sensor board for Indoor

Air Quality monitoring." https://www.sgxsensortech.com/content/uploads/2016/07/MiCS-VZ-89TE-V1.0.pdf

[15] Dept of ECE. Multi-Functional Microcontroller Based Monitoring, Alarming and Protection System. https://aurak.ac.ae/publications/Multi-Functional-Microcontroller-Based-Monitoring,-Alarming-and-Protection-System.pdf

[16] Operating principle. Figaro. 5 May 2019. https://www.figaro.co.jp/en/technicalinfo/principle/mos-type.html

[17] Perera, A., Sundic, T., Pardo, A., Gutierrez-Osuna, R., & Marco, S. (2002). A portable electronic nose based on embedded PC technology and GNU/Linux: hardware, software and applications. IEEE Sensors Journal, 2(3), 235–246. doi:10.1109/jsen.2002.800683

[18] Fonollosa, Jordi. Chemical Sensor Systems and Associated Algorithms for Fire Detection: A Review. Sensors. 3 December 2017; Accepted: 8 February 2018; Published: 11 February 2018

[19] "CE203303 - PSoC® 3 and PSoC 5LP Breathing LED." Cypress. 10 May 2019. https://www.cypress.com/documentation/code-examples/ce203303-psoc-3-and-psoc-5lp-breathing-led

[20] Committee, Insulated Conductors. "Preventing and Mitigating Manhole." *Study Lib*, IEEE, 7 July 2015, studylib.net/doc/18729080/preventing-and-mitigating-manhole-events.

[21] "Figaro Products." 10 May 2015. https://www.figaro.co.jp/en/product/sensor/

Appendix

Author Contributions

Abstract - Stephen

1.1 Problem/Background

1.2 Project Objective/Scope

1.3 Society Impact/Factors

2.0 Approach

2.1 Design Process - Stephen

2.2 Organization/WBS - Stephen

2.3 Schedule - Stephen

2.4 Deliverables - Stephen and Gossaye

3.0 System Overview - Stephen

3.1 Requirements - Earl

3.2 Architecture Overview - Stephen

3.3 Design Budgets - Stephen and Earl

4.0 Risk Analysis - Stephen

5.0 Final Design

5.1 Work element 1: First Prototype - Johnny

5.2 Work element 2: The Current Device - Stephen

5.3 Work Element 3: Housing - Gossaye

5.4 Work Element 4: Programming - Johnny

5.5 Work Element 5: Warning Components - Stephen

5.6 Work Element 6: Reaction Chamber - Stephen

5.2 Work Element 7: Data Analysis - Stephen

6.0 Summary and Conclusions - Stephen

7.0 References - Stephen