Understanding Usability Requirements of Electronic Devices for the Fire Service

An Interactive Qualifying Project
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Bachelor of Science

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3 ABSTRACT

To facilitate the implementation of improved gas sensing technology for use in firefighting overhaul operations—the process of searching for and extinguishing residual fires after a structural fire—this paper explores several key areas. These include the environmental, technological, and user requirements of the gas sensing device. The primary objective of this research was to determine the end-user requirements in a gas sensing device and produce an interface prototype to balance the user requirements with the technological and environmental requirements. The user and environmental requirements were determined through surveying members of the fire service about their experiences using gas sensors during overhaul operations, as well as their requirements for a sensor device (weight, size, etc.). The technological requirements were determined through written questions sent to members of a research team working on the sensor technology. This information was then used to develop a prototype interface incorporating user requirements, while balancing environmental and technological requirements to facilitate the adoption of this innovative technology.

The survey was distributed to a variety of members of the firefighting community, including both career and volunteer fire fighting divisions throughout the United States. Participants were asked to comment on their previous experiences using toxic gas sensors during overhaul operations. They were also asked about their notification, interface, and design preferences and requirements in a toxic gas sensor. The results of the survey were then analyzed to determine key features and their respective importance levels to the final users of the device. These features, as well as the technical requirements determined though the questionnaire, were then incorporated into the final design of the interface design, which was constructed.

The final design was then constructed. The case was constructed using SolidWorks, and 3D printed using polylactic acid (PLA) filament. A screen was installed in the case and programmed to show a simulated view. The settings pages and the additional information pages were programmed. Buttons were 3D printed and installed into the case. The final design was integrated together to provide the user with a realistic prototype. The final prototype while not containing the gas sensing technology, mimics the user-desired response to various conditions. The feedback from the survey was used to determine the technological design, as well as the user requirements of the device.

4 INTRODUCTION

4.1 PROBLEM STATEMENT

Firefighting is fraught with both immediate and long-term risks to health and safety. Despite the downward trend in on-duty fatalities, fire effluent toxicity has become the predominant cause of death and injury among firefighters [1]. Modern fires have featured an increasing concentration of synthetic materials. Despite their fire resistance, once alight, synthetic materials tend to produce more toxic gases than natural materials [1]. Short term toxic gas exposure can cause acute health concerns and even death. Heart attack deaths account for an average of 50 firefighter fatalities per year [2]. Exposure to toxic gases produced in fires, like cyanide can cause heart arrythmias, leading to heart attacks and death [2]. Consistent low-level exposure to toxic gases has been shown to cause long term health impacts, increasing the likelihood for certain cancers [1]. The persistent exposure to toxic byproducts due to their occupation contributes to a 14% higher risk of dying from cancer than the general population [3].

The overhaul phase of firefighting presents an increased risk to firefighter safety. As they seek out and extinguish residual fires, often hidden within walls and ceilings, their exposure to a variety of toxic gases consistently exceeds occupational limits. Many of these gases are known carcinogens [4]. This process involves visual inspection and thermal imaging cameras to find and expose fires. Hand tools and power tools are used to reach hidden fires to allow for extinguishing. Materials that are still burning must be soaked in water or removed from the building. The resulting environment is humid and can have a large variation in temperature. Surfaces are often wet and may be icy [5]. During this time, the environment can contain little to no visible smoke, leading to the illusion of safe conditions. The air clarity combined with the high humidity, manual exertion, and frequent high temperatures lead firefighters to remove their respiratory protection despite the imminent risk of toxic gas exposure and guidelines from firefighting agencies.

Currently various devices are available to detect toxic gases during overhaul, however, most require time consuming calibration, and can detect, at most 6 gas species (See Appendix 1). A calibration free sensor based on absorption spectroscopy is currently in development to detect 6 distinct gas species in real time, allowing firefighters to actively monitor their risk during the overhaul phase.

A challenge to this technology's implementation is ensuring the sensor is a valuable addition to the firefighter's toolkit. This requires an intuitive interface to allow for straightforward operation with minimal training requirements. Additionally, the sensor must provide significant benefits to the firefighter to justify the additional weight of another device.

4.2 PROJECT GOAL

This project aims to facilitate the implementation and adoption of this emerging gas detection technology within the firefighting community. The usability and required functions of the device will be studied through direct user feedback. The main objective is to develop an intuitive interface for use by all fire personnel, regardless of background. Current sensor interfaces and functions will be analyzed to identify familiar design elements to ensure seamless device adoption with minimal training requirements.

The interface of the device will be chosen to optimize usability while accommodating the environment of operation and the needs of the technology. The device environment and technology requirements will be analyzed to ensure functionality of the device in the target atmosphere. An interface prototype will be developed to demonstrate the proposed functionality of the device.

4.3 Objectives

Determine End-User Requirements:

To optimize end-user experience and increase the likelihood of technology adoption, feedback from firefighters will be sought during the research and prototype phase. Various concept sketches will be presented to firefighters of different backgrounds to determine interface preferences [6]. Feedback on device requirements to prioritize usability will be used in the final design.

Determine Technology and Environmental Requirements:

To ensure functionality of the device, the requirements of the sensor technology will be researched. The environment of use will be researched to determine the requirements of the device to function in its intended environment.

Produce Final Interface Prototype:

A final interface prototype will be produced integrating the feedback from firefighters and the technology and environment requirements.

Cost Benefit Analysis:

A cost benefit analysis will be performed on the final interface prototype. The analysis will weigh the practical benefits of the device against its physical burden. The goal is to ensure that the device provides sufficient value to justify its inclusion in a firefighter's gear, to allow for widespread adoption of the technology.

4.4 Project Plan

This research was completed over 22 weeks from October 2023 to May 2024 (See Appendix 2). During the first eight weeks, the problem statement, objectives, and methods were be developed. During this time, the usability and the technological surveys were developed. The usability survey was submitted to the WPI IRB for approval. The technological survey was sent to UCLA members of the project. During weeks seven through thirteen, the usability survey was conducted and the results analyzed. Preliminary construction and hardware experimentation then began. During weeks thirteen through twenty-two, the final prototype was constructed and the final report completed. A preliminary report draft was developed by week eight. Then in week fifteen, a preliminary prototype and a report draft were completed. Week twenty-two marked the completion of the final report, as well as the final prototype (See Figure 1).

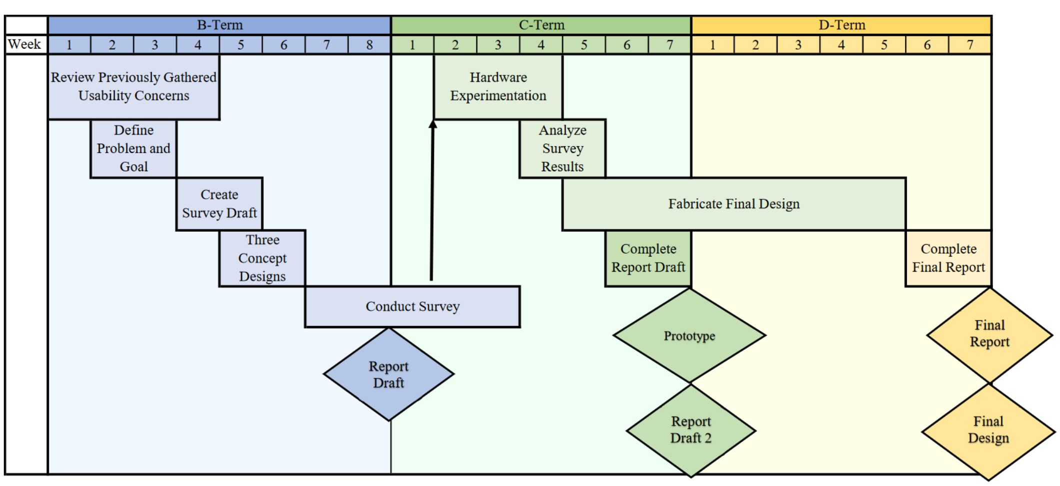


Figure 1:Project Timeline Gantt Chart

5 BACKGROUND

5.1 CURRENT DEVICES AND THEIR FUNCTIONS

On the market, there currently exists a wide variety of devices for gas monitoring. Gas monitors with specializations in the toxic species present in fires were studied (See Tables 1-5). This section provides an overview of their design and operational features.

Display and User Interface:

A common feature across these devices is an LCD display that indicates gas concentrations. Out of the nine devices analyzed, eight employ monochromatic backlit screens to enhance visibility under various lighting conditions. One device utilizes a color LCD screen, which may offer better differentiation of alerts and gas concentrations (See Table 1).

Table 1:Existing gas sensor displays technologies

Device	Screen Display Type
Honeywell BW Solo (Single Gas Detector | BWTM Solo | Honeywell, n.d.)	-
RKI GX-3R Personal Gas Monitor [8]	LCD
RKI GX-6000 Muli-Gas [9]	LCD
RAE Systems AreaRAE Pro Gas Monitor [10]	LCD
Mulit RAE [11]	LCD
QRAE3 [12]	Monochrome graphic display
X-am 5100 [13]	Curved Display
RAE Systems ToxiRAE Pro PID [14]	LCD
5X from MSA [15]	Color display

Control Elements:

All devices provide user control buttons. The devices all used at least one, and up to five buttons, proportional to the complexity of the device. The button sizes also vary, from fingertip sized, to larger sizes to accommodate operation while wearing gloves. Several units boast remote monitoring and control capabilities, for increased usability of the device in chaotic environments (See Table 2).

Table 2: Existing gas sensor control element's location, function, and size

Device	Button			
	Number	Location	Function	Size (Largest Dimension) (cm)
Honeywell BW Solo (Single Gas Detector | BWTM Solo | Honeywell, n.d.)	1	Side	All Control	1.35
RKI GX-3R Personal Gas Monitor [8]	2	Front	Power / Mode, Air	1.07
RKI GX-6000 Muli-Gas [9]	5	Front	Lock, Air, Reset, Shift, Power/Enter	2.11
RAE Systems AreaRAE Pro Gas Monitor [10]	3	Front	-	2.38
Mulit RAE [11]	3	Front	Mode, Y/+, and N/-	1.85
QRAE3 [12]	2	Front	-	2.67
X-am 5100 [13]	2	Front	+, OK	0.83
RAE Systems ToxiRAE Pro PID [14]	2	Front	-	1.66
5X from MSA [15]	3	Front	Up, Down, Power	1.99

Alert Mechanisms:

All devices alerted the user of hazardous conditions through three channels, audio, visual, and haptic feedback. Visual feedback included screen display changes, flashing, and LED flashing. Multiple devices prioritized a wide field of view of visual feedback to increase the chances of the user taking notice of the alarm. The devices emitted audio feedback standardized at 95 dB at 30cm from the device. Haptic alerts were comprised of patterns of vibration. Continuous vibration was used in more extreme situations, with discrete vibrations often used to signal system failure or low battery (See Table 3).

Table 3: Existing gas sensor alert causes and alert types (visual, audible, and haptic)

Device	Alert Causes	Alert Styles		
		Visual	Audible	Haptic
Honeywell BW Solo (Single Gas Detector | BWTM Solo | Honeywell, n.d.)	-	Lights up red	95 dB	vibrating
RKI GX-3R Personal Gas Monitor [8]	3 Increasing alarms, STEL, TWA, overscale alarm, and device malfunction	Flashing LED	continuous buzzer (100 dB @ 30 cm)	vibrating
RKI GX-6000 Muli-Gas [9]	Gas, Man down, and device malfunction	5 LED	95 dB at 1 ft.	vibrating
RAE Systems AreaRAE Pro Gas Monitor [10]	-	Yes	108 dB	vibrating
Mulit RAE [11]	Gas, Man down	Yes	Yes	vibrating
QRAE3 [12]	Man down, pump status, low battery	Flashing red LED's	95 dB at 30cm	vibrating
X-am 5100 [13]	-	Yes, 180 degrees	90 dB at 30 cm	vibrating
RAE Systems ToxiRAE Pro PID [14]	Man down	Flashing red LED's	95 dB @ 30 cm	vibrating
5X from MSA [15]	Man down	2 ultrabright LEDs on top	95 dB	vibrating

Physical Design:

Devices range from palm-sized single gas sensors to large, suitcase-sized multi-gas detectors (See Figure 2 and Figure 3). Figure 2 shows the graph of the number of gases monitored to the volume of the device. Figure 3 displays the same graph, containing a trendline (neglecting outliers) that clearly shows a positive relationship between size and gases measured. Devices that can measure more gases generally have a larger volume. The most prevalent units are handheld units. These units are often equipped with belt clips for portability. Larger units typically incorporate handles or shoulder straps (See Table 4).

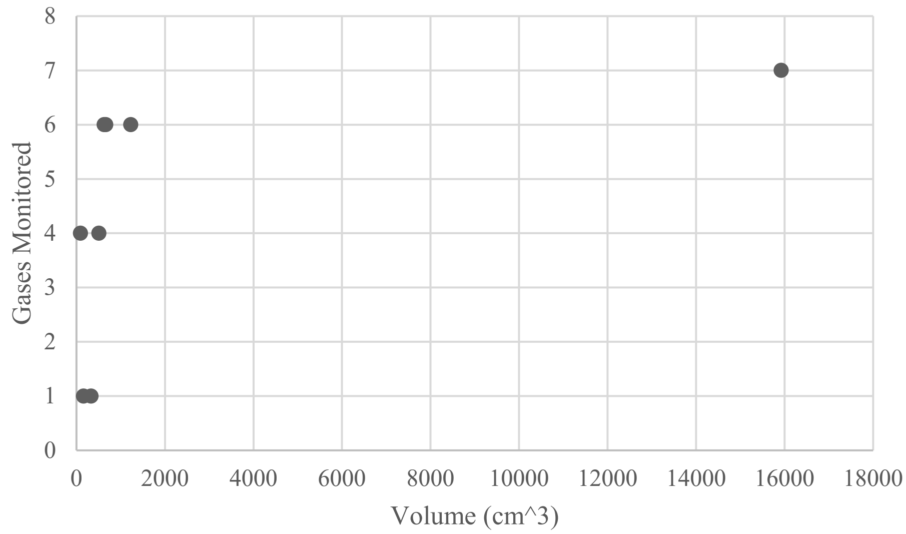


Figure 2: Gases Monitored vs. Size of sensor (Volume) of existing gas sensors

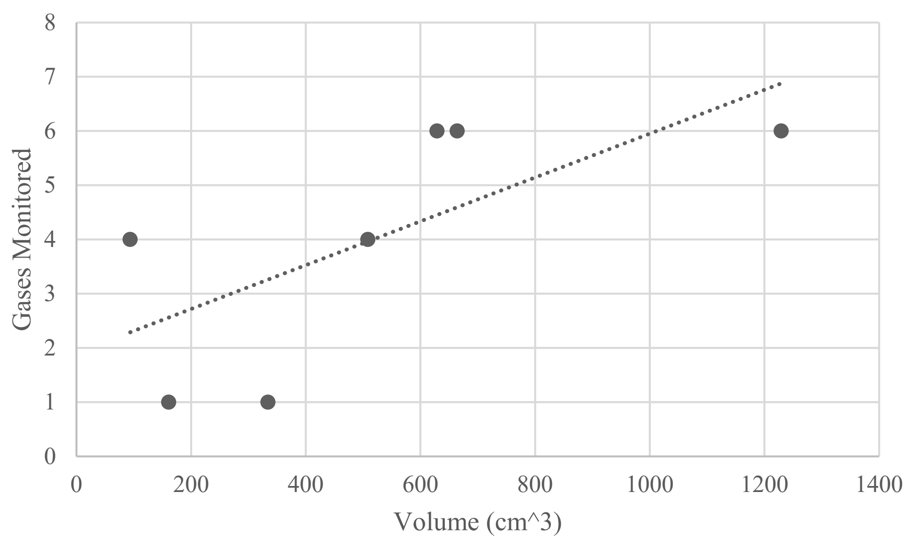


Figure 3:Gases Monitored vs. Size of sensor (Volume) of existing gas sensors with trendline (neglecting outliers, RAE Systems AreaRAE Pro Gas Monitor)

Table 4: Existing gas sensor physical design characteristics, including weight, size, attachment mechanism, humidity operation range, and temperature operation range.

Device	Weight (kg)	Device Volume (cm^3)	Attachment Style	Humidity Operating Range (RH)	Temperature Operation Range (°C)
Honeywell BW Solo (Single Gas Detector | BWTM Solo | Honeywell, n.d.)	0.102 to 0.116	161	Alligator Clip	0%-95%	-40~ +60
RKI GX-3R Personal Gas Monitor [8]	0.105	94	Alligator Clip	10%-90%	-20~ +50
RKI GX-6000 Muli-Gas [9]	0.397	664	Belt Clip, Hand Strap	0-95%	-20 ~ +50
RAE Systems AreaRAE Pro Gas Monitor [10]	6.50	15925	Handle	0%-95%	-20 ~ +60
Mulit RAE [11]	0.879	1229	Shoulder Strap	0%-95%	-20 ~ +50
QRAE3[12]	0.411	509	Stainless-steel alligator clip; Swivel belt clip (optional); Pouch (optional)	0%-95%	-20 ~ 50
X-am 5100 [13]	0.220	334	NA	10-95 %	–20 ~ +50
RAE Systems ToxiRAE Pro PID [14]	0.235	217	-	0%-95%	-20 ~ 55
5X from MSA [15]	0.453	629	Belt Clip	15%–90 %	-

Power Source:

Devices predominantly feature rechargeable Lithium-Ion batteries to allow for portability and long battery life. Select devices offer Alkaline battery configurations. Smaller single gas sensors use replaceable batteries, to prevent the need for recharging (See Table 5).

Table 5: Existing gas sensor devices power source information including battery types and range

Device	Battery			
	Type 1	Type 2	Life 1 (hours)	Life 2 (hours)
Honeywell BW Solo (Single Gas Detector | BWTM Solo | Honeywell, n.d.)	Replaceable 2/3AA Lithium battery	-	-	-
RKI GX-3R Personal Gas Monitor [8]	Rechargeable Lithium-ion battery	-	25	-
RKI GX-6000 Muli-Gas [9]	Rechargeable Lithium-ion battery	Alkaline	14	8
RAE Systems AreaRAE Pro Gas Monitor [10]	Rechargeable 7.2 V / 10 Ah Li-ion battery pack with built-in charger	Alkaline Battery Adapter	20	12
Mulit RAE [11]	Rechargeable Lithium-ion battery	Alkaline adapter with 4 x AA batteries	12-18	6
QRAE3 [12]	Rechargeable Lithium-ion battery	-	8-11	-
X-am 5100 [13]	Rechargeable	-	200	-
RAE Systems ToxiRAE Pro PID [14]	Rechargeable Lithium-ion battery	-	12	-
5X from MSA [15]	Rechargeable Lithium-ion battery	AA alkaline	20	-

5.2 Other Possible Interfaces and Functions

Alternative interface and design options not currently used on gas sensors are discussed below.

Display and User Interface:

Touchscreens could offer a modern interface to reduce the need for physical buttons. However, they prove tricky to operate while wearing gloves. Touchscreens can also malfunction when exposed to heat or water.

Full remote monitoring could be employed to prevent the need for a display and control, which could simplify the operation. However, this requires an additional person to monitor and relay the information of the sensor, which could open the possibility of a lack of communication causing safety hazards.

Control Elements:

A full QWERTY keyboard could be used to allow for increased control of the device. However, under the use condition, where the user will likely be wearing thick gloves, while working in a potential chaotic environment, many buttons will likely inhibit use of the device.

The button sizes could be increased to allow for easier usability while wearing thick gloves. This would require fewer buttons or a larger device size but could improve device usability.

Twist knobs could potentially offer precise control of the device. However, they are susceptible to accidental adjustments when bumped.

Alert Mechanisms:

Remote alert mechanisms employing text alarms could be employed to alert users of potentially hazardous conditions. However, during the overhaul process it is unlikely that a firefighter would notice an alert on their cell phone.

Physical Design:

A carabiner could be used to attach the device to the firefighter while in use. This could provide for increased security of the device while in use.

Power Source:

Direct wired connections are an option to supply power to the device and would prevent the need for charging, however their reduction in portability would significantly impair the usability of the device.

5.3 Existing Research on Usability Priorities

Previous research on usability priority of a gas sensing device was conducted by another member of the research team and will be presented and analyzed below.

Applications for Use:

The main interest is determining use of a self-contained breathing apparatus (SCBA) during overhaul operations (See Figure 4). Currently SCBA use in overhaul situations is determined based on smoke levels, and current CO and HCN sensors. A sensor to accurately measure levels of a greater variety of gases would eliminate some uncertainty of when SCBA use is required. Another suggested use is locating gas leaks. During gas leak calls, the firefighters could use this device, potentially in a separate mode to determine location of the gas leak.

Figure 4: Self Contained Breathing Apparatus (SCBA)

Physical Concerns:

From a physical standpoint, firefighters expressed the need for the device to be easy to carry. This would include a way to attach the device to their attire, a suggested example was a carabiner with a retractable cord. The device should ideally be of handheld formfactor with a weight of about two pounds. The air intake must accommodate debris, be waterproof, and sturdy, to accommodate the overhaul environment. The physical interface must have few extremely large buttons to allow for easy operation while wearing thick gloves. The screen must be backlit to allow for easy reading even in limited visibility scenarios.

Notification Specifications:

The device should provide both light and sound notifications to indicate the user of the environmental state. The device should include a snooze or acknowledge button to snooze the notification when the firefighter is wearing the SCBA. Alarms should clearly indicate safe or not safe, including a large safety factor. A notification of some interest is a rapid rise alarm, which would notify the user when the gas levels are rising rapidly.

6 SURVEY

6.1 METHODS

6.1.1 Determine Firefighter Usability Requirements

Research Methodology:

To determine end-user requirements of the sensor device, both quantitative and qualitative research tactics were employed via an online survey distributed to members of the fire service (See Appendix 3). Firefighters were asked about their previous experience using toxic gas sensors during overhaul operations, as well as their technical requirements for a sensor (length of battery life, weight, etc.)

Previous interviews were conducted with fire service members to guide the development of questions and the possible desired features (See 5.3 Existing Research on Usability Priorities).

This quantitative and qualitative approach allowed for the determination for both physical characteristics of the device (weight, size, etc.), as well as the desired behavior of the sensor (notification preferences, interface design, etc.).

Participant Selection:

Participants were be selected both by the researchers, their peers, and firefighter organizations. All firefighters were eligible to participate in this research. This survey was initially distributed to the Worcester Fire Department, the Los Angeles Fire Department, the Harvard Fire Department, and various firefighter organizations. These locations represent a range of department sizes as well as differences in geographical locations to improve diversity of respondents.

A snowball research technique was employed to gain additional respondents. The participants were provided the link to the survey and welcomed to pass the link along to any other firefighters they knew who might be interested in completing the survey.

Data Collection:

The data was collected via a confidential Google Form Survey. This form did not collect enough personal identifying information to identify specific individuals. The demographic information collected included rank, location (state only), age range, and gender identity (See Appendix 3). This information was used to ensure a representative sample of the US firefighting community has been achieved. This survey took approximately 20-30 minutes to complete.

The questions in the survey included multiple choice, multiple select, Likert scale[16], and open response questions [6]. These questions assessed firefighters' previous experiences with sensors during overhaul operations. They determine the firefighters' interface and behavior preferences for a gas sensor for use during overhaul operations (See Appendix 3). To ensure clarity of the questions, this survey was pilot tested by graduate students of the WPI's Fire Protection Engineering Department which included a former firefighter.

Distribution Method:

This survey was distributed by reaching out to firefighters via an email containing the link to the survey. The snowball sampling technique was then used to encourage firefighters to send the link to other firefighters they know to fill out the survey as well.

Ethical Considerations:

This survey is confidential with limited identifying information being recorded. Broad demographic information was requested but optional. This information is not sufficient to identify specific participants. Participation was optional. Specific responses were not reported.

Data Analysis Plan:

The data collected from this survey was analyzed via statistical analysis methods to determine the features most valued by firefighters. Open response questions were used to guide feature development. These features were then incorporated into the final design. To determine if a representative sample of fire personnel has been reached, the demographic information collected was compared with the demographic information of the total US firefighter population.

Expected Outcomes and Relevance:

This research determined the key usability features of a toxic gas sensor for use during overhaul operations. This data was used to guide the development of a design of the sensor interface to ensure usability. It was also used to perform cost-benefit analysis on the design to guide future iterations.

Limitations and Future Research:

To accurately determine requirements for firefighters of all backgrounds, a large sample size of firefighters with diverse backgrounds must be reached. This includes both career and volunteer firefighters. Therefore, the survey was originally distributed to fire departments and firefighter organizations in cities of various sizes with both career and volunteer firefighter populations.

Though outside the scope of the current study, the developed prototype should be presented to firefighters for usability tests and feedback to further improve the usability of the device.

6.1.2 Determine Technology and Environmental Requirements

6.1.2.1 Technology Requirements

To determine the technology requirements for the sensor device and to ensure the physical design of the device accommodates and facilitates the functionality of the sensor technology. A questionnaire was sent to the team at UCLA in charge of the development of the sensor technology. This questionnaire aimed to determine the dimensions and layout, circuit design, power needs, and airflow requirements of the device both in its predicted final prototypical state and its predicted manufacturable state (See Appendix 4).

This information was used to determine the technological requirements of the device to ensure the final design adequately accommodates the sensor technology to ensure functionality and usability.

6.1.3 Environmental Requirements

To determine environmental requirements for the sensor device to ensure functionality in the target environment, additional research was combined with qualitative data collected from research in the End User Requirements (See Determine End-User Requirements). Existing research was analyzed to quantitatively define overhaul conditions. The End-User Requirements Survey contained questions inquiring into a qualitative explanation into overhaul conditions (See Appendix 3).

This information was analyzed to determine environmental considerations for use when designing the sensor to ensure functionality.

6.2 RESULTS

6.2.1 End User and Environmental Requirements

Demographics:

This survey was distributed to a variety of fire departments via email. The fire departments included volunteer and career fire departments to ensure diversity of respondents. 47 responses were collected over the survey period. General demographic information was collected from participants to determine representative of survey group. Role (Career, Volunteer, etc.), Rank (Firefighter, Lieutenant, Fire Chief, etc.), years of experience, age, gender, and state information was collected.

The results showed that 78.3% percent of respondents were career, while the total population of firefighters in the United States in 2020 contained 35% career firefighters[17]. 15.2% of respondents were volunteer firefighters, with the total population in the United States in 2020 contained 65% volunteer firefighters (See Figure 5) [16].

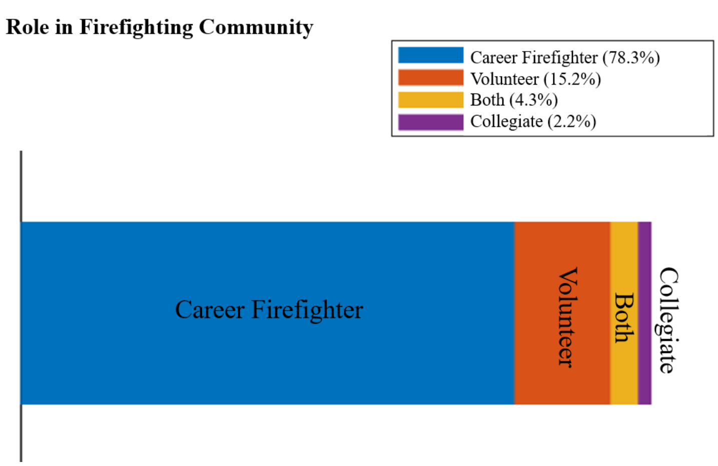


Figure 5:Survey Results Role Stacked Bar Chart

The rank with the largest number of respondents were Fire Chiefs (28.3% of respondents), and Lieutenants (28.3% of respondents). This was followed by firefighters with 19.6% of respondents (See Figure 6).

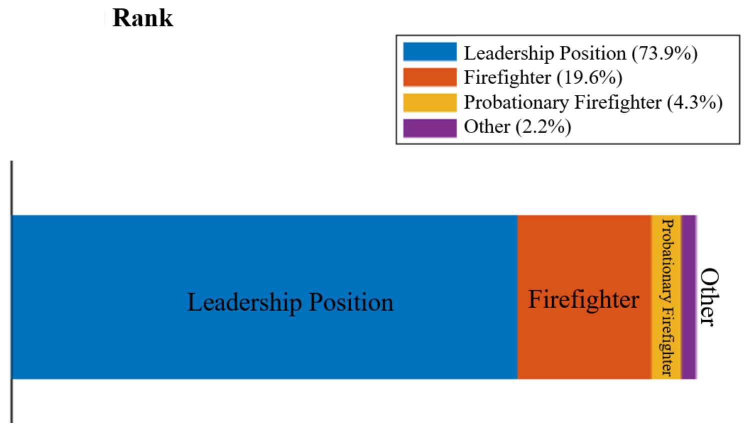


Figure 6: Survey Results Rank Stacked Bar Chart

The majority of respondents had 21+ years of experience in the fire service (50% of respondents), followed by 16-20 years of experience (19.6% of respondents), and 11-15 years of experience with 10.9% of respondents (See Figure 7).

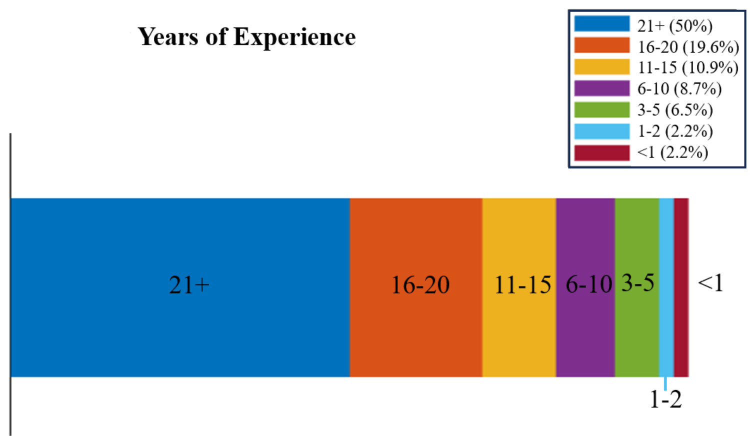


Figure 7: Survey Results Years of Experience Stacked Bar Chart

The largest number of responses were from fire services members of age 46-55 years (44.4% of respondents), followed by 36-45 years (22.2% of respondents). In the United States in 2020, 50% of firefighters were within 30-49 years old (See Figure 8)[17].

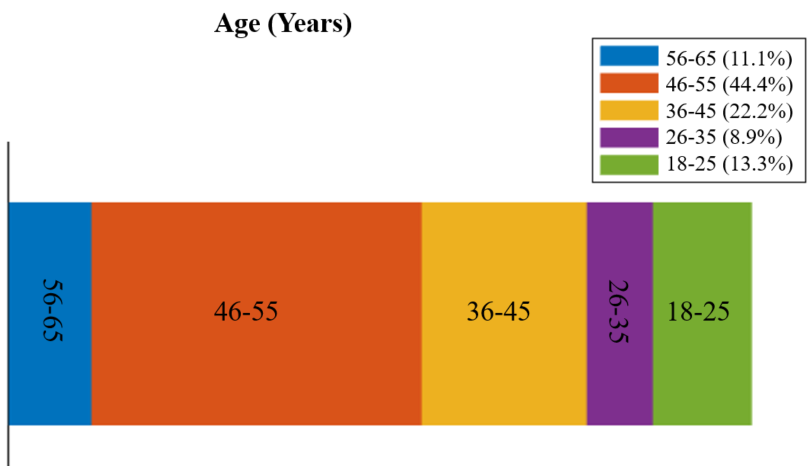


Figure 8: Survey Results Age Stacked Bar Chart

95.7% of respondents were male, while 2.2% were female (See Figure 9). In the United States in 2020 9% of firefighters were females[17].

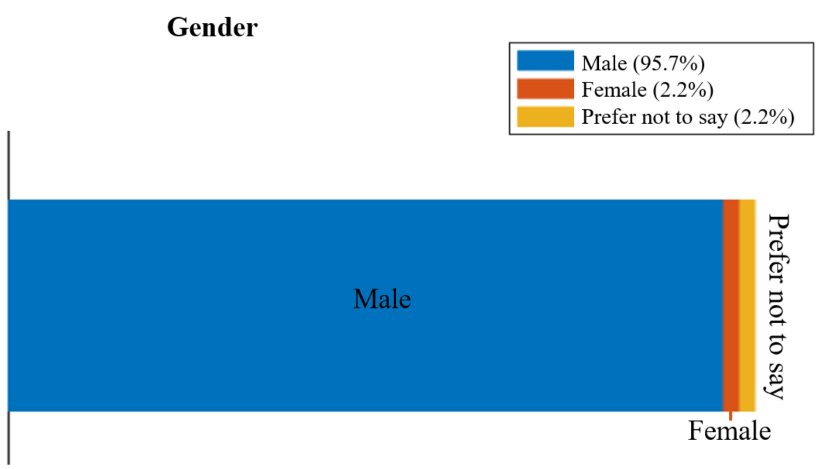


Figure 9: Survey Results Gender

71.7% of respondents were from Massachusetts (See Figure 10), with the majority of respondents working in New England (97.8% of respondents).

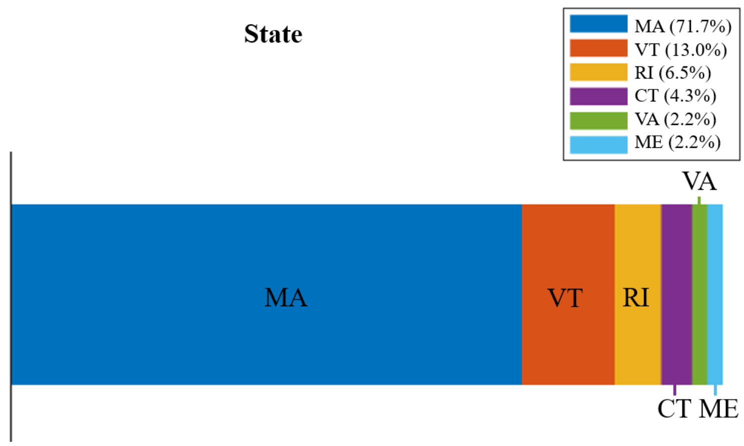


Figure 10: Survey Results State Pie Chart

This survey reached a more senior audience then is representative of the collective United States fire service population. The ranks reached are typically senior roles. The majority of respondents had 21+ years of experience and were within or older than the average age of firefighters in the United States. As this survey was distributed to members of the fire service with leadership roles, it was likely passed to others with leadership roles, contributing to the bias towards more senior members.

<u>Overview of Questions:</u>

This survey aimed to determine both the physical environment of overhaul operations, as well as the experiences of fire service members when using a toxic gas sensor.

The survey inquired about the conditions associated with overhaul operations (multiple select and open response). The next question inquired about the firefighter's experience with using gas sensors during overhaul operations, aiming to determine what gases were tracked, as well as what gases the firefighters find most important to track. We also asked about the respondent's interest in a gas sensor that does not require calibration (a key separating feature of the technology).

To determine the size and weight requirements of the sensor, a set of weights were given and respondents were asked to rate how likely they would be to carry the sensor. This process was repeated with sizes to determine the size requirements. We then asked how firefighters would like to carry the sensor to determine an attachment style for the design. The power requirements of the device were determined by asking how the device will ideally be powered (rechargeable vs replicable batteries), as well as how long it needs to hold a charge.

To determine the ideal user interaction with the sensor, we inquired about the data to be displayed on the main page as well as the option for additional pages of information. The preferred type of concentration data (molar concentration vs OSHA limits) was surveyed to determine the data type. Notification preferences were determined by first determining scenarios in which the user would like to be notified, then how they would like to be notified (visual, audio, haptic), then how they would like to be notified through each of those channels. We also asked about a possible snoozed state, which was stated as a desired feature in preliminary interview (See 5.3 Existing Research). To determine the physical interaction with the device, we asked how the user would like to interact with the device (buttons, remotely, touchscreen, etc.) as well as the size requirements for operation with buttons. The respondents were then given the ability to write in any other feature they desire in a gas sensor.

To determine the display style preferences, the respondents were provided with three mock designs (See Figure 28) and asked to choose their favorite (or none), as well as provide the positive and negative aspects of each design.

Overhaul Operation Conditions and Technical Requirements:

Forty-six fire service members responded to the question inquiring on the length of overhaul operations. Overhaul operations last on average from 30 minutes to 2 hours. The conditions most noted were standing water (93.5% of respondents), smoke (93.5% of respondents), debris (82.6% of respondents), limited visibility (69.6% of respondents), high humidity (65.2% of respondents), and high temperatures (60.9% of respondents) (See Figure 11).

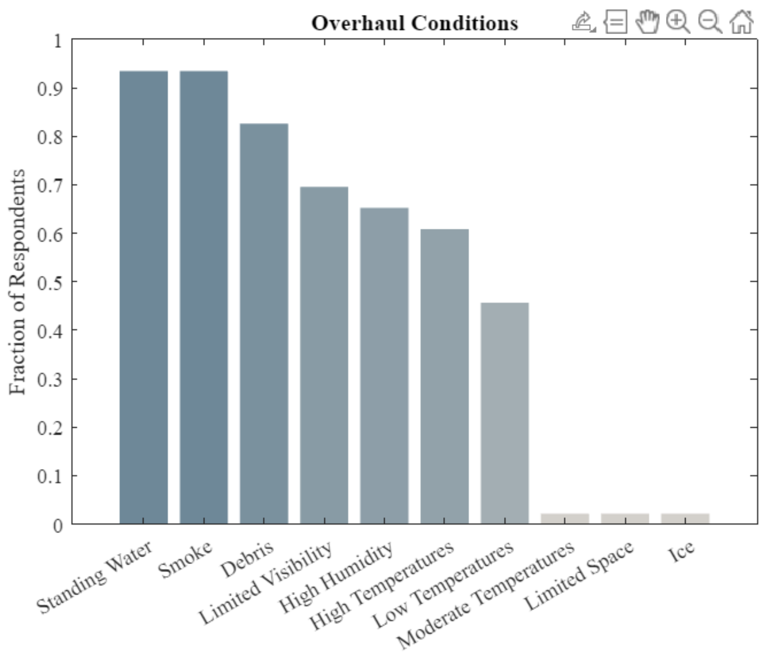


Figure 11: Survey Results Overhaul Conditions vs. Percent of Respondents

The most common gases tracked during overhaul operations were Carbon Monoxide (CO), Oxygen gas (O_2), and Hydrogen Cyanide (HCN).

Of the given gases, those that were deemed most important to be tracked by the respondents were CO and HCN (See Figure 12). Another gas that was noted in several responses was the interest in tracking O_2.

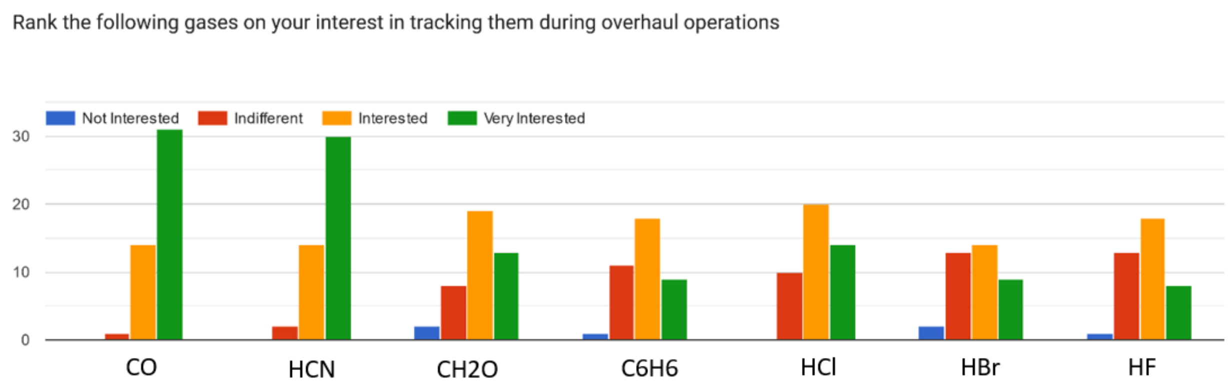


Figure 12: Survey Results Gases to Track (CO, HCN, Formaldehyde (CH2O), Benzene (C6H6), Hydrogen Chloride (HCl), Hydrogen Bromide (HBr), and Hydrogen Fluoride (HF))

The majority of respondents were very interested in a gas sensor that did not require calibration. With the average score of interest being a 4.3, out of 5, with 1 being uninterested, and 5 being extremely interested (See Figure 13).

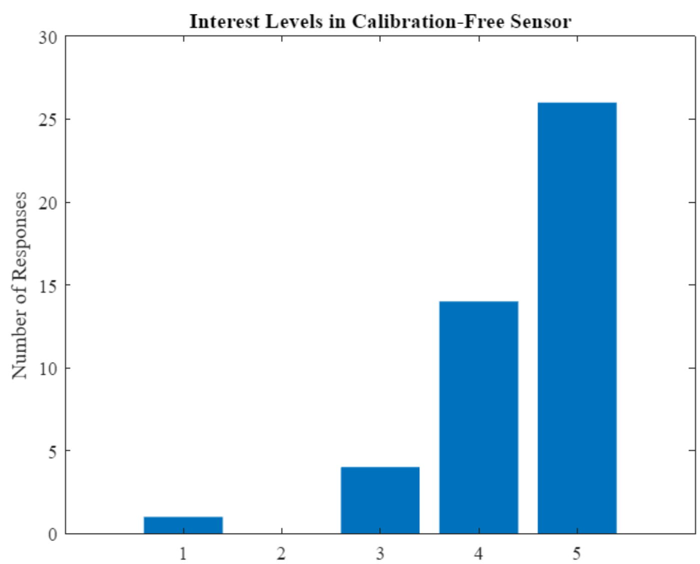


Figure 13: Survey Results Interest in a Calibration-Free Sensor (1: uninterested - 5: extremely interested)

<u>Size and Weight Requirements:</u>

To determine the weight requirements of the sensor, the respondents were asked to rate how likely they would be to carry a sensor of the following weights (extremely unlikely, unlikely, possibly, likely, extremely likely): Under 1 lb., 1-2 lbs., 3-4 lbs., 5-6 lbs., 7+lbs. Respondents were overwhelmingly likely to carry a sensor under 1 lbs., and from 1-2 lbs. About half of respondents would carry a sensor from 3-4 lbs. 5-6 lbs. and 7+ lbs. showed a majority of respondents unwilling to carry the sensor (See Figure 14).

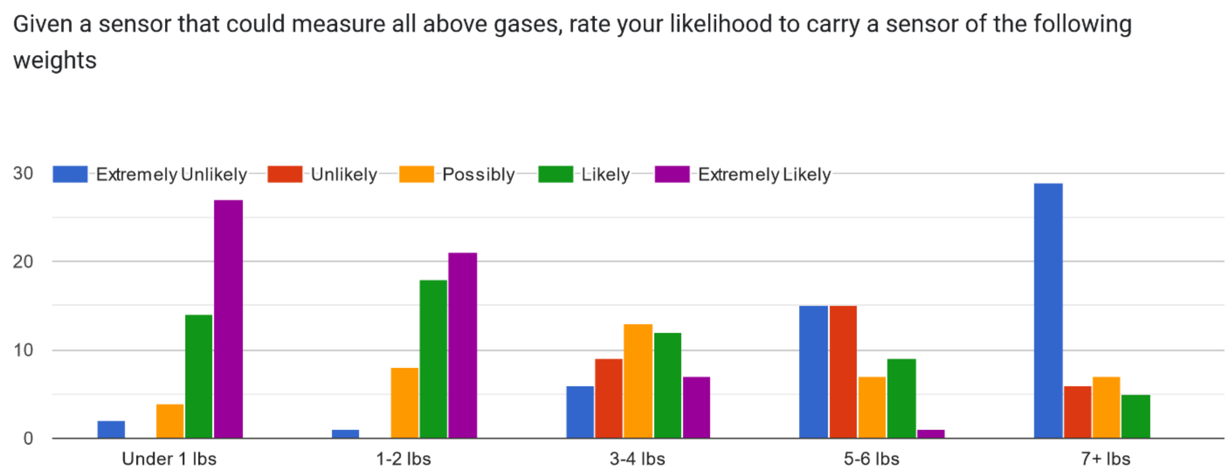


Figure 14: Survey Results Weight Requirements

To determine the size requirements a similar procedure was conducted, asking respondents to rate how likely they would be to carry a sensor of the following sizes (extremely unlikely, unlikely, possibly, likely, extremely likely): deck of cards, multimeter, book, and shoebox. Respondents were extremely willing to carry a sensor the size of a deck of cards, and just over half were willing to carry a sensor the size of a multimeter. Sensors the size of a book and shoebox showed the majority of respondents unwilling to carry the sensor (See Figure 15).

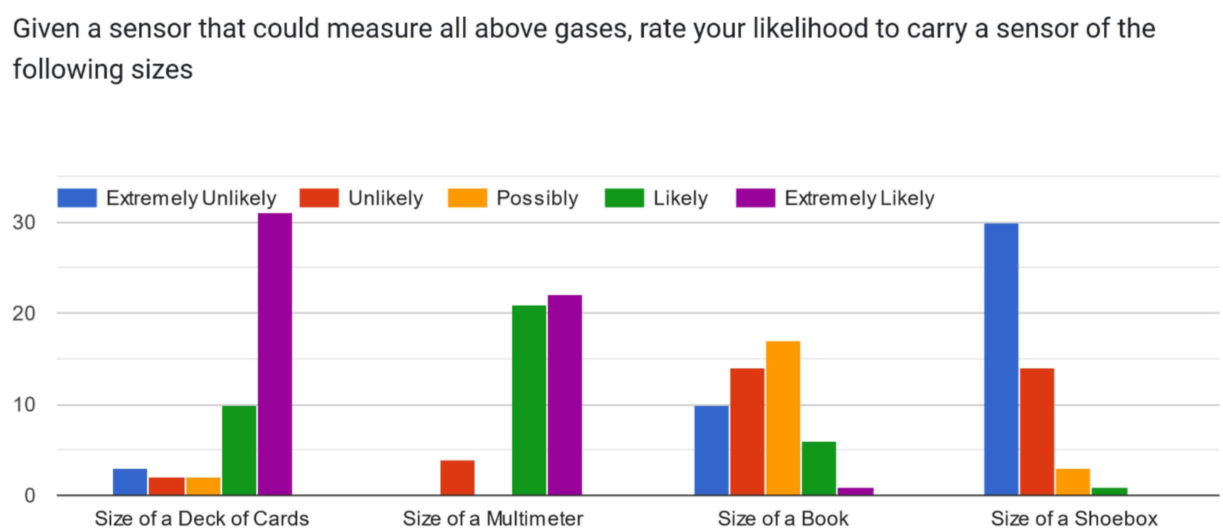


Figure 15: Survey Results Size Requirements

The respondents overwhelmingly showed interest in carrying the sensor with a carabiner (87% of respondents) (See Figure 16)

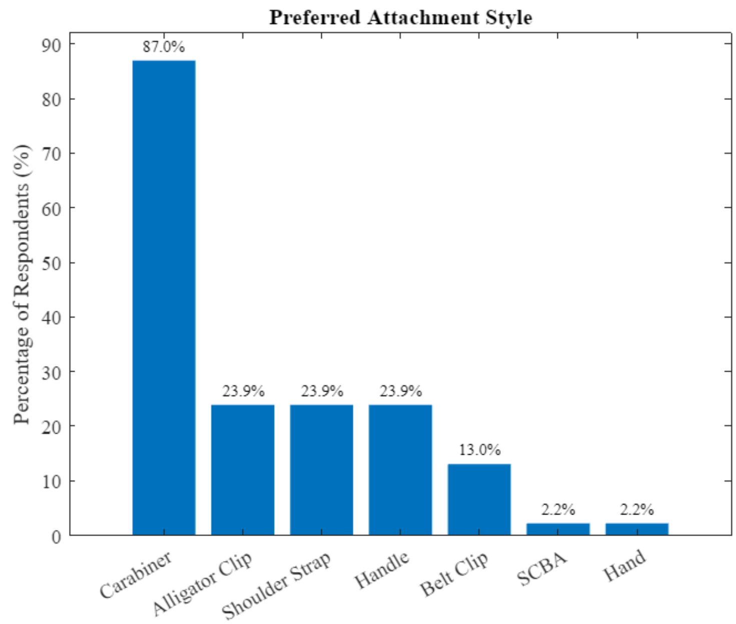


Figure 16: Survey Results Preferred Attachment Style

The majority of respondents preferred to power the device through rechargeable Lithium-Ion batteries (85% of respondents) (See Figure 17).

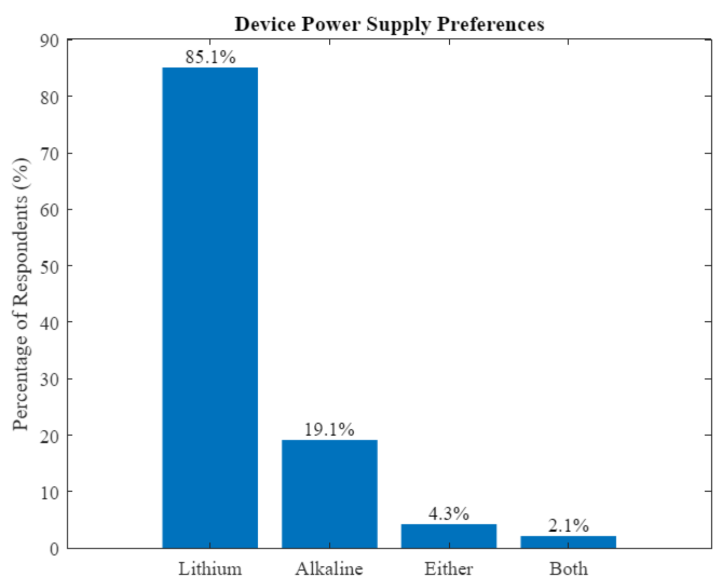


Figure 17: Survey Results Power Supply Preferences

To determine the size of batteries required, we asked about the amount of time the device needs to hold a charge. Over 75% of respondents were satisfied with a device that holds a charge for 8-10 hours (See Figure 18).

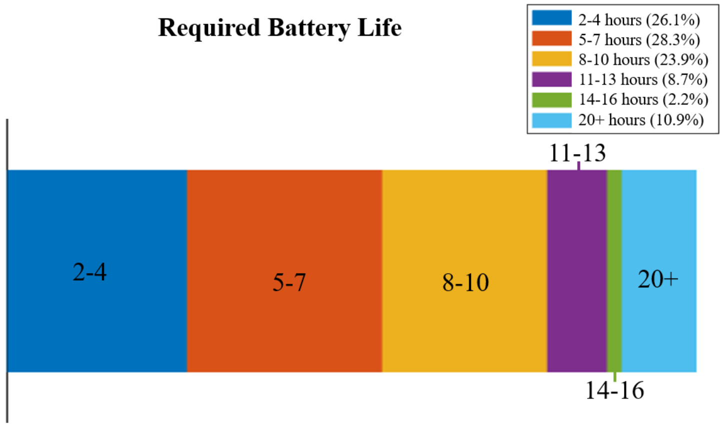


Figure 18: Survey Results Required Battery Life

<u>*User Interaction:*</u>

To determine the information to be displayed on the main page, respondents were asked to choose what information they would most like to be displayed on the sensor. The most important information was the concentration information of all gasses (95.7% of respondents), and the battery level of the device (95.7% of respondents), with nearly all respondents requesting this information. Respondents also indicated that they would like to see if the concentration of gases is above or below exposure limits (78.3% of respondents) (See Figure 19).

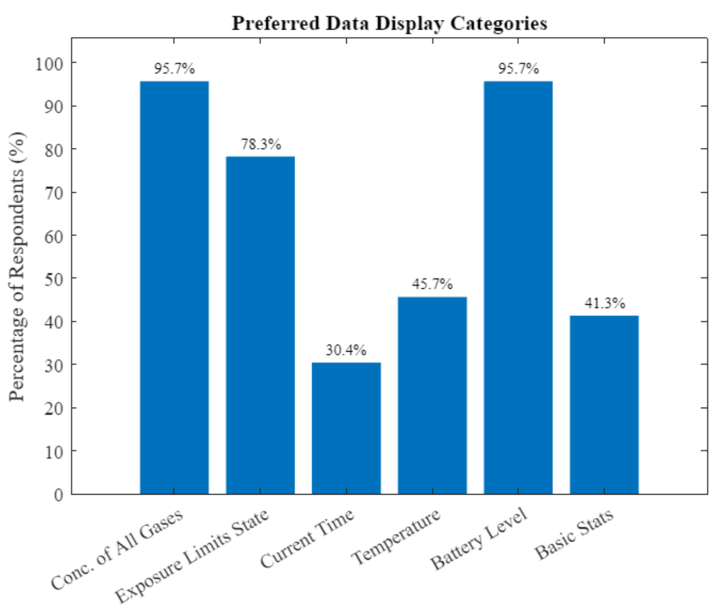


Figure 19: Survey Results Data Display Preferences

To determine the format for displaying the data, we asked the units in which the respondents would like to view the data in, molar concentration(ppm) or percent of OSHA limits. 87.5% of respondents indicated that they would like to view the data in molar concentrations, while 60.4% of respondents indicated that they would like to view the data in percentages of OSHA exposure limits.

To determine additional information that would be useful to the user, the respondents were asked to check any additional stats they would like to view, including: Maximum concentration over the last minute, Maximum concentration since the device was turned on/reset, Average concentration over the last minute.

The majority of respondents indicated that they would like to view the maximum concentration since the device was turned on/reset (53.2% of respondents) (See Figure 20).

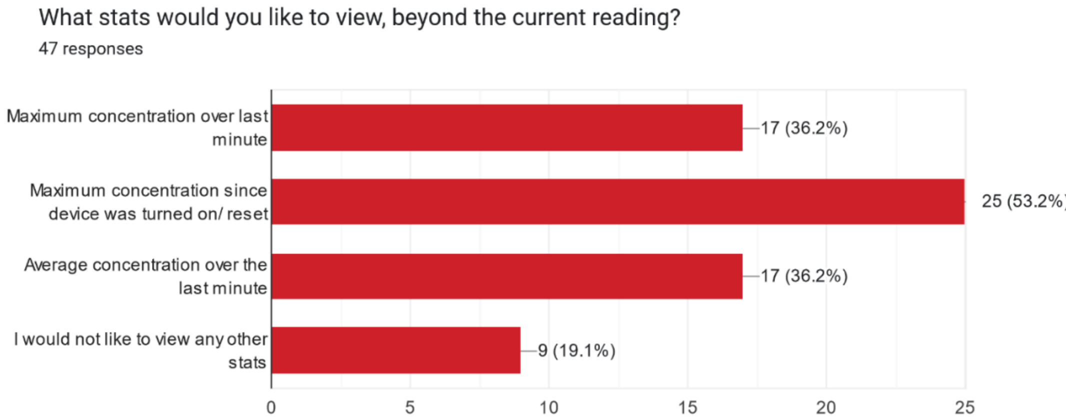


Figure 20: Survey Results Notification Scenario Preferences

To determine notification preferences, users were asked to check all conditions in which they would like to be notified in some way by the device, including: Conditions exceeding exposure limits, Rapid Rise conditions, Low Battery of Device, and Conditions returning below exposure limits. The majority of respondents indicated that they would like to be notified in some way when conditions exceed exposure limits, rapid rise conditions, and low battery of device (See Figure 21)

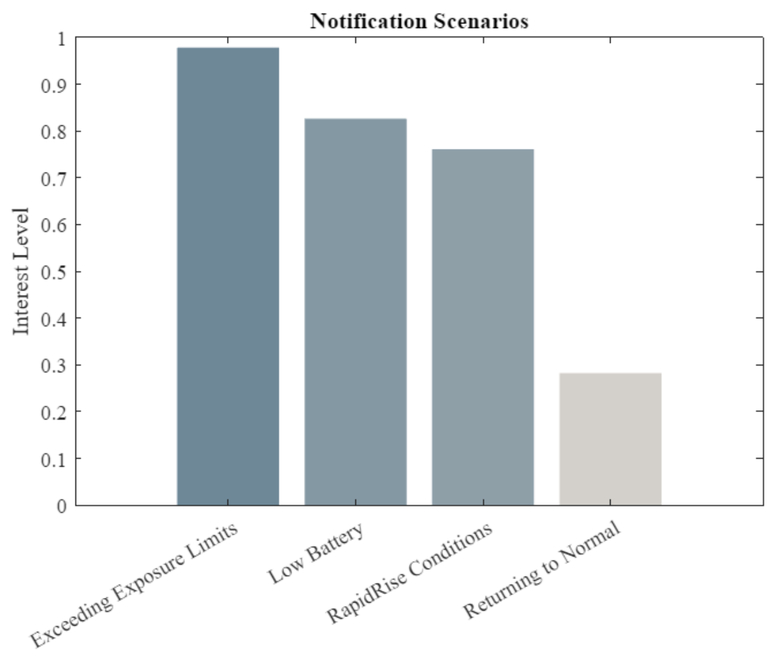


Figure 21: Survey Results Notification Scenario Preferences

To determine the channels in which to notify the user during these conditions, respondents were asked to check how they would like to be notified in the previously mentioned conditions. They could choose multiple among visual, audio, and device vibration (haptic feedback). Respondents indicated that they would like to receive audio visual and haptic feedback during both conditions exceeding exposure limits, as well as rapid rise conditions. During low battery of device, respondents indicated that they would like to receive notifications through visual and possible audio channels. When conditions return below exposure limits, users would like some sort of visual notification, without audio or haptic feedback (See Figure 22).

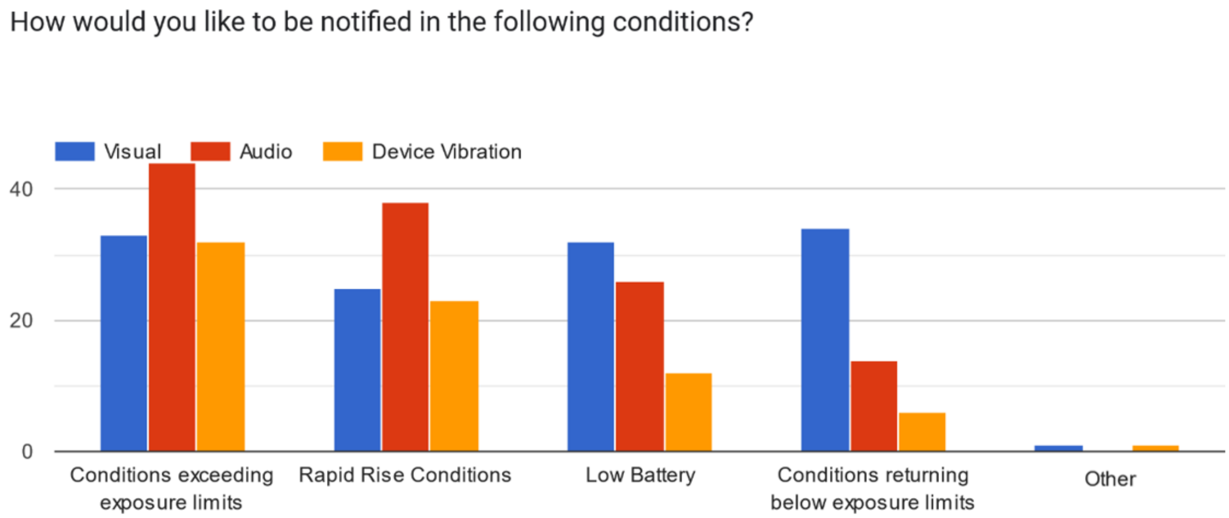


Figure 22: Survey Results Notification Channel Preferences

To determine how to notify users though these channels, respondents were asked to choose how they would like to be notified visually, audibly, and haptically. Visually, users would prefer to be notified though a flashing LED (91.7 % of respondents), as well as possibly though a change in the screen (39.6% of respondents) (See Figure 23).

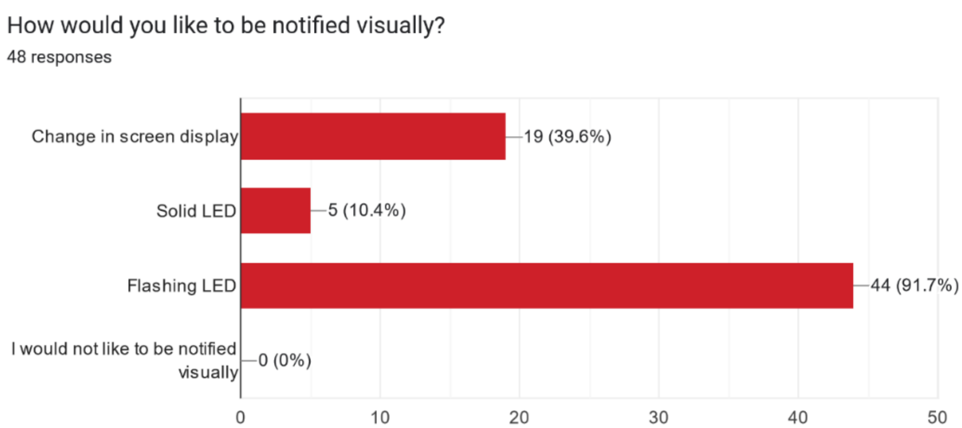


Figure 23: Survey Results Visual Notification Preferences

To determine screen display preferences, users were asked to indicate their preference between a black and white screen, a colored screen, or no preference. 18.7% of respondents indicated that they would prefer a black and white screen, 45.8% indicated they would prefer a colored screen, with 35.4% indicating no preference.

The majority of users would prefer to be notified though beeping/alarm (85.4% of respondents) (See Figure 24)

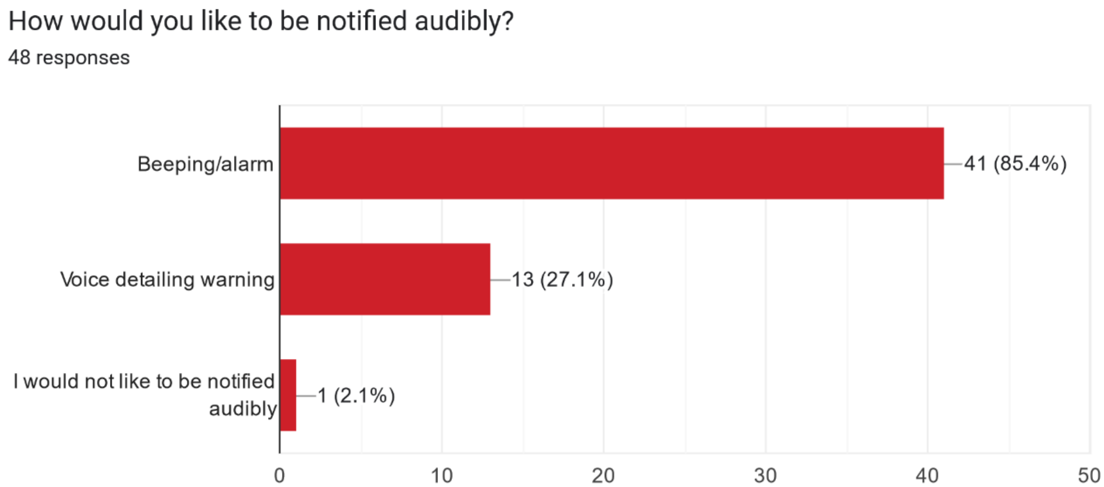


Figure 24: Survey Results Audible Notification Preferences

For haptic notification, respondents preferred to be notified though a pattern of vibration (43.8% of respondents) as opposed to continuous vibration, repeated vibration, or single vibration (See Figure 25).

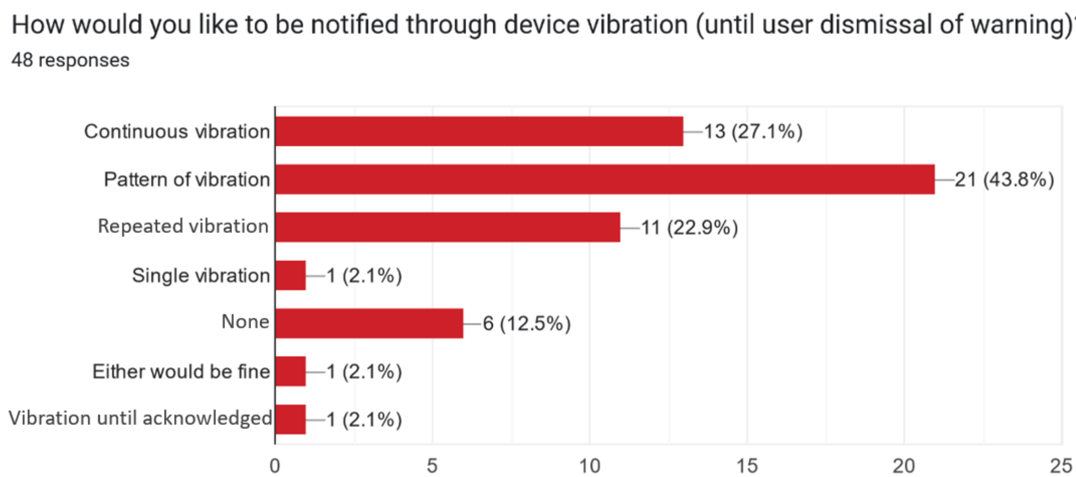


Figure 25: Survey Results Haptic Notification Preferences

To determine physical device interaction preferences, respondents were asked to record how they would like to interact with the device. The vast majority of respondents indicated that they would like to use buttons and switches to interact with the device (89.6% of respondents), rather than touchscreens, or remotely (See Figure 26).

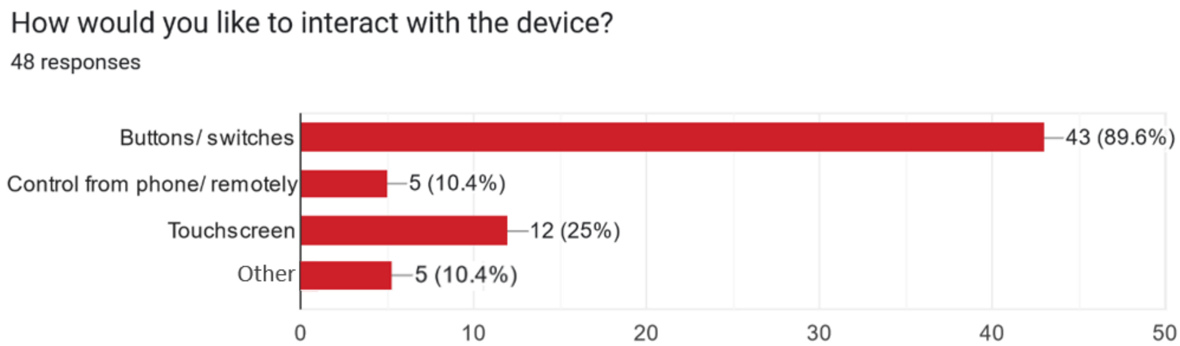


Figure 26: Survey Results Device Interaction Preferences

Users who choose to interact with the device via buttons were then asked to provide insight on how large the buttons would need to be to be usable. The majority of responses indicated the need for the buttons to be operable in firefighter gloves, and be about 1 inch (2.54 cm) in size.

To determine if a snooze feature would be desired, respondents were asked to indicate their preference in a snooze button (to renotify after a set period of time), a dismissal button (to pause notifications until a change in state), or neither. The majority of respondents indicated interest in a snooze buttons (54.2% of respondents) (See Figure 27).

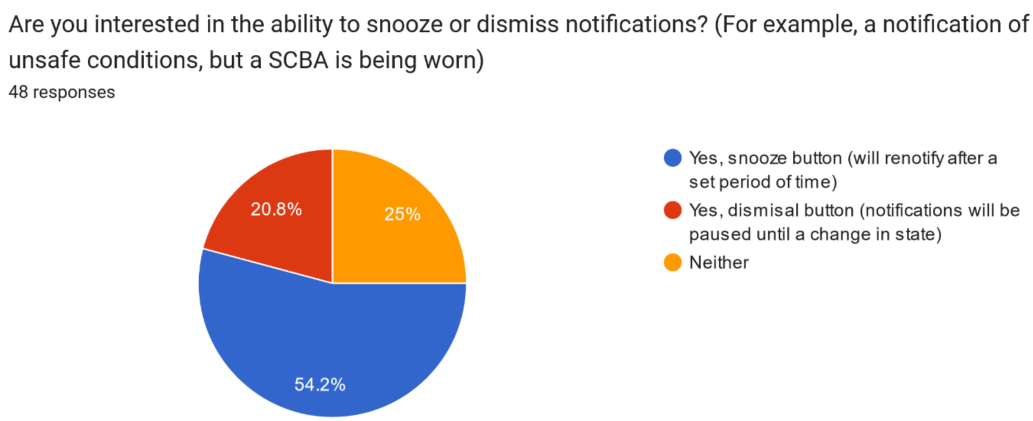


Figure 27: Survey Results Snooze/Dismissal Interest

Users who displayed interest in a snooze button were then asked to provide insight on how long the snoozed state should last. Responses ranged from 30 seconds to 10 minutes, with the majority of responses indicated around 2 minutes before renotification.

Screen Design:

To determine screen design preferences, respondents were provided with three screen design options (See Figure 28). They were asked to indicate their preference in design, then provide the positive and negative aspects of each design. The most popular design was the second design with 43.8% of respondents indicating that they would prefer that design (See Figure 29).

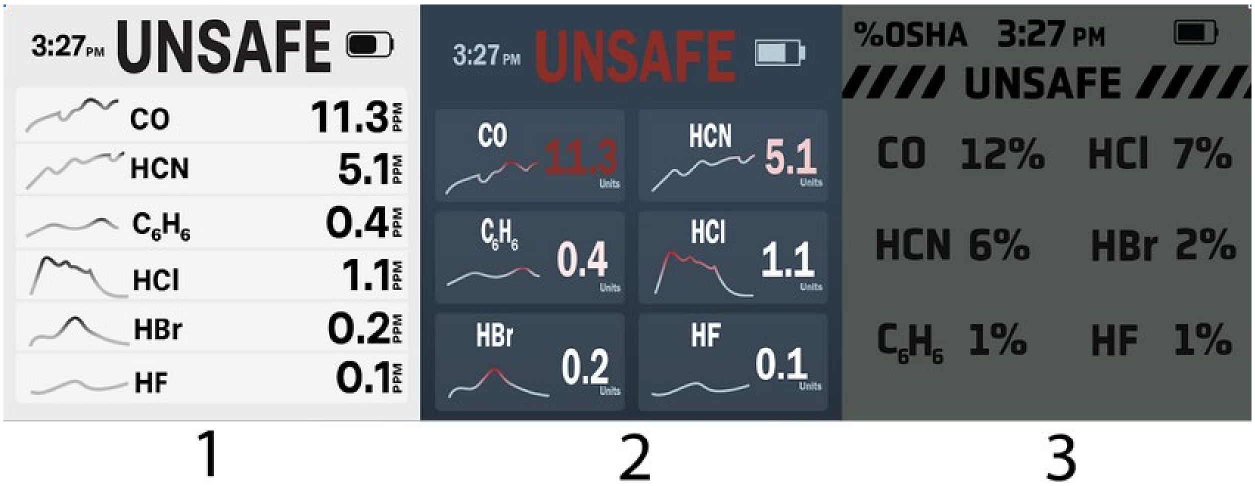


Figure 28: Screen Design Options

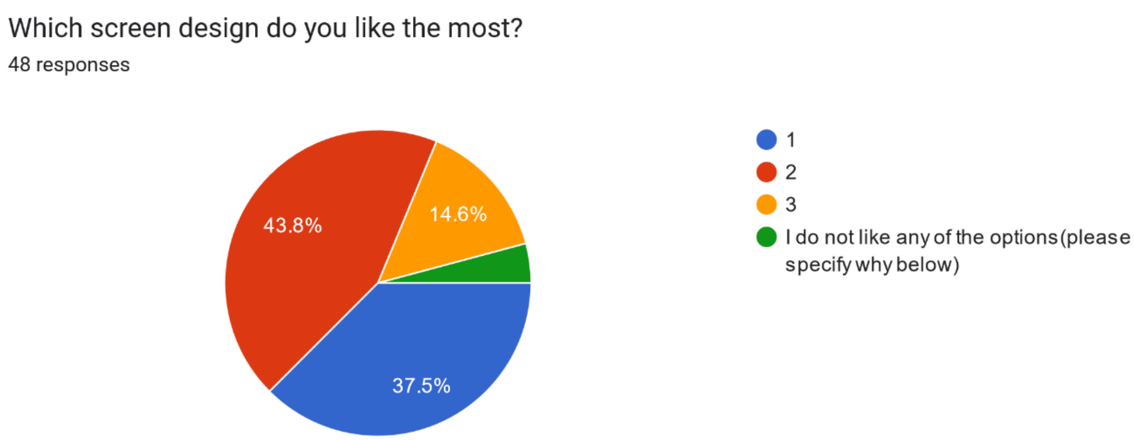


Figure 29: Survey Results Screen Design Preferences

The first design was a modern black and white design containing the current readings of the gases in molar concentrations. The design included a trendline to show the comparison between the current reading and the past readings. The most liked features of this design were the clarify and high contrast nature of the display. The negative aspects of the design were noted to be the graphs.

The second design was a modern dark blue that used red to show unsafe conditions. The current readings of the gases were displayed. This design also included a trendline to show the comparison between the current reading and the past reading. The most liked feature was the red color to show the unsafe condition, while many respondents felt that the dark blue did not create enough contrast for easy readability.

The third design was a very simple monochromatic display that showed the current concentrations of the gases as well as the safe/unsafe state of the current condition. Most respondents indicated liking the simplicity of the design, but not liking the layout and the lack of color contrast.

Takeaways:

The gases deemed most important to track were Carbon Monoxide and Hydrogen Cyanide, so an effort was made to ensure that these species were included in the final device. There was also some interest in tracking Oxygen gas, but this is out of scope of the current technology, so it was not included. The calibration-free feature was shown to be very important to users, which demonstrates a possible market of the device in the future.

The goal is to have a device of a size and weight that is both technologically feasible, yet users are still willing to carry it. The majority of respondents were willing to carry a sensor of a size of a multimeter, with mixed results for the size of a book. The goal of the sensor was be to be smaller than the size of a book, and ideally the size of a multimeter. The device was designed to be attached via a carabiner, as the vast majority of respondents noted that as their preferred method of carrying the device.

The powering of the device was achieved through rechargeable lithium-ion batteries, with a battery life of between 8-10 hours, to satisfy the majority of respondents.

The main page of the sensor contained concentration data in molar concentrations (ppm), the battery level of the device, as well as the status of the gas (above or below exposure limits). An additional page was available containing the maximum concentration of each gas since the sensor was turned on.

When conditions exceeded exposure limits, the user is notified through audio, visual, and haptic warnings. The audio warnings consisted of a beeping tone. Visually, an LED flashes next to the gas species that is over exposure limits, as well as the display changing to convey the warning. Haptically, the device vibrates in a pattern.

During rapid rise conditions, the notification is the same as for exceeding exposure limits, but the beeping and vibration pattern is different to allow the user to distinguish between the different conditions.

When the device has low battery, the device displays this clearly on the screen, as well as beep to notify the user.

A colored screen is deployed as more respondents indicated they would like a colored screen. Also, respondents preferred the high contrast and attention catching screen mockups, which are only possible with a colored screen.

The device contains a small number of essential buttons to interact with the device. The size of the buttons was prioritized over the number to ensure functionality with firefighting gloves. The device contains a snooze button which silences notifications for 2 minutes before renotifying the user. This snooze button silences notifications about dangerous conditions, as well as rapid rise and low battery alarms, as the user will likely be wearing their SCBA at the time.

The screen is designed similar to the second example screen. The contrast was increased, and a lighter background was used to ensure readability in low visibility environments.

Research Limitations:

This survey reached a demographic of firefighters, specifically more senior members of the fire service. This is likely because the survey was distributed to members in leadership positions. Senior members are also more likely to have used a gas sensor before, and therefore are more willing to provide feedback.

Because of this slight bias in the study, it is important to take into account that the device needs to be usable for all members of the fire service, regardless of experience level. Care was taken to ensure that this device is very user friendly and self-explanatory to ensure that less experienced members can also use the sensor with ease.

6.2.2 Technological Requirements

The results of the questionnaire to determine the technological requirements of the sensor allow for the determination of the size, airflow pattern, general shape, and other considerations for design.

Size:

The ideal final sensor is approximately 15cm by 10cm by 5cm in size, including the electronic components. This includes three gas sensing chambers in series. The sensor uses various boards for computations, as well as a final board for display purposes.

Airflow Considerations:

The device uses three gas sensing chambers in series with each other. It requires airflow though the three sensors, as well as a filter to remove excess soot from the air before entering into the device. This preserves the longevity of the device. The filter used will be constructed of metal mesh.

7 INTERFACE DESIGN

7.1 SYSTEM OVERVIEW

The interface prototype aimed to provide a realistic user interface, without containing the underlying sensor technology. At the end of its development cycle, the sensor technology will be integrated into the user interface to produce a final sensor for testing. This interface prototype aimed to provide the user with a model of the gas sensor, without being usable. It aimed to feel realistic and employed many of the same components as a functional sensor to increase a sense of realism.

The model aimed to include a functional screen as well as buttons, LEDs, and haptic feedback to demonstrate the user's interaction with the device. The development was be broken up into hardware, as well as software development.

The hardware development of the design includes all the physical components and design of the device. The end-user requirements survey, as well as the technical and environmental requirements surveys, findings were employed to determine the physical design. The sensor will contain the following subsystems: external case, display screen, buttons, haptic feedback, LEDs, and fans. The behavior of these subsystems (except for the case) was controlled via a Raspberry Pi to simulate their responses to various user inputs (as well as simulated gas sensor readings). These subsystems were developed in parallel, then integrated to produce a realistic final product (See Figure 30).

	Subsystem	Parts Ordered	Concept Test	Intermediate Prototype	Final Design
Software	User Interactions				
	GUI				
	UX				
Hardware	Buttons				
	Screen				
	Battery				
	Raspberry Pi				
	Audio				
	Haptic				
	Case				
	Fans				

Completed
In Progress
Not Yet Started
Not Applicable

Figure 30: Subsystem Progress Matrix

7.2 External Case

The case was designed using the computer aided design (CAD) software, SolidWorks, to ensure that the design can be reproduced. It was 3D printed using Polylactic Acid (PLA) filament. The case design went through three iterations to improve design and accommodate the other subsystems.

The first iteration was designed using final user feedback, as well as technological and environmental feedback. It was designed using SolidWorks, and printed in PLA filament (See Figure 31). It featured a hand-held design, slightly bigger than a multimeter. It featured a slot for a removable and cleanable filter to preserve the functionality of the sensor. It featured very large slots for buttons to allow usability with firefighting gloves. The screen was large to allow for readability, and it featured an inlet for the gas sampling path from the bottom of the sensor thought the back to prevent clogging from falling debris.

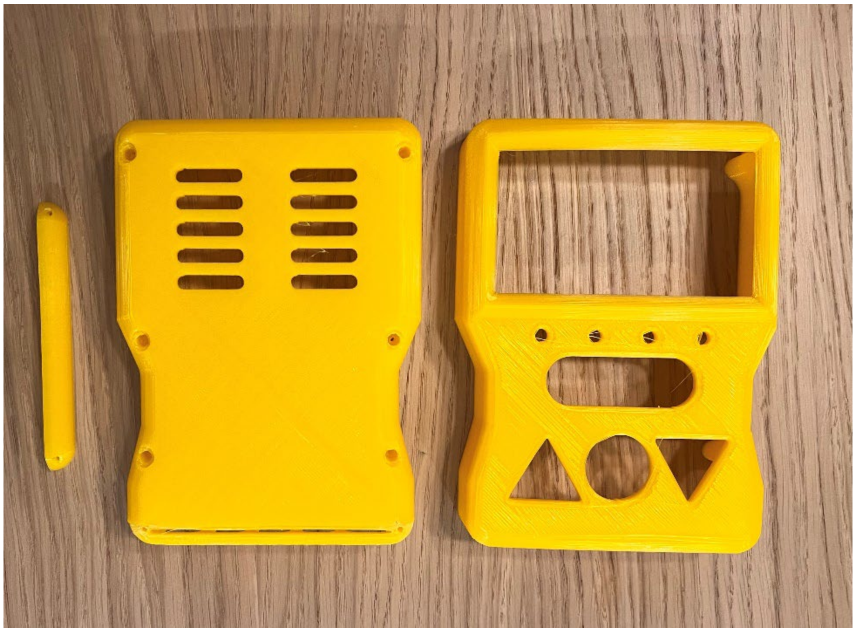


Figure 31: First Iteration 3D printed Case

The second iteration was designed to fix various compatibility issues present in the second iteration. It featured the arrow and power buttons moved upward on the casing to allow for fan compatibility. It also featured internal standoffs to allow for button and Raspberry Pi mounting locations. It was printed out of PLA filament, maintaining the same features as described above in the first iteration (See Figure 32).


Figure 32: Intermediate Case Prototype

The final case of the device (See Appendix 5 is three 3D printed PLA parts. The concept design of the case was designed to accommodate the various subsystems of the device, while maintaining the ideal dimensions provided by UCLA. The case was modeled in SolidWorks. The case consisted of a top piece, a bottom piece, and a filter cover, to allow for removal and filter cleaning. The case was then sliced and printed (See Figure 5). Breadboard button compatibility issues were fixed in this final iteration, allowing the buttons to be able to be pressed. The case was printed and finished using sandpaper and spray paint (See Figure 33).

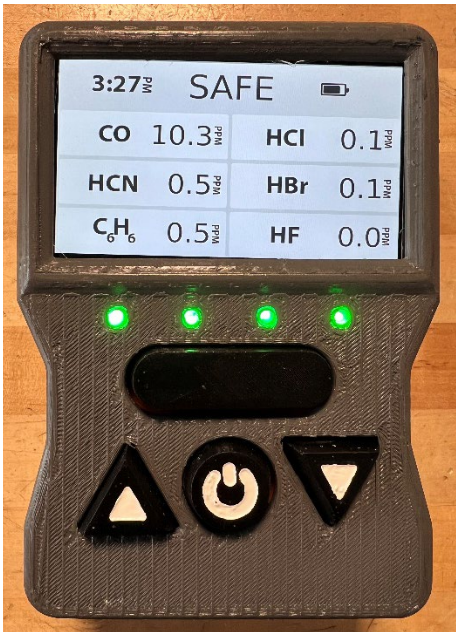


Figure 33: Final Sensor Case and Main Page

7.3 Buttons

The buttons were designed in parallel with the case to ensure compatibility. They underwent a concept test, a preliminary prototype, then finally, the final design. The buttons were designed to maximize usability while using firefighting gloves.

The concept test consisted of using breadboard buttons (See Figure 34), with a 3D printed cap to enlarge the button. This design allows for flexibility of size and shape of the buttons, while maintaining functionality.

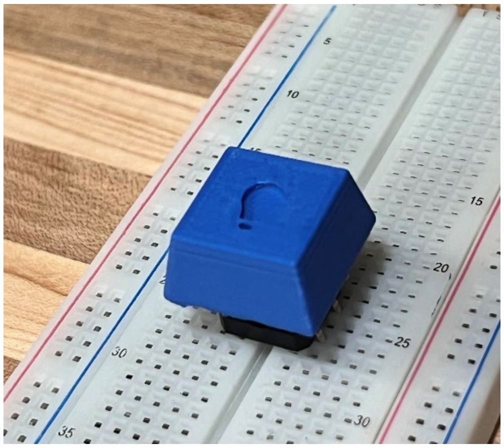


Figure 34: Button Concept Test

The preliminary prototype consisted of designing and printing prototype buttons compatible with the second iteration of the case (See Figure 35). These buttons fit over traditional breadboard buttons, allowing for a larger surface area for use with gloves. An up arrow, a down arrow, a power button, and a snooze button were printed to allow for desired user interaction with device.

Figure 35: Button Preliminary Prototype

The final buttons of the device consisted of both the breadboard buttons, and the caps. The breadboard buttons are used to interface with the Raspberry Pi. The breadboard buttons were ordered through WPI's ECE department. The concept prototype involved both testing the breadboard buttons, as well as various iterations of 3D printed buttons. The breadboard buttons were wired to a Raspberry Pi, which was used to control LEDs to ensure their functionality. The button caps were 3D printed to fit over breadboard buttons (See Figure 33). The buttons were finished using paint to achieve the icons on the surface.

7.4 Haptic Feedback

As haptic feedback was determined to be desirable from the user-feedback survey, a haptic motor was installed into the case to produce vibrations as the device and user interact. The development of the haptic feedback system consisted of a concept test and the final integration.

The concept test consisted of wiring a 3V vibration motor to a Raspberry Pi 4B GPIO pin and ground, and sending pulses of input into the motor to check its function. The motor successfully produced clear, distinct vibrations that could be clearly detected, and audibly heard.

The haptic motor was then integrated into the final product by wiring the power of the motor to a GPIO pin on the Raspberry Pi. The pin was then set to high and low in various patterns to produce the two distinct notifications for the device. The motor was then attached to the side of the case for stability.

7.5 LEDs

The LED system was developed using a similar pipeline, with a concept test and a final integration.

The concept test consisted of using red-green bi-directionally LEDs attached to two GPIO pins on a Raspberry Pi 4B. When a button was pressed, the direction of the current was switched to alternate the color of the LED between red and green. This design allows for multiple colors of light to be produced, while only requiring one LED.

The LEDs were integrated into the final design by gluing them into the case. They were then soldered to resistors and to wires to connect to the Raspberry Pi GPIO pins. One set of pins were set to high to achieve a red color, the another set of pins were set to high to achieve a green color.

7.6 AUDIO

The audio subsystem of the device includes a speaker powered by the Raspberry Pi. A small speaker was originally employed with an audio amplifier to produce sound from the Raspberry Pi's 3.5 mm headphone jack. However, the audio amplifier board was damaged and was no longer a viable option. A small 3.5 mm headphone jack compatible speaker will be used. The speaker was successfully used to play sound from the Raspberry Pi. The Raspberry Pi was programed to play mp3 files containing two different sounds to communicate the rapid rise, as well as the unsafe state to the user.

7.7 FANS

To ensure the functionality of the sensing technology, airflow is required though the sensor. This was achieved through a designed airflow path though the sensor using fans. The fans used were powered through the Raspberry Pi 4B 5V output. The fans were tested outside of the housing to ensure their functionality. After being determined to be functional and able to be powered through the Raspberry Pi board, they were incorporated into the case design to ensure compatibility.

7.8 SCREEN

The screen of the device consisted of a color digital screen attached to a Raspberry Pi via a DSI connector. The concept prototype involved testing the screen connector and compatibility with the Raspberry Pi. The intermediate prototype consisted of checking compatibility with the 3D printed case by installing the screen (See Figure 32).

The graphical user interface (GUI) of the device consists of the screen display on the device. It includes the main page, setting page, as well as additional information pages. The concept prototype of the GUI contained three screen design options (See Figure 28) as well as a python script utilizing tkinter to create a graphical output. The concept GUI prototypes were developed using Adobe Illustrator and presented to firefighters to determine design preferences. The python script included logic to display the labels of the gases, as well as their current concentrations (defined via a function in a separate file). Their current concentrations were updated twice per second, and the color highlighting was changed based on their concentration (See Figure 36).

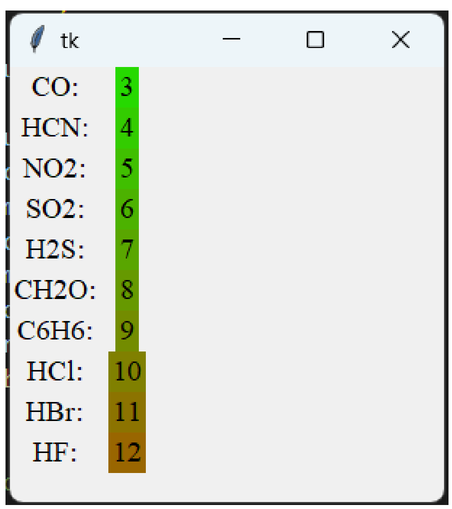


Figure 36: GUI Concept Test

The final screens were created by developing final Adobe Illustrator concept images to determine the layout and design of the screen. The feedback from the interfaces provided on the survey was used to develop the final screen designs (See Figures 33 and 37). The main page was designed using the feedback on the most desired concept image in the survey. The dark design was most preferred, but many thought it was too dark. However, the color indication of unsafe was desired, so the design was developed to be lighter, while maintaining the red color to convey unsafe conditions. The settings page was designed with a style similar to the main page. The settings page contains options to change the measurement unit, set the time, reset the device, change the snooze timer settings, and change the display mode. The additional information page contains the maximum concentrations of each gas since the device was turned on, as requested by the survey respondents (See Figure 37). These pages were programmed to the screen using Pythons Tkinter library, then loaded on the Raspberry Pi.

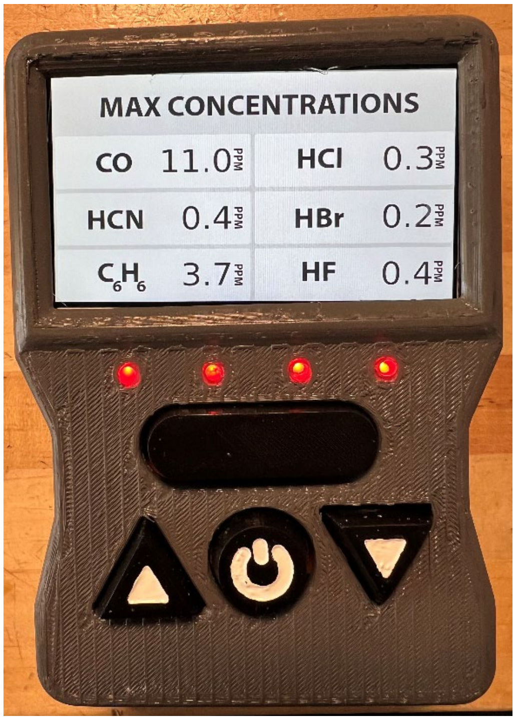


Figure 37: Additional Information Page

7.9 Integration

To integrate the various subsystems into a functional device, the hardware was integrated, followed by the software integration. The fans, screen, and LEDs were glued into the final case for security. The haptic motor was attached to the side of the case. The breadboard buttons were wired and installed into the case. The LEDs were soldered to jumper wires and resistors. They were then attached to the Raspberry Pi. The button caps were then installed onto the breadboard buttons. The speaker was plugged into the Raspberry Pi's 3.5 mm audio jack. The battery was installed and the haptic motor and fans were wired. The case was screwed shut.

To produce the desired device-user interactions, the Raspberry Pi was used to code device output and inputs. The device was coded using a state machine structure. The device contained various states, each representing a set of outputs (See Figure 38). Each state had a predefined set of exit conditions which would be used to transition between states.

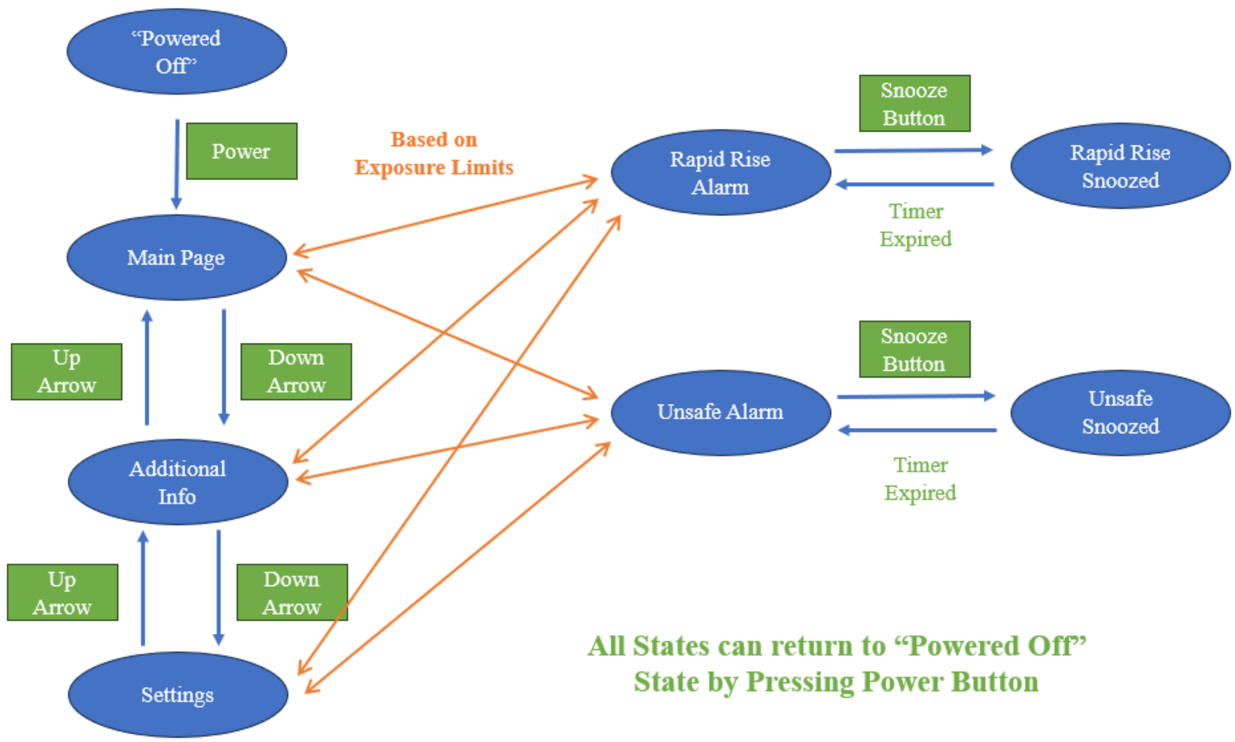


Figure 38: State Machine Diagram

The states include Powered Off, Main Page, Additional Info, Settings, Rapid Rise Alarm, Rapid Rise Snoozed, Unsafe Alarm, and Unsafe Snoozed. The Powered Off state shows the device "turned off". As the device is never truly turned off, the powered off state mimics the behavior of the device being turned off. The screen is black, all the outputs are off. Once the power button is pressed, the device turns on and transitions into the main page. The main page contains all of the main information for the gases. It contains the current concentrations of the gases. While in the main page state, the gases are all at safe levels, therefore the haptic motor, and speaker are off, and the LEDs are green. As the up and down arrows are pressed, the main screen is changed with the additional info, and setting pages, which display the various pages on the screen, while maintaining the haptic motor and speakers off, and green LEDS. If at any time, one of the gases goes over the exposure limits, the device is transitioned into the unsafe alarm state. At this point a warning is displayed on the screen and the LEDs turn red. An unsafe notification sound is played and the haptic motor begins notifying the user (See Figure 39). The device can then be transitioned into a snoozed state by pressing the snooze button. The snoozed state contains the main page, with unsafe displayed on the top. The LEDs are maintained red, but the speaker and haptic motors are silent. After the expiration of the timer (set to 2 minutes per user feedback, but can be adjusted in settings), the device transitions back to the alarming state. The device contains two alarming states based on the gas conditions. The rapid rise alarm signifies that the gas has risen by at least 10% of its exposure limits within one second. The unsafe alarm signifies that the gas has risen above its exposure limit (See Figure 40). The device transitions back to the main page if the gases return to safe levels (See Figure 41).

Figure 39: Unsafe Notification State

Figure 40: Rapid Rise Notification State

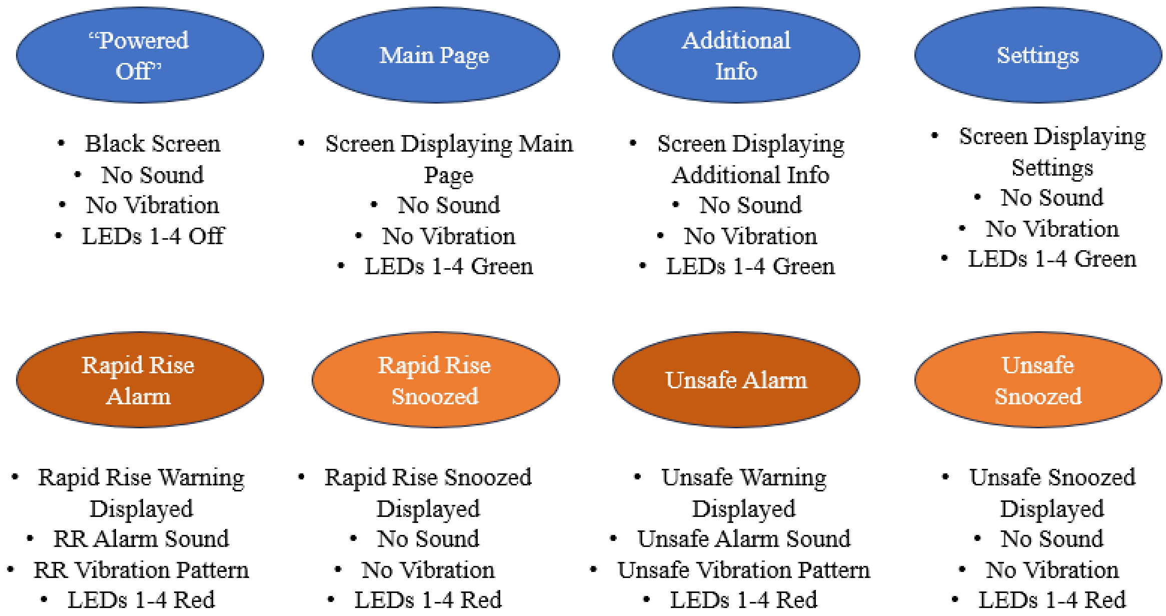


Figure 41: State Function Definitions

The safe and unsafe exposure limits were determined via the OSHA exposure guidelines[18]. The lowest recommended exposure limit for all species were used. These limits should be explored in the future as current limits were chosen as realistic placeholders.

7.10 Cost of System

The device prototype has various physical components that were purchased to increase the sense of realism of the device. The Raspberry Pi, audio amplifier, speaker, haptic motor, fans, display, and power supply were purchased online. The cases and buttons were 3D printed using WPI's prototyping lab. The total cost of the prototype was $113.44 (See Table 6).

Table 6: Cost of System

Product	Item #	Source	Quantity	Price Per Item ($)	Total Cost ($)
Raspberry Pi Model B 2 GB	2648-SC0193(9)-ND	Digikey	1	45.00	45.00
3W Mini Adui Stereo Amplifier	1738-1068-ND	Digikey	1	5.90	5.90
Speaker 80HM 800MW Top Port 88D8	433-1104-ND	Digikey	1	1.82	1.82
Vibration ERIM Motor 3V	1597-1244-ND	Digikey	1	1.20	1.20
2 PCS Brushless Cooling Fan	-	Amazon	1	9.99	9.99
4.3 inch DSI Display	24159	Waveshare	1	24.99	24.99
3000mAh Portable Charger	-	Amazon	1	16.95	16.95
3D Printing Cost	-	WPI	-	-	7.59
				Total	**$113.44**

8 PROPOSED FINAL DESIGN

8.1 DISCUSSION

The prototype developed was for the purpose of displaying the ideal user-devise interaction determined via the feedback from the target market. The final device should be developed with increased care to ensure functionality in the target environment.

The device was 3D printed using PLA filament. While ideal for fast prototyping and budget friendly designs, it is likely not the ideal material for the final device. The deformation temperature of PLA is about 60-65°C [19]. As the temperatures during overhaul conditions were noted by survey participants to regularly be high (See Figure 11), this presents a risk of device deformation. A heat tolerant plastic should be used to prevent damage to the device, while maintaining the manufacturability and low weight of the device.

The device should also be water-proof. Standing water and high humidity was noted regularly during overhaul operations (See Figure 11). This functionality was out of scope of the prototype device, but it should be taken into account that the device will be used in environments where standing water and high humidity will be present. The gas sensing technology and electronics should be safely isolated from the outside environment to prevent damage.

The device should also be tolerant to drops and concussions. As noted by the majority of survey respondents, the device should be tolerant to the harsh conditions of overhaul (See Figure 11), including resistance to drops. As the internal gas sensing technology was not yet ready for deployment, the internal design of the device could not be determined, so the internal concussion resistance could not be designed. The final device should take this into account and ensure the protection of all sensitive technologies inside of the device during concussions.

The gas exposure limits should be revisited by an expert in the field to ensure safety for all users. The OSHA exposure limits were used for the purpose of this project as placeholders. The actual exposure limits should be determined by safety experts to ensure the safety of all users.

The device does not currently contain the gas sensing technology. Therefore, the internal design of the case has not yet been explored. The final device likely should run off of an integrated PCB containing the gas monitor microcontrollers, as well as the microcontrollers to control the function of the device. Possible electrical noise interactions should be explored to ensure the functionality of the gas sensing chamber.

The internals of the final device should also be explored to determine required thermal isolation. The working temperature limits of the internal electronics should be taken into account as the device will be used in conditions where a large possible temperature variation is possible.

The final design of the device should also be evaluated by in person user tests to determine functionality. The device should be presented to members of the fire service to ensure that the device is easy to use. Tweaks to the design should be made to ensure functionality and ease of use for all members of the fire service. As the survey reached mainly senior members of the fire service, care to test usability on less experienced members should be taken to ensure usability during stressful situations.

Though out of scope of the current project, higher quality sound files should be procured for audio feedback. Free audio files were used for this project due to time and budget constraints.

8.2 COST BENEFIT ANALYSIS

This device must improve the safety and effectiveness of firefighters during overhaul operations to justify its inclusion in already heavy and bulky firefighting equipment.

The disadvantages of this device include its weight, size, and gas monitoring limitations. The final device will weight approximately 2 lbs. This will add a burden to the fire service members in their already heavy equipment. The device is approximately the size of a multimeter, and is carried via a carabiner that can be attached to the firefighter's suit. This device takes up additional space, increasing the burden. This device also currently will only likely be able to track six gases. Ideally every harmful gas should be tracked, but due to size constrictions, six is the maximum feasible.

The advantages of this device include its calibration-free design, size/weight to functionality ratio, and usability. This device does not require calibration, a distinguishing feature from all other gas sensors on the market. This prevents the need for the storage of harmful gases for the purpose of frequent calibration tests. The device also tracks more gases than devices of its size due to the novel gas sensing technology. The devices interface has also been developed using direct user feedback to ensure the usability of the interface for all members of the fire service.

As many fire service members endure the same disadvantages with devices with fewer advantages then this device, we believe that the devices pros outweigh the cons of the device. However, at the end of the sensor development cycle more testing should be performed to ensure the advantages of the device outweigh the burdens of the device.

9 CONCLUSION

The goal of this research was to develop an interface for a toxic gas sensing device using end-user feedback. This was achieved over 22 weeks through the following steps. The problem was defined and overhaul conditions were researched. Previous research was reviewed to guide the development of survey questions. Technical questions were developed for the researchers at UCLA to ensure the technology requirements were met. The end-user survey questions were curated to qualitatively determine overhaul conditions, previous gas sensor experience, and interface design preferences and needs. Various screen designs were developed for testing. WPI Institutional Review Board (IRB) approval for human studies was achieved to allow the distribution of the survey.

The survey was then distributed to various firefighter organizations and departments. The survey data was then analyzed using MATLAB to determine trends. The design was then developed using insights gained from survey data. The parts needed for the prototype were determined and ordered. The button, haptic, LED, fan, case, and screen concept tests were performed. Various incompatibilities were fixed in intermediate concept tests. The final prototype was then constructed using various 3D printed parts, and electronic components. The prototype was then programmed to demonstrate desired user-device interactions. This included creating simulated data to demonstrate all functionality of the device.

10 REFERENCES

[1] A. A. Stec, “Fire toxicity – The elephant in the room?,” *Fire Saf J*, vol. 91, pp. 79–90, Jul. 2017, doi: 10.1016/J.FIRESAF.2017.05.003.

[2] J. C. Varone, T. N. Warren, K. Jutras, J. Molis, and J. Dorsey, “REPORT OF THE INVESTIGATION COMMITTEE INTO THE CYANIDE POISONINGS OF PROVIDENCE FIREFIGHTERS,” *NEW SOLUTIONS*, vol. 18, no. 1, pp. 87–101, 2008, doi: 10.2190/NS.18.1.f.

[3] “NFPA statistics - Firefighter deaths.” Accessed: Nov. 09, 2023. [Online]. Available: https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/fatal-firefighter-injuries/firefighter-deaths?l=35

[4] D. M. Bolstad-Johnson, J. L. Burgess, C. D. Crutchfield, S. Storment, R. Gerkin, and J. R. Wilson, “Characterization of firefighter exposures during fire overhaul,” *AIHAJ*, vol. 61, no. 5, pp. 636–641, 2000, doi: 10.1080/15298660008984572.

[5] “Connecticut Fire Academy-Recruit Program Salvage & Overhaul Slide 2 Salvage and Overhaul,” 2014.

[6] “Surveys for UX Research.” Accessed: Dec. 13, 2023. [Online]. Available: https://www.userinterviews.com/ux-research-field-guide-chapter/surveys

[7] “Single Gas Detector | BW™ Solo | Honeywell.” Accessed: Dec. 13, 2023. [Online]. Available: https://sps.honeywell.com/us/en/products/safety/gas-and-flame-detection/portables/honeywell-bw-solo?utm_source=google&utm_medium=cpc&utm_campaign=23-sps-hgas-usa-onesps&s_kwcid=AL!7892!3!646579072269!p!!g!!honeywell%20bw%20solo&https://sps.honeywell.com/us/en/products/safety/gas-and-flame-detection/portables/honeywell-bw-solo%3Futm_source%3Dgoogle%26utm_medium%3Dcpc%26utm_campaign%3D23-sps-hgas-usa-onesps%26s_kwcid%3DAL!7892!3!646579072269!p!!g!!honeywell%2520bw%2520solo&_bt=646579072269&_bk=honeywell%20bw%20solo&_bm=p&_bn=g&_bg=145507823933&gclid=CjwKCAiA3aeqBhBzEiwAxFiOBrTy37vIoTgU91pj4kvavBG8Fv92OuFma2D7-6Kz_EGAtU6Ovj2cHRoCUZ8QAvD_BwE#specifications

[8] “Four Gas Monitor, confined space detector features simultaneous detection of LEL, O2, H2S & CO. World’s smallest and lightest portable multigas Detector. RKI’s high quality safety instrument.” Accessed: Dec. 13, 2023. [Online]. Available: https://www.rkiinstruments.com/product/gx-3r-gas-detector/

[9] “RKI Instruments GX-6000 Gas Monitor | TG Technical Services.” Accessed: Dec. 13, 2023. [Online]. Available: https://www.buygasmonitors.com/rki-instruments-gx-6000-gas-monitor/#tab-description

[10] “Honeywell RAE Systems - AreaRAE Pro.” Accessed: Dec. 13, 2023. [Online]. Available: https://raegasdetection.com/catalog/product/view/id/2739/s/honeywell-rae-systems-arearae-pro/category/140/

[11] “Multi-Gas Detector | MultiRAE | Honeywell.” Accessed: Dec. 13, 2023. [Online]. Available: https://sps.honeywell.com/us/en/products/safety/gas-and-flame-detection/portables/multirae

[12] “RAE Systems QRAE 3 Multigas Monitor - Pumped/CSA/No-Wireless/LEL/Cl2/O2/CO/Accessories Kit - M026-11111-111.” Accessed: Dec. 13, 2023. [Online]. Available: https://www.rae-gasmonitors.com/m026-11111-111.html

[13] "X-am 5100 H2O2, HBr, HCl, HF, HNO3, N2H4, PCl3 or POCl3 gas detector | SafetyGas." Accessed: Dec. 13, 2023. [Online]. Available: https://en.safetygas.com/portable-gas-detector-exotic-gases-xam-5100

[14] "ToxiRAE Pro PID | Honeywell." Accessed: Dec. 13, 2023. [Online]. Available: https://sps.honeywell.com/us/en/products/safety/gas-and-flame-detection/portables/toxirae-pro-pid#resources

[15] "MSA ALTAIR 5X PID Multigas Detector | MSA Safety Shop." Accessed: Dec. 13, 2023. [Online]. Available: https://www.msasafetyshop.com/en/msa-altair-5x-pid-multigasdetector-2

[16] R. Likert, "A technique for the measurement of attitudes," *Archives of Psychology*, vol. 140, 1932.

[17] R. Fahy, B. Evarts, and G. Stein, "U.S. fire department profile | NFPA Research," U.S. fire department profile. Accessed: Feb. 05, 2024. [Online]. Available: https://www.nfpa.org/education-and-research/research/nfpa-research/fire-statistical-reports/us-fire-department-profile

[18] "Permissible Exposure Limits – OSHA Annotated Table Z-1 | Occupational Safety and Health Administration." Accessed: Mar. 31, 2024. [Online]. Available: https://www.osha.gov/annotated-pels/table-z-1

[19] "How PLA Temperature Resistance Compares to Other 3D Printing Materials." Accessed: Mar. 31, 2024. [Online]. Available: https://www.wevolver.com/article/how-pla-temperature-resistance-compares-to-other-3d-printing-materials

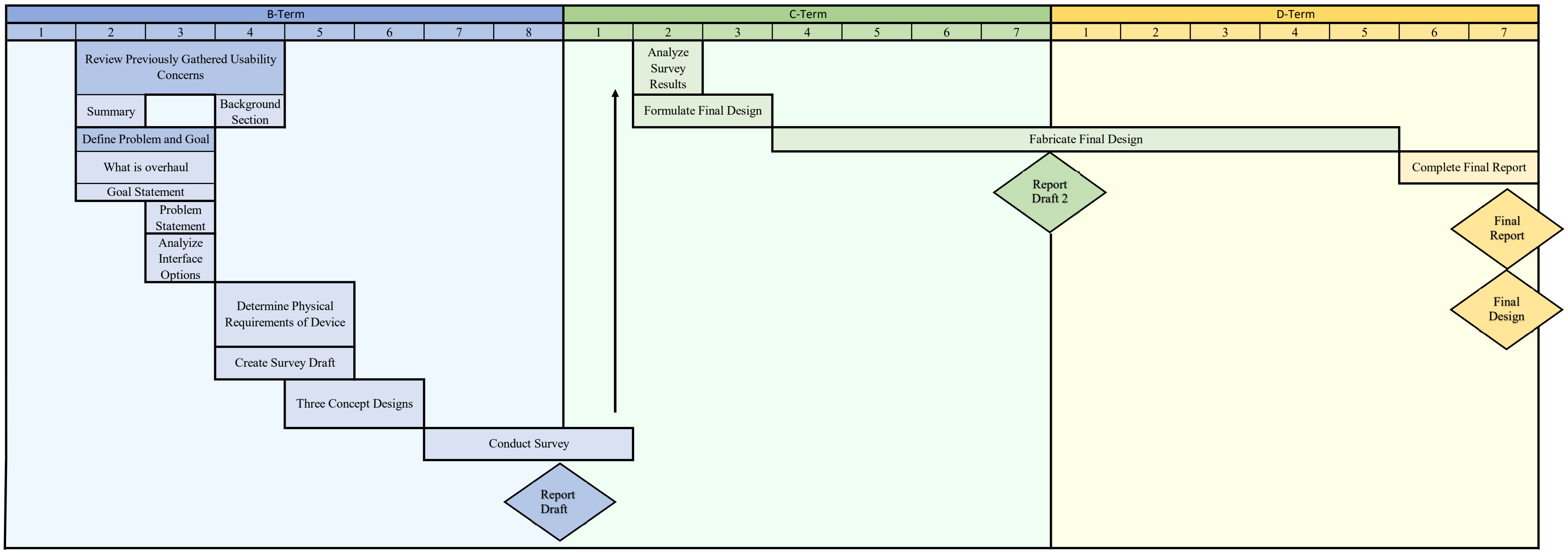
Appendix 1: Other Device Specifications

Device	Price	Source	Data Logging	Gases Monitored	Screen Display	Button				Weight
						Number	Location	Function	Size (Largest Dimension)	
Honeywell BW Solo	$ 563.17	Tequipment	Y	1	Single Number	1	Side	All Control	1.35 cm	0.102 to 0.116 kg
RKI GX-3R Personal Gas Monitor	$ 499.99	RKI Instruments	only alarms and calibration	4	LCD, Values	2	Front	Power / Mode, Air	1.07 cm	0.105 kg
RKI GX-6000 Muli-Gas	$ 3,760.50	Technical Services	Y	6	LCD, Values	5	Front	Lock, Air, Reset, Shift, Power/Enter	2.11 cm	0.397 kg
RAE Systems AreaRAE Pro Gas Monitor	$ 14,364.00	Northside Sales Co	Y	7	LCD	3	Front		2.38 cm	6.50 kg
Mulit RAE	$ 5,240.00	Northside Sales Co	Y	6	LCD	3	Front	Mode, Y/+, and N/-	1.85 cm	0.879 kg
QRAE3	$ 1,457.00	Technical Services	Y	4	Monochrome graphic display	2	Front		2.67 cm	0.411 kg
X-am 5100	$ 1,823.57	Safety Gas	Y	1	Curved Display	2	Front	+, OK	0.83 cm	0.220 kg
RAE Systems ToxiRAE Pro PID	$ 1,217.00	Honeywell	Y	O2, VOCs	LCD	2	Front		1.66 cm	0.235 kg
5X from MSA	$ 2,390.00	MSA	Y	6	Color display	3	Front	Up, Down, Power	1.99 cm	0.453 kg

Device Volume (cm^3)	Attachment Style	Alert Causes	Alert Styles			Battery		Languages Avaliable	Humidity Operating Range
			Visual	Audible	Haptic	Type	Life		
161	Alligator Clip		Lights up red	95 dB	vibrating	Replaceable 2/3AA Lithium battery		11	0% - 95% RH
94	Alligator Clip	3 Increasing alarms, STEL, TWA, overscale alarm, and device malfunction	Flashing LED	continuous buzzer (100 db @ 30 cm)	vibrating	Rechargable Lithium-ion battery	25 hours		10 to 90% RH
664	Belt Clip, Hand Strap	Gas, Man down, and device malfunction	5 LED	95 dB at 1 ft.	vibrating	Rechargable Lithium-ion battery or Alkaline	14 hours for Li, 8 hours for Alkaline	9	0- 95% RH
15925	Handle		Yes	108 dB	vibrating	Rechargeable 7.2 V / 10 Ah Li-ion battery pack with built-in charger Alkaline Battery Adapter	20 hours for Li-ion, 12 hours for Alkaline		0%-95%
1229	Shoulder Strap	Gas, Man down	Yes	Yes	vibrating	Rechargeable Li-ion or Alkaline adapter with 4 x AA batteries	12- 18 hours for Li-ion, 6 hours for Alkaline	19	0%-95%
509	Stainless-steel alligator clip; Swivel belt clip (optional); Pouch (optional)	Man down, pump status, low battery	Flashing red LED's	95 dB at 30cm	vibrating	Rechargeable Li-ion	8-11 hours	18	0% to 95%
334	NA		Yes, 180 degrees	90 dB at 30 cm	vibrating	Rechargable	200 hours		10 to 95 % H. R.
217		Man down	Flashing red LED's	95 dB @ 30 cm	vibrating	Rechargeable Li-ion	12 hours		0% to 95%
629	Belt Clip	Man down	2 ultrabright LEDs on top	95 dB	vibrating	Rechargeable Li-ION or AA alkaline	20 hours	18	15–90 % RH

Temperature Operation Range
-40°C to +60°C
-20°C ~ +50°C
-20°C ~ +50°C
-20°C ~ +60°C
-20°C ~ +50°C
-20° to 50° C
–20 to +50
-20° to 55°C

Appendix 2: Project Timeline



Appendix 3: Usability Survey

Gas Sensor Usability Requirements

To support a project funded by the FEMA Fire Prevention & Safety Grants (R&D), a calibration-free gas sensor technology is being developed for detection of toxic gases during overhaul operations. To ensure that this technology is integrated into an intuitive and easy to use interface, we are seeking fire personnel feedback on the desired functions of a toxic gas sensor.

This survey is to be completed by firefighters of all backgrounds. This survey is confidential optional. No identifying information(names, email, etc.) will be collected. You are not required to take this survey and may stop at anytime without submitting your answers. This survey will take approximately 20 minutes to complete.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: The Gas Sensor Usability Requirements IQP Group (Email: gr-GasSensorInterface@wpi.edu) and IRB Manager (Ruth McKeogh, Tel. 508-831-6699, Email: irb@wpi.edu).

We encourage you to send this form to other firefighters who might be interested in completing the survey.

Demographic Information

1. What is your role in the firefighting community?

Mark only one oval.

- ◯ Career Firefighter
- ◯ Volunteer Firefighter
- ◯ Other: ______________________

2. What is your rank?

Mark only one oval.

- Probationary Firefighter
- Firefighter
- Driver Engineer
- Lieutenant
- Captain
- Battalion Chief
- Assistant Chief
- Fire Chief
- Other

3. How many years of experience do you have in the fire service?

Mark only one oval.

- <1
- 1-2
- 3-5
- 6-10
- 11-15
- 16-20
- 21+

4. What is your age?

Mark only one oval.

- 18-25
- 26-35
- 36-45
- 46-55
- 56-65
- 66+

5. What is your gender identity?

Mark only one oval.

- Male
- Female
- Non-binary/Non-conforming
- Prefer not to say

6. What state are you located in?

____

7. How many (number) structure fires do you typically respond to in a given month? (If unsure please provide your best numerical guess)

____

Technical Requirements

8. Have you ever performed overhaul operations?

Mark only one oval.

- Yes
- No

9. How long do overhaul operations typically last?

____

10. Please check the conditions that are consistent with your experience of overhaul conditions. If there is a condition not specified, please write it in "other" option.

Check all that apply.

- [ ] High Humidity
- [ ] Standing Water
- [ ] Debris in air
- [ ] Smoke
- [ ] High Temperatures
- [ ] Low Temperatures
- [ ] Limited Visibility
- [ ] Other: ________________________________

11. Have you ever used a gas sensor during overhaul operations?

Mark only one oval.

- Yes
- No

12. If so, what gases did you track?

13. What is your interest in a gas sensor that does not require calibration (compared to a sensor that does require calibration)?

Mark only one oval.

	1	2	3	4	5	
Not	◯	◯	◯	◯	◯	Very Interested

14. Rank the following gases on your interest in tracking them during overhaul operations

Mark only one oval per row.

	Not Interested	Indifferent	Interested	Very Interested
Carbon Monoxide (CO)	⬭	⬭	⬭	⬭
Hydrogen Cyanide (HCN)	⬭	⬭	⬭	⬭
Formaldehyde (CH2O)	⬭	⬭	⬭	⬭
Benzene (C6H6)	⬭	⬭	⬭	⬭
Hydrogen Chloride (HCl)	⬭	⬭	⬭	⬭
Hydrogen Bromide (HBr)	⬭	⬭	⬭	⬭
Hydrogen Flouride (HF)	⬭	⬭	⬭	⬭

15. What other gases do you wish to track during overhaul operations?

____

____

____

____

____

16. Rank the importance of the following features for a toxic gas sensor

Mark only one oval per row.

	Not wanted	Indifferent	Nice to Have	Critical
Refresh time less then 5 seconds	⬭	⬭	⬭	⬭
No Calibration Required	⬭	⬭	⬭	⬭
Easy to Use Interface	⬭	⬭	⬭	⬭
Under 2 lbs	⬭	⬭	⬭	⬭
Under 4 lbs	⬭	⬭	⬭	⬭
Small enough to carry on a belt	⬭	⬭	⬭	⬭
Can withstand drops and impacts	⬭	⬭	⬭	⬭
Battery Life over 12 hours	⬭	⬭	⬭	⬭
Battery Life over 6 hours	⬭	⬭	⬭	⬭

Size and Weight Requirements

17. Given a sensor that could measure all above gases, rate your likelihood to carry a sensor of the following weights

Mark only one oval per row.

	Extremely Unlikely	Unlikely	Possibly	Likely	Extremely Likely
Under 1 lbs	⬭	⬭	⬭	⬭	⬭
1-2 lbs	⬭	⬭	⬭	⬭	⬭
3-4 lbs	⬭	⬭	⬭	⬭	⬭
5-6 lbs	⬭	⬭	⬭	⬭	⬭
7+ lbs	⬭	⬭	⬭	⬭	⬭

18. Given a sensor that could measure all above gases, rate your likelihood to carry a sensor of the following sizes

Mark only one oval per row.

	Extremely Unlikely	Unlikely	Possibly	Likely	Extremely Likely
Size of a Deck of Cards	⬭	⬭	⬭	⬭	⬭
Size of a Multimeter	⬭	⬭	⬭	⬭	⬭
Size of a Book	⬭	⬭	⬭	⬭	⬭
Size of a Shoebox	⬭	⬭	⬭	⬭	⬭

19. How would you like to carry this gas sensor?

Check all that apply.

- [ ] Carabiner
- [ ] Alligator Clip
- [ ] Belt Clip
- [ ] Handle
- [ ] Shoulder Strap
- [ ] Other: ______________________________

20. How would you prefer this device to be powered?

Check all that apply.

- [ ] Rechargable Battery (Lithium-ion)
- [ ] Replaceable Batteries (Alkaline)
- [ ] Other: ______________________________

21. How long does this device need to hold a charge?

Mark only one oval.

- ( ) 2-4 hours
- ( ) 5-7 hours
- ( ) 8-10 hours
- ( ) 11-13 hours
- ( ) 14-16 hours
- ( ) 17-19 hours
- ( ) 20+ hours

User Interaction

22. What data would you like to be displayed on the sensor?

Check all that apply.

- [ ] Concentrations of All Gases
- [ ] Above Exposure Limits /Below Exposure Limits State
- [ ] Current Time
- [ ] Temperature
- [ ] Battery Level of Device
- [ ] Basic stats (max over last minute, etc)
- [ ] Other: ______________________

23. Would you like additional pages of information available on the device (beyond main screen with information chosen above)?

Mark only one oval.

- ( ) Yes
- ( ) No

24. If so, what information would you like to see on additional pages?

____

____

____

____

____

25. What concentration data would you like displayed?

Check all that apply.

- [ ] Molar concentrations (ppm)
- [ ] Percentage of OSHA exposure limit
- [ ] Other: ______________________

26. What stats would you like to view, beyond the current reading?

Check all that apply.

- [ ] Maximum concentration over last minute
- [ ] Maximum concentration since device was turned on/ reset
- [ ] Average concentration over the last minute
- [ ] I would not like to view any other stats
- [ ] Other: ______________________________

27. When would you like to be notified by the sensor?

Check all that apply.

- [ ] Conditions exceeding exposure limits
- [ ] Rapid Rise conditions
- [ ] Low battery of device
- [ ] Conditions returning below exposure limits
- [ ] Other: ______________________________

28. How would you like to be notified in the following conditions?

Check all that apply.

	Visual	Audio	Device Vibration
Conditions exceeding exposure limits	☐	☐	☐
Rapid Rise Conditions	☐	☐	☐
Low Battery	☐	☐	☐
Conditions returning below exposure limits	☐	☐	☐
Other	☐	☐	☐

29. How would you like to be notified visually?

Check all that apply.

- ☐ Change in screen display
- ☐ Solid LED
- ☐ Flashing LED
- ☐ I would not like to be notified visually
- ☐ Other: ______________________

30. How would you like to be notified audibly?

Check all that apply.

- [ ] Beeping/alarm
- [ ] Voice detailing warning
- [ ] I would not like to be notified audibly
- [ ] Other: ____________________

31. How would you like to be notified through device vibration (until user dismissal of warning)?

Check all that apply.

- [ ] Continuous vibration
- [ ] Pattern of vibration
- [ ] Repeated vibration (for example, every 30 seconds the device vibrates)
- [ ] Single vibration
- [ ] I would not like to be notified through device vibration
- [ ] Other: ____________________

32. Would you prefer a colored screen display, or a black and white screen display?

Mark only one oval.

- ( ) Colored
- ( ) Black and White
- ( ) No Preference

33. How would you like to interact with the device?

Check all that apply.

- [ ] Buttons/ switches
- [ ] Control from phone/ remotely
- [ ] Touchscreen
- [ ] Other: ______________________

34. If you would like to use buttons, what size of buttons are required for easy use?

____
____
____
____
____

35. Are you interested in the ability to snooze or dismiss notifications? (For example, a notification of unsafe conditions, but a SCBA is being worn)

Mark only one oval.

- ( ) Yes, snooze button (will renotify after a set period of time)
- ( ) Yes, dismisal button (notifications will be paused until a change in state)
- ( ) Neither

36. If interested in a snoozed state, how long would you like it to last before re-notifying?

____
____
____
____
____

37. Are there any other features you want in a gas sensor?

Example Screen Interfaces

This section seeks feedback on some screen interface mock-ups. All questions in this section are **optional**.

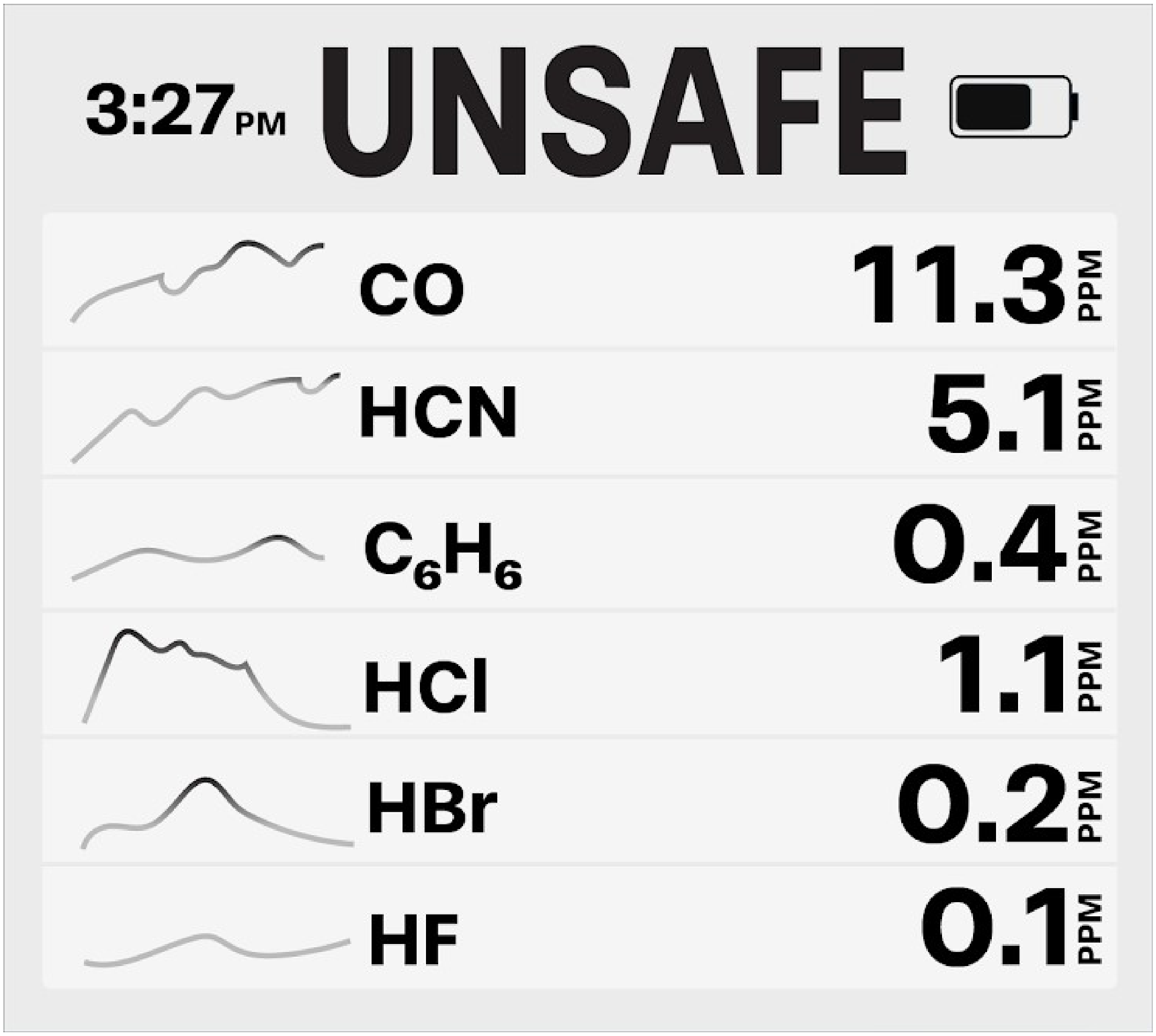
Please note all numbers used are fictitious

38. Which screen design do you like the most?

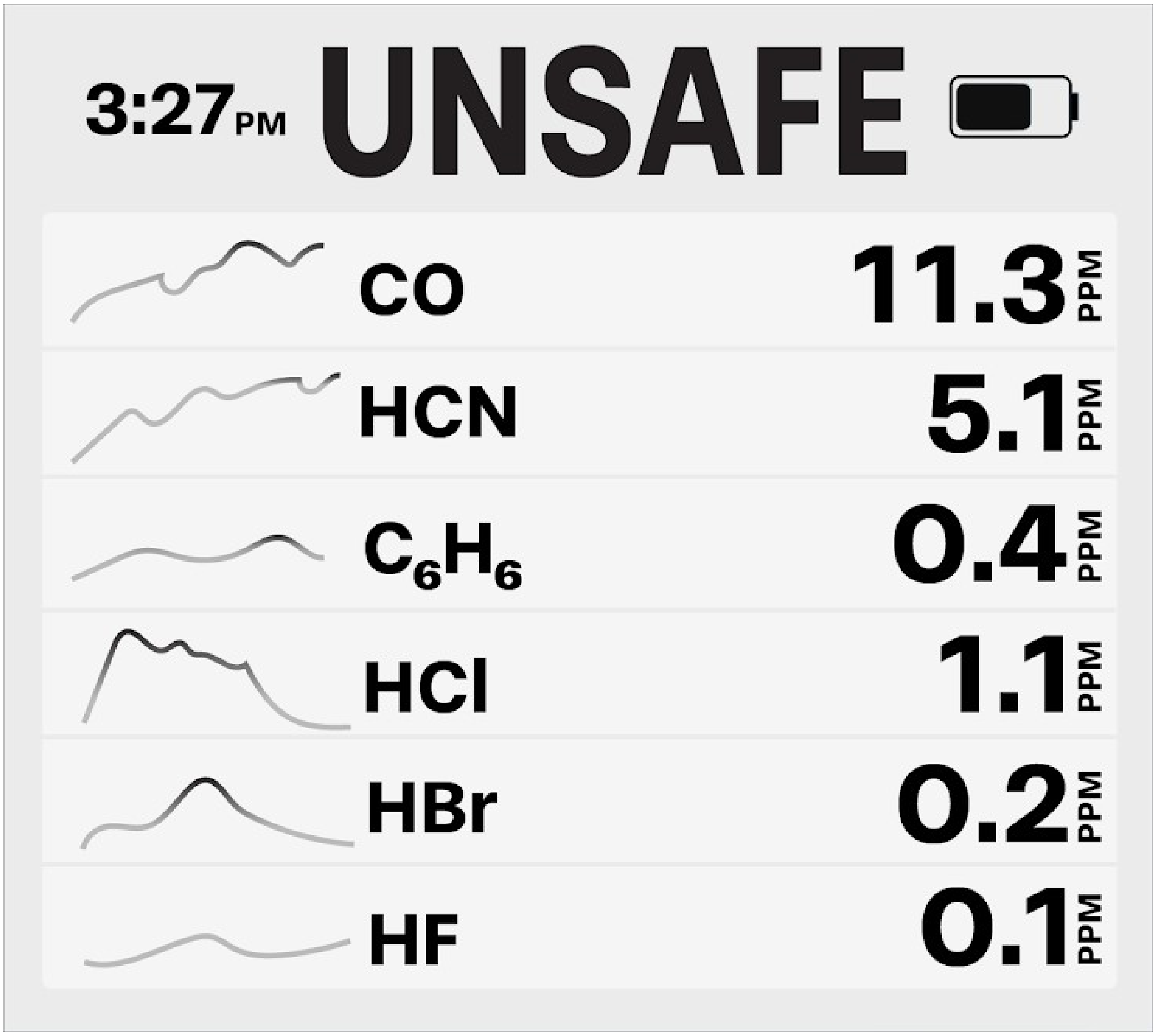
Mark only one oval.

- 1
- 2
- 3
- I do not like any of the options(please specify why below)

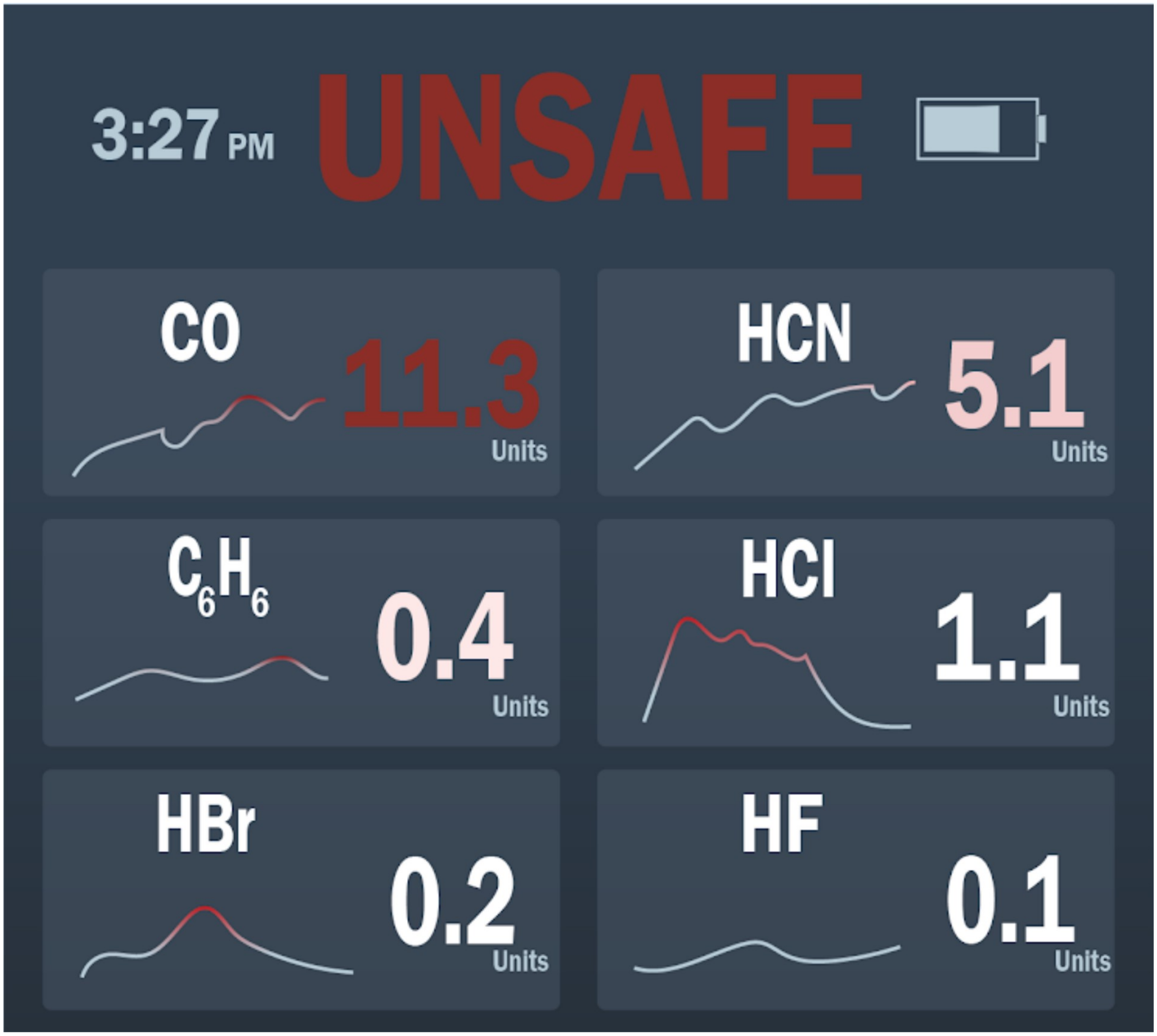
39. For the interface screen design shown below, what features do you **like**?



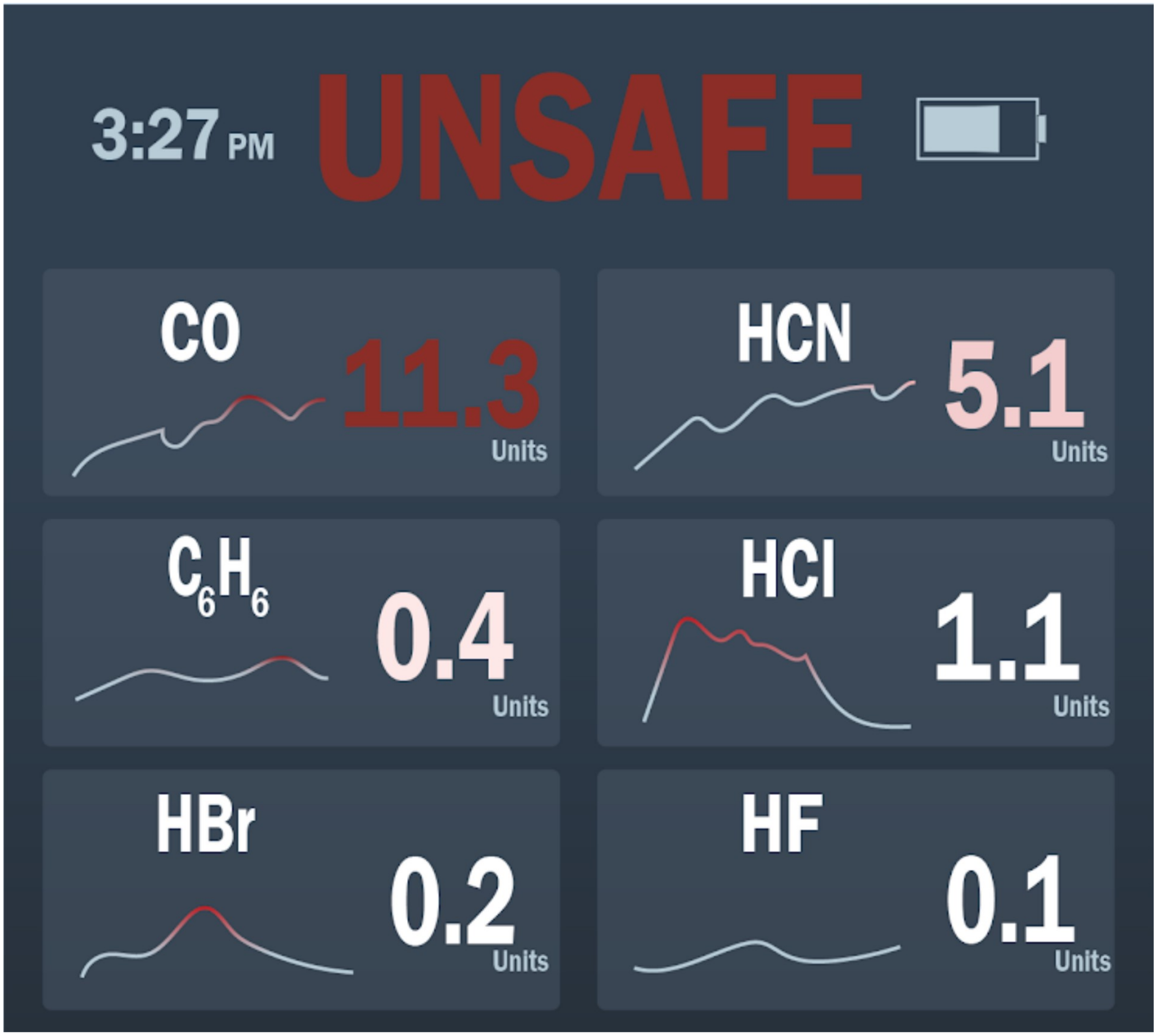
40. For the interface screen design shown below, what features do you **dislike**?



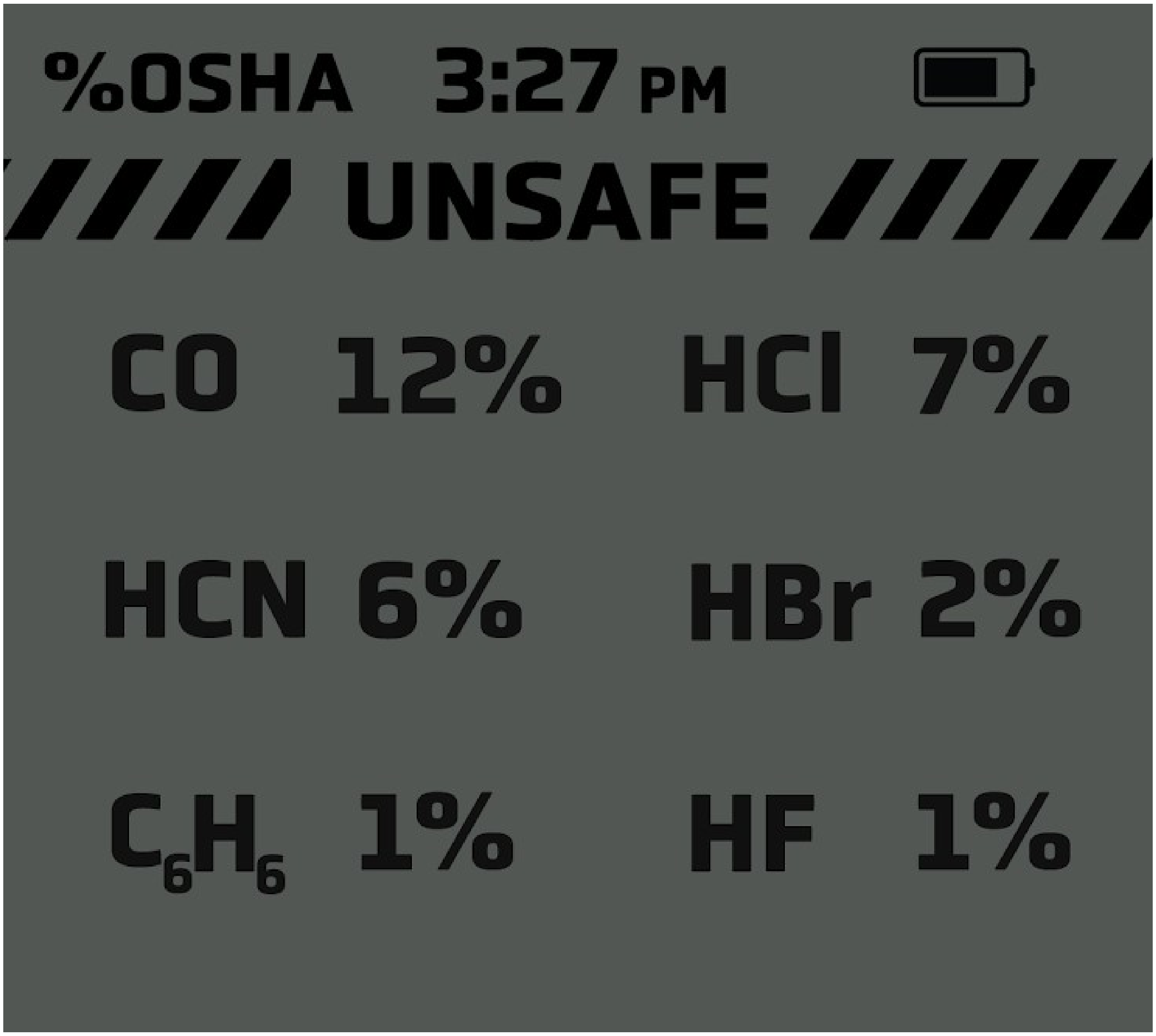
41. For the interface screen design shown below, what features do you **like**?



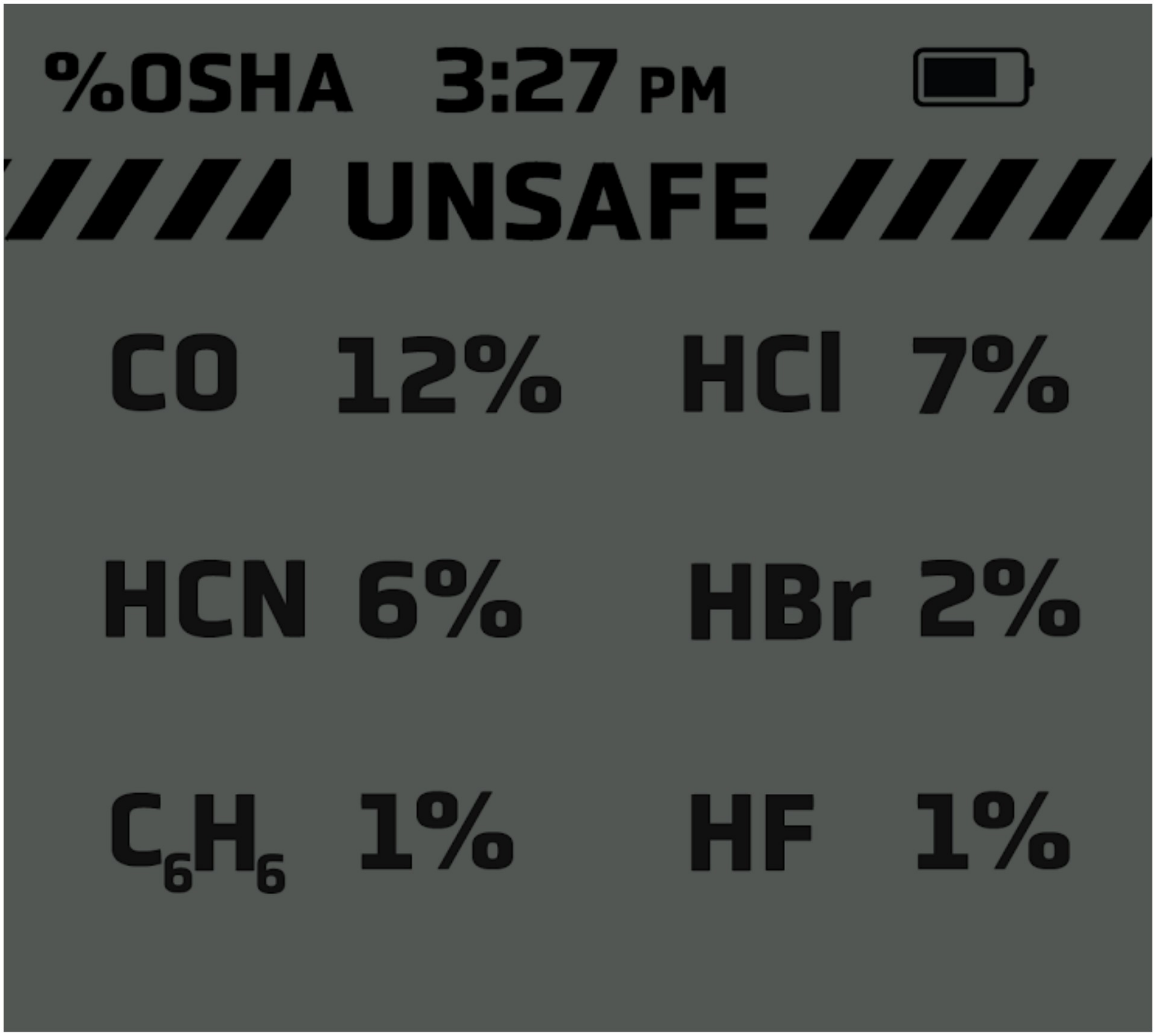
42. For the interface screen design shown below, what features do you **dislike**?



43. For the interface screen design shown below, what features do you **like**?



44. For the interface screen design shown below, what features do you **dislike**?

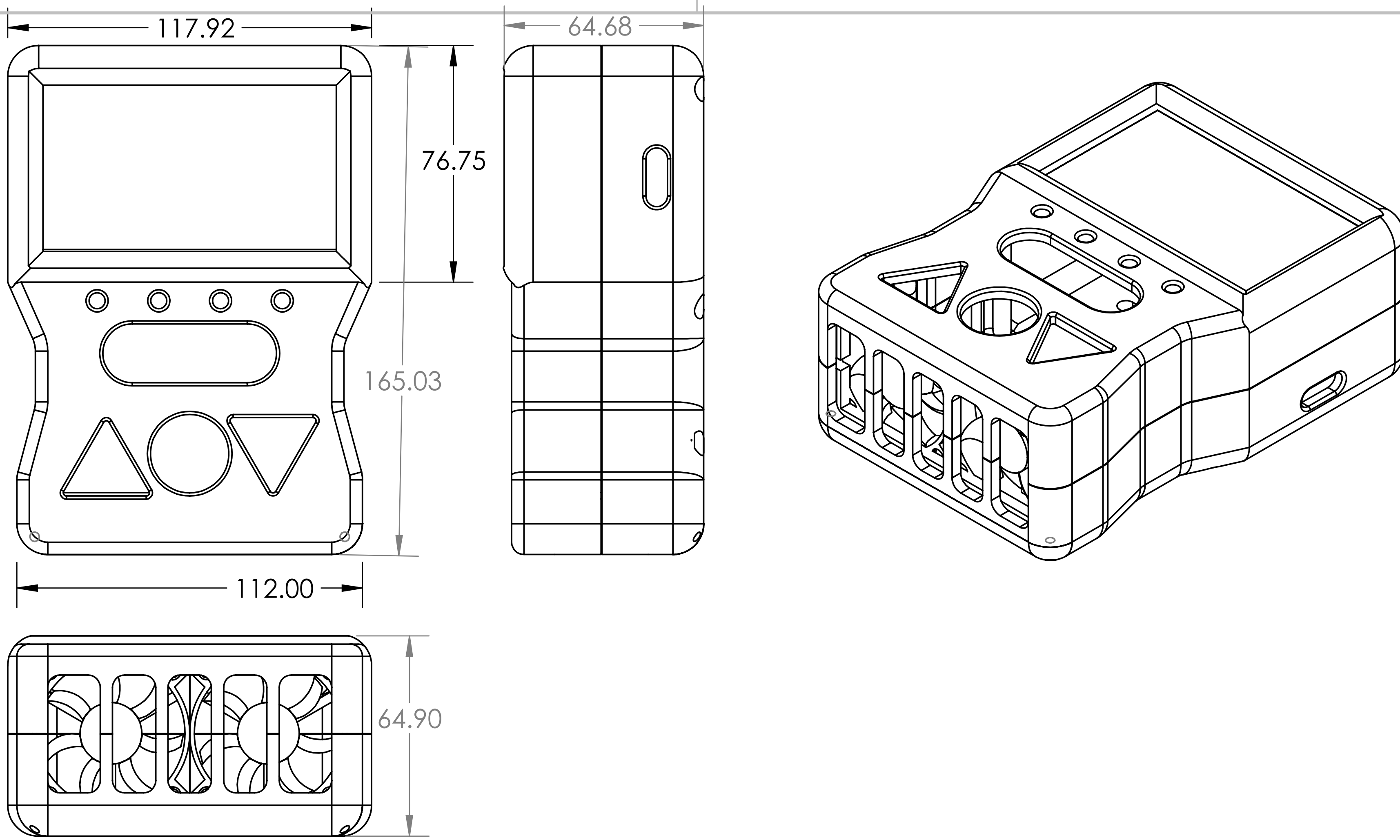


Appendix 4: Technology Survey

Sensor Device Technology Requirements

1. **Device Dimensions and Layout**
   - What is the estimated weight of the ideal end user device?
2. **Circuit Design and Power Needs:**
   - What are the expected power consumption considerations or requirements for the device?
   - What are the current computational needs for the device?
     - What is the hardware currently being used for computations?
     - What hardware is expected to be used for computations for the final prototype?
     - Benchmark hardware (raspberry pi)
   - What is the data output of the device?
   - Is electromagnetic interference a concern?
     - If so, what components should be isolated to prevent issues?
3. **Airflow Requirements**
   - What are the airflow requirements for the device?
     - Are there expected to be multiple cells? Will they be configured in series or parallel?
     - How much airflow is required for the device? What is the flow rate required?
   - Is a filter needed for the functionality/ longevity of the device?
     - Does particulate matter need to be filtered out?
     - If so, are there specific filters that will not interfere with the accuracy of the device?

Appendix 5: Case Model



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NEXT ASSY	USED ON
APPLICATION	

UNLESS OTHERWISE SPECIFIED:

DIMENSIONS ARE IN MILIMETERS
TOLERANCES:
FRACTIONAL ±
ANGULAR: MACH ± BEND ±
TWO PLACE DECIMAL ±
THREE PLACE DECIMAL ±

INTERPRET GEOMETRIC TOLERANCING PER:

MATERIAL
PLA

FINISH

DO NOT SCALE DRAWING

	NAME	DATE
DRAWN	SL	2/13/2024
CHECKED		
ENG APPR.		
MFG APPR.		
Q.A.		

COMMENTS:

TITLE:
Gas Sensor

SIZE	DWG. NO.	REV
A	Gas Sensor	1

SCALE: 1:2 WEIGHT: SHEET 1 OF 1