Design of a Stimuli Delivery System for Awake Animal Neuroimaging Regimes

A Major Qualifying Project Report
Submitted to the Faculty of
Worcester Polytechnic Institute

In Partial Fulfillment of the Requirements for the
Degree of Bachelor of Science
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April 19, 2018

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Table of Contents

Abstract

Treating brain disorders requires a deep understanding of neural mechanisms which is often accomplished through functional neuroimaging of awake animal test subjects. The purpose of this project was to aid in this area of research by developing a system that could reliably and semi-quantitatively deliver airborne stimuli to test subjects undergoing MRI regimes to visualize the effects on relevant neural pathways. The system was divided into three main components for research and development purposes: stimuli delivery, quantification, and evacuation. To reliably deliver stimuli, a compressor and a computer-actuated series of solenoid valves were used with a pressure regulator and flow meter to precisely deliver airflow to a downstream odor bank. This odor bank consisted of a double-sided rack capable of holding 4 vials per side. The 4 vials on the front side of the odor bank were designed to be loaded with liquid stimuli and the second set of vials on the back were left vacant to collect any liquid stimuli that may escape the first set. Air was pumped through the stimulus to infuse it with odor and carry the odorized airstream to the test subject. The flow rate of the delivery airstream could be altered by the user to adjust the strength of the resultant odor. Quantification of the system was performed by determining the mass of the substance that had been dissipated during each testing sequence. Multiple odorants of differing volatilities and chemical structures were chosen to create a range of representative behaviors. Smoke testing was performed to confirm that air passing by the subject was then filtered and released back in the environment. Initial results show that the system is capable of delivering up to 4 air-borne stimuli sources to the test subject in a semi-quantified amount. Between stimuli introduction cycles, this system successfully purged odors to reduce confounding factors. Future uses for the device include research into addiction and fear mitigation as well as commercial uses involving scent marketing and virtual reality.

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8	Conclusions and Recommendations	Jonathan	All

Acknowledgments

The team would like to thank the following individuals for their guidance, expertise, and assistance on the project:

Abbreviations

BBL-IS	Brain and Behavioral Laboratory – Immersive System
CCNI	Center for Comparative Neuroimaging (CCNI)
CFM	Cubic Feet per Minute
D	Diameter
DALY	Disease Adjusted Life Year
EN	Electronic Nose
Fd	Friction Factor
FID	Flame Ionization Detector
fMRI	Functional Magnetic Resonance Imaging
GC-FID	Gas Chromatography coupled with Flame Ionization Detectors
GC-MS	Gas Chromatography coupled with Mass Spectrometry
GLC	Gas-Liquid Chromatography
GSC	Gas-Solid Chromatography
HVAC	Heating, Ventilation, and Air Conditioning
L	Length
MDE	Major Depressive Episode
MRI	Magnetic Resonance Imaging
MS	Mass Spectrometry
N2O	Nitrous Oxide
NIOSH	National Institute for Occupational Safety and Health
PET	Positron Emission Tomography
PID	Photo-Ionization Detector
PM	Particulate Matter
PPM	Parts per Million
PTFE	polytetrafluoroethylene
PTSD	Post-Traumatic Stress Disorder
Re	Reynold's Number
Roe	Density
SAMHSA	Substance Abuse and Mental Health Services Administration
SMI	Serious Mental Health Illness
SPME	Solid-Phase Micro Extraction
TMT	Trimethylthiazoline
TWA	Time Weight Average
UMASS	University of Massachusetts Medical School
v	Kinematic viscosity
Vel	Velocity
VOC	Volatile Organic Compound
WHO	World Health Organization
3D	Three Dimensional
4D	Four Dimensional

Table of Figures

Tables of Tables

1. Introduction

According to the 2016 edition of the annual Substance Abuse and Mental Health Services Administration (SAMHSA) report, an estimated 18.3% of adults in the United States suffered from a mental illness in that reporting period. Of those 44.7 million adults, 23.2% suffered from a serious mental illness (SMI), representing a total of 4.2% of all adults in the United States. The same report determined that, in the age group of 18 to 25-year-olds, the percentage who suffer from an SMI has been experiencing a sharp increase since 2013, as seen in Figure 1.[1]
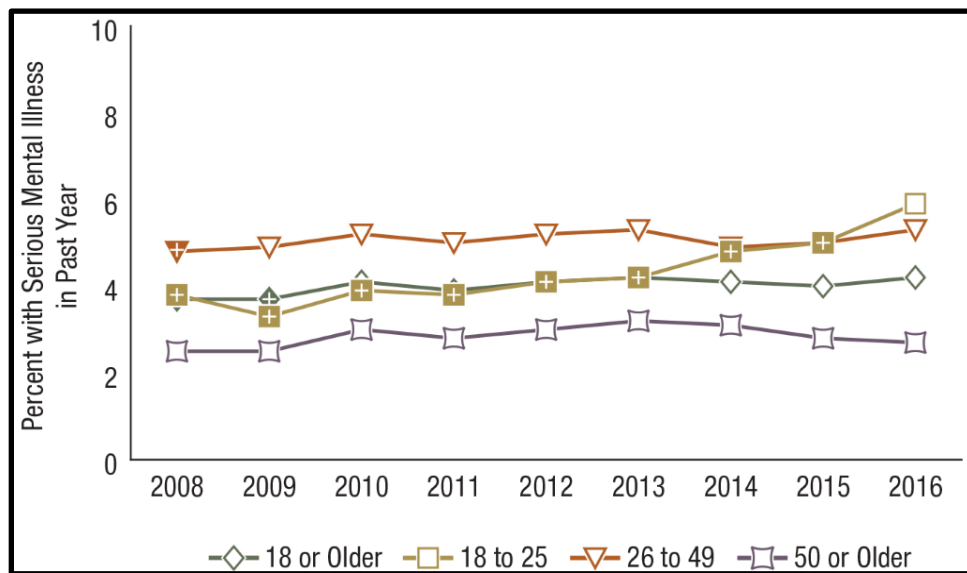
Figure 1: This graph, compiled by the SAMHSA, shows the yearly trends concerning the percentage of US citizens who suffer from a severe mental illness. The data is separated into age groups, and shows a dramatic increase in young adult cases in recent years.[1]

An even more startling statistic states that the 12-month prevalence of major depressive episodes (MDEs) in adolescents increased from 8.7% in 2005 to 11.3% in 2014.[2] These trends of serious mental disorders becoming increasingly ubiquitous in the lives of younger generations

are alarming, and require further inquiry to determine the causes and attributing factors of mental illness.

To further investigate this growing issue, neuroimaging will be an indispensable tool. However, a thoroughly regimented and effective solution cannot be devised without first understanding the way neurological issues are expressed in the brain. Accomplishing this task will require the use of neuroimaging to characterize the regions of the brain and brain pathways involved with mental illnesses and neurological disease states.

The Center for Comparative Neuroimaging (CCNI), a research group at the University of Massachusetts (UMass) Medical School Department of Psychiatry, is a small but influential entity operating in this field. Their research is among the first of its kind in mapping and characterizing the neural pathways of awake animal subjects, which is an essential step in creating a more accurate representative model of human brain functions. Their current endeavors are focusing on identifying the effects of nicotine and menthol on addiction and the subsequent effects on the brain. A reliable method for this type of stimuli delivery is currently lacking in the testing procedures at the CCNI.

In their current approach to MRI testing, the CCNI begins by preparing an anesthetic solution and administering it to the test subject in the preparation room. After administration, the test subject is inspected to ensure that it is asleep before it is loaded into a specially designed restraint system. The test subject is held in this container and the entire apparatus is inserted into the MRI machine. After 15-20 minutes, the test subject begins to gain consciousness, and once it is fully awake, testing may begin. Depending on the specific goal and procedure of the test, stimuli are introduced to the test subject using an odor-soaked piece of gauze attached to a yardstick. Throughout the test procedure, MR imaging is used to detect and analyze which parts

of the brain are responsible for recognizing and processing odors. Between administrations of different stimuli, an evacuation system composed of a lab vacuum and a tube is used to extract excess odor and clear the testing environment for the next stimuli.

While this procedure may deliver acceptable results, there are many areas of improvement that can be focused on. The first of these improvements concerns the method of stimulus delivery. In the current system, a human facilitator must present the stimuli to the subject, which introduces a wide variety of unmeasured variables including the exact time of stimuli delivery, the proximity of the stimuli to the subject, and the quantity of stimuli deposited on the gauze stick. This procedure then raises the question of exactly how much stimuli has entered the specimen's system and how much lingers in the container. In addition, there is no way to tell if the facilitator's physical presence near the test subject presents a confounding variable which could affect the conclusions drawn from neuroimaging. Lastly, using the current scavenging system, there is no way to accurately measure if all of the previous odor stimuli have been removed from the testing area.

To aid in the CCNI's research, the team was tasked with designing and developing a stimuli introduction system for use in awake animal model MRI testing, in an attempt to increase the accuracy of their current test method. The team must also characterize this system's ability to reproducibly deliver the odor stimuli in a controlled manner. Finally, the reliability and effectiveness of the system will be evaluated throughout a suite of experimental setups. Encompassing these needs and the objectives of this project, the team's end goal as stated by the CCNI will be to "design, develop, and characterize an odor delivery system for an MRI subject holder that enables the precise delivery of one or more odors during MR imaging regimes."

Our approach to creating a reliable and quantifiable olfactory delivery system can be broken up into three main components: research, ideation, and testing. After identifying the needs and objectives of the clients, the team outlined that the final design must include a method to control the duration of odor delivery, the saturation of odor, and the number of odors delivered. There are many odor delivery systems currently on the market that fulfill some, but not all, of these needs. The team researched existing solutions and components, such as pumps and sensors, that could perform these necessary functions. As a result of research, prototypes of possible designs will be created and evaluated based on performance and efficiency. An appropriate air pump, odor bank, and system of tubing will then be selected to control the duration of odor delivery. The number of odors capable of being delivered during one scan was identified based on the needs of the CCNI and the corresponding number of odor banks and tubes will be included in the design. The team also designed the tubing to optimize odor delivery and prevent cross-contamination among odors. Team members then created and performed tests to demonstrate the success of the design and its capacity to fulfill the outlined objectives of the CCNI. After validating individual design elements and constructing a final device which fulfills all of the client's needs, the group would then be able to work towards optimizing the device to accomplish the client's wants and reach goals. Advice will also be given to the CCNI on improving the efficacy of the design for future research goals.

2. Background

2.1 Project Need

As stated in a 2006 World Health Organization (WHO) report, roughly one billion people in the world in 2005 were affected with some type of neurological disorder.[3] To put this statistic into perspective, the estimated total world population at the time of this study was roughly 6.5 billion people, which means that nearly one in six people in the world were battling some form of neurological disease.[4] The sheer number of affected individuals resulted in more hospitalizations and a greater loss in productivity than any other disease group, including cardiovascular diseases and cancer. In terms of resources, neurological diseases account for roughly 11% of the world's disease burden, costing the United States alone roughly $500 billion a year in treatment costs.[5] Trends have shown that the prevalence of neurological diseases and the effects that they have on society are on the rise. A 2016 report on global disease burdens stated that from the time of the 2006 WHO report to 2016, the disease adjusted life years (DALYs) associated with neurological disorders increased dramatically. The two largest spikes in this area were attributed to Alzheimer's and Parkinson's disease with increases by 37.5% and 35.6%, respectively.[6] Additionally, as the global life expectancy rises due to improved medical practices, neurological issues are expected to become a larger and more prevalent concern. In order to combat these trends, it is clear that there needs to be a better understanding of the human brain, and how functional pathways are affected by different neurological disease states. To achieve these goals, the field of neuroscience will play a vital role in identifying and characterizing pathways in the brain that are affected by various disease states.[5]

2.1.1 Neuroimaging

One of the most important tools in the discipline of neuroscience is neuroimaging, a term that encompasses numerous methods for scanning and creating three-dimensional (3D) representations of the brain and related structures comprising the nervous system. The advent of imaging technology allowed scientists to observe not only the anatomical aspects of the brain, but also its functional role in various processes. There are many techniques and technologies involved in the process of neuroimaging ranging from positron emission tomography (PET) to functional magnetic resonance imaging (fMRI).[7] While these imaging processes are helpful in diagnosing neurological disease states and brain damage in humans, it is often valuable for researchers to use animal models in their imaging experiments. Animals, specifically mice and rats, are frequently used for such experiments due to the similarities in their anatomy with humans, and the comparatively lower costs associated with animal testing.[8]

2.1.2 Animal Imaging

In many regards, animal brains, particularly mammalian, share several of the same anatomical structures with humans. However, certain animals make more compatible models than others. For this reason, different animal models are chosen depending on the purpose of the study. The most commonly used mammalian species in the field of neuroscience research is the rodent. Rodents share many of the same neurological features with humans and are cost effective alternatives to human neuroscience imaging. Additionally, mice and rats have a typical lifespan of less than two years, which translates to comparatively short lifelong tests that can expose the effects of aging. One drawback of using animals for neuroimaging tests is that animals move when restrained, which can cause motion artifacts in the resultant MRI data.[9]

Generally, researchers anesthetize animals to prevent movement during neuroimaging, although this method limits the type of research that can be performed. For example, unconscious animals typically do not react to stimulus introduction, so using anesthetics prevents any testing that involves stimulus introduction. Additionally, certain types and concentrations of anesthesia can affect fMRI results by altering the hemodynamic readouts of the tests. The primary anesthetic used by the CCNI, isoflurane, is a volatile anesthesia that can increase baseline cerebral blood flow.[10] The combined effects of anesthesia and the fact that unconscious animals have limited testing abilities results in limited use of animals in neuroimaging research.

2.1.3 Awake Animal Imaging

To overcome the shortcomings of unconscious animal imaging, researchers have devised methods that allow neuroimaging modalities to be used on awake animals while reducing the motion artifacts present in the resultant images. Several methods exist involving both invasive and non-invasive procedures to produce similar results. A 2016 report published in the Journal of Neurophysiology described a method for imaging awake rodents that involved a surgical procedure implanting a head post fixation system, pictured in Figure 2.

The rodent subjects were first anesthetized in preparation for a surgery where a square nut was cemented to their craniums with an orthodontic resin. The nut acted as a head post which was attached to a fixation system that was then loaded into the MRI bore for testing. The rodents were given a week of recovery time after the surgery and underwent an acclimation procedure for 8-10 days. Acclimation involved being handled by researchers, exploration of the testing environment, loading into the testing apparatus, introduction to the stimuli, and becoming familiar to the confined space and noise of the MRI. To minimize the effects of helplessness, or stress associated with confinement, experienced by the subjects, a small dental stick was

included in the head restraint portion of the testing apparatus. This bar was able to restrict minor

head movements, but would break for larger movements, thus allowing the subjects to free

themselves when experiencing discomfort. Once the subject became acclimated and more

comfortable with the restraint system and testing procedure, imaging accompanied with stimulus

introduction was conducted.[10]
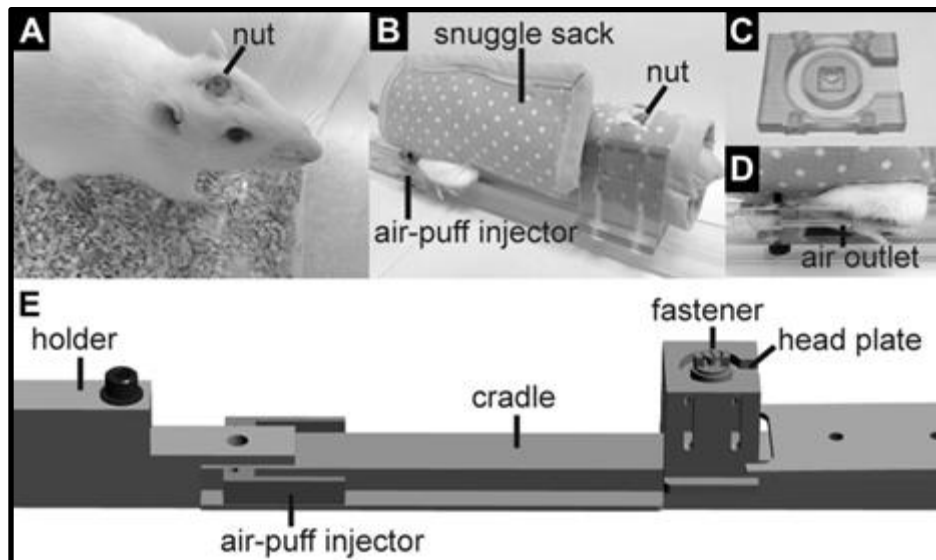
Figure 2: Testing apparatus used in an experiment tasked with finding a novel method for functionally imaging awake animal subjects with minimal restraints.[10]

Less invasive methods of imaging awake animal subjects also exist, as exemplified by the

team's client, the CCNI. The research group used a similar acclimation process as in the method

outlined previously, though the restraint system used was much less invasive. Rather than using a

bone screw to limit movement, a novel device designed by Insight Neuroimaging Systems was

used to restrain the subjects without restricting respiratory movement. A headpiece with a bite

bar and supports that can be lightly inserted into the ears minimized cranial movement to reduce

motion artifacts in the scans.[11][12] The custom-built restraint system prototype used by the CCNI

can be seen in Figure 3. Using the aforementioned restraint systems, conscious animal modeling

has the potential to change the landscape of neuroimaging research.
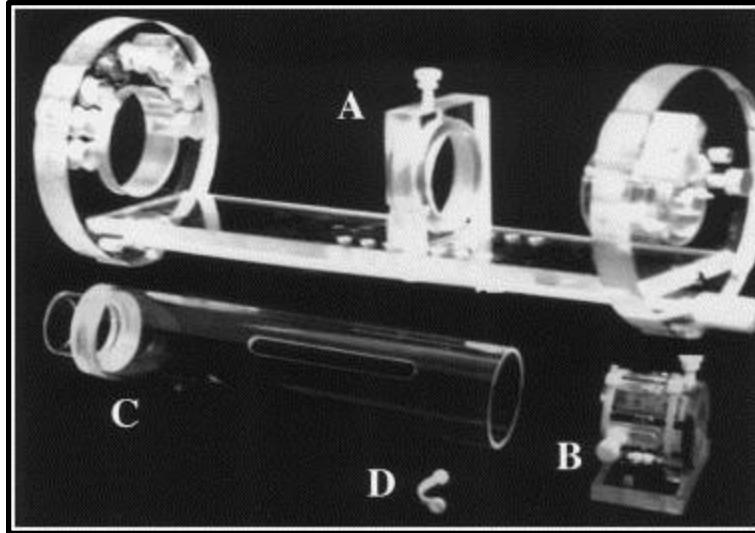
Figure 3: Various components of the unique restraint system created for the CCNI by Insight Neuroimaging Systems. A signifies the mounting unit for the head and shoulder holders to be attached. Point B represents the head holder which contains slits for ear bars, which are shown at point D. Component C is the subject's body holder which fits through the mounting unit and is attached at one end to the head holder.

2.1.4 Odor in Neuroscience

Regardless of the species being subjected to neuroimaging sequences, sensory stimulation plays an important role in neuroscience. Among all of the senses, olfaction has been identified to have the strongest emotional connection and can also be linked with memory. The olfactory bulb, a neural structure which processes smell, is connected to two sections of the brain that are highly link with memory and emotion: the hippocampus and amygdala.[13] As a result, olfaction has been a crucial tool in the study of neuroscience, specifically with reference to understanding the interactions between the parts of the brain responsible for stimulus sensation and emotional processing.

One study analyzed the connection between olfaction, emotion, and memory by creating episodic memories in the test subject using odor markers. Episodic memory is the snapshot of a moment in time. When a person recalls this snapshot, they are generally able to define the what

is the smell, where it was located and the context of that situation. However, time is not the only marker when someone recalls a moment. Emotion, semantic knowledge, visual, auditory and olfactory stimuli can also be the main marker of a moment. For example, an individual could interact with and identify the smell of a candle located in a store. Upon smelling the candle again, the individual could report details of the event. In this way, odors are linked with the identification, location, and context of a memory. In this study, subjects were shown a landscape portrait in which sections of the image were circled. Test subjects could randomly choose these circled parts of the picture and a corresponding odor would then be delivered, thereby encoding the odor with a memory of that part of the picture. Four days later, the test subjects were then presented with all of the odors randomly and were asked if they recognized them. If they recalled an odor, they were then asked to elaborate on the context in which they recognized it. The ability to recall memories is influenced by the emotional content of the odor. Positive and negative odors cause a high rate of memory retrieval and recognition of odors and neutral odors have a less effective recall rate.[14]

Because of their link to memory, odors in neuroscience can be useful tools to understanding the brain's functionality. Odor can influence learning ability, identify neuropsychology and olfactory dysfunctions, and be linked to pain and comfort in relationships. They signal when animals are stressed, sickly, or ready to mate, as well as many other states of emotional well-being. These odors can therefore be used in testing to simulate these situations and analyze the neurological response.[15][16]

While the field of odor neuroimaging may be relatively new, researchers around the globe are making strides in proving that odor is an indispensable sensory facet to understanding the brain. Due to the intertwining of the areas of the brain responsible for processing olfactory

information with those responsible for emotion and memory, two mental processes that are frequently affected my mental disorders, odor is of particular interest to many researchers in the area of neuroimaging.[17] For example, in 2005 a team of Canadian researchers used odor stimuli with positron emission tomography (PET) to analyze the effects of stimuli on the ability of a subject to visualize odors. This study used neuroimaging with odor stimuli in a step to understand the interconnectedness between various neural pathways, in an attempt to further characterize how sensory information work in tandem.[18]

Another research team in 2004 used functional magnetic resonance imaging (fMRI) machines to analyze subject responses to odorants. Many odors were used during testing, but each subject had a particular odor that was strongly associated with a memory. When these unique odors were exposed to the individuals who associated them with a specific memory, the amygdala and hippocampus areas of their brains showed increased activation. This research was integral to furthering the understanding of the amygdala's role in memory organization and could not have been demonstrated as effectively without the use of odor stimuli introduction with neuroimaging models.[19]

2.1.5 Role of the Client

The Center for Comparative NeuroImaging is the primary client for the team's project. As a subsection of the University of Massachusetts' Department of Psychiatry, the researchers at the CCNI work to further understand mental illnesses and other neurological diseases through imaging.[20] The CCNI is one of the foremost laboratories using awake animal neuroimaging models to aid in their research. The facility was one of the first to not only reliably use awake animal models to conduct their fMRI research, but to also characterize and fully define an awake animal functional brain pathway. The CCNI has made their mark on the field of functional neuroimaging using conscious animal models and their unique fMRI restraint system.[21] Past research endeavors include identifying the functional fear pathway in rodents, characterizing pathways involved with arousal, and analyzing the differences in fear processing between genders.[22][23][24] Due to the similarities between rodent and human brains, these studies have vast implications in the fields of human anxiety disorders (including phobias, depression, and PTSD), attachment issues, and other subsets of neurological disorders. To perform their next suite of experiments focusing on addiction, the team at the CCNI requires a stimulus delivery and quantification system that can be used in their MRI room.

2.1.5.1 Summary of the Client's Previous Work

The CCNI was established in 2001, initially to augment the understanding of how the brain changes as a result of mental health disorders such as addiction, anxiety, and depression, through research on animal models. The CCNI namely utilizes functional magnetic resonance imaging (fMRI) to analyze the brain. The group has performed general preclinical research in many areas, including analyzing the effects of brain trauma on functional brain connectivity in rat subjects.[25] In this study, rats with brain trauma and rats without brain trauma were tasked

with mentally engaging activities such as performing a beam walk and solving a maze. For analysis, fMRI tests were run to study the cerebral anatomy. Studies like this one aim to identify the brain connections that are damaged during trauma in an effort to diagnose the resultant effects. The CCNI has also imaged the brain activity of rats while inducing emotional stress in the form of a predatory scent.[24] In the study, female rats in various states of the estrous cycle were put into plastic containers, and exposed to 100 uL of odor, such as water, lemon, or trimethyl-3-thiazoline (TMT), which is the odorous compound associated with fox urine, and is used to represent predatory scents. The study observed that rats in the estrus phase showed significantly higher fear responses in the brain compared to subjects in other cycles. Ultimately, the goal of the study was to establish relationships between fear responses and resultant brain activity. In 2007, the CCNI's focus shifted to translational studies that incorporate clinical human imaging research with animal research in an attempt to identify the similarities between the two models and to use the abundance of animal data as a way of bolstering the less common human data. Currently, the CCNI is interested in research centered on the study of neural networks that are associated with mental health disorders, multimodal imaging, and a determination of the usefulness of complementary or alternative medicines for use in modifying emotional and cognitive networks. In this regard, the CCNI conducts numerous addiction experiments that are characterized and analyzed through brain activity visualizations. For example, a recent study from the group focused on addressing the role that mentholated cigarettes play in addiction.[26] The study used rats as subjects and injected them with nicotine, menthol, and a combination of the two. MR imaging was then conducted. The researchers were able to find that menthol, in addition to nicotine, worked to increase the symptoms of addiction in the tested subjects. Moving forward, the CCNI expects their research to add to the level of

understanding concerning the brain and neural networks, which will lead to further identifying and defining the causes of mental disorders and the development of novel treatments.

2.1.6 Current Limitations

Although they have used stimuli delivery techniques in their previous research, the CCNI's next set of experiments focusing on parental attachment will involve odor and fine particulate matter acting as stimuli. Previous attempts at these experiments involved using scented gauze or an aquarium pump for stimuli introduction. For experiments using liquid-based odors, the researchers dipped a piece of gauze in the source of the scent, and then attached the gauze to a yardstick for delivery to the subject within the MRI bore. For aerosolized odors, they used a 30-gallon Whisper brand aquarium pump to facilitate the movement of the gaseous odor through a series of tubing. The tubing terminated with a nose cone surrounding the animal's snout both to ensure proper delivery of the stimuli and to prevent large amounts of stimuli from escaping the system. However, these methods lack reproducibility and reliability since the amounts of stimuli they deliver cannot be easily quantified.

Odor quantification methods in general are still in the developmental stages as research tools, since odorous compounds are difficult to isolate and detect for prolonged periods. The last two decades have seen improvements in ambient air odor quantification as concerns over air quality have risen, but the processes used to accomplish this task still have their drawbacks. Even the standardized objective method of odor quantification, dynamic olfactometry, has limitations that restricts the types of testing it can be involved with. The technique, which uses a device to dilute odors with specified concentrations of ambient air and presents those mixtures to a panel of analysts, is expensive and includes the human olfactory system for analysis. Although a large sample of analysts is likely to minimize subjectivity, the fact that odors cannot be quantified

without utilizing the human sense of smell greatly limits the type of research olfactometry can be involved with. Other methods like electronic noses and gas chromatography coupled with mass spectrometry (GC-MS) are often limited in the number and types of odor that they can detect, and cannot relate a quantitative measure of odor with the qualitative parameter detected by the patient or subject.[27] Although no singular method is accepted as demonstrating total versatility, accuracy, precision, and objectivity, the limitations of one method can often be removed from the experimental design, or multiple methods can be combined for one analysis. In the following sections, methods that are currently available on the market or documented in academia for delivery, quantification, and evacuation of odor and fine particulate matter are discussed. Through researching and analyzing the strengths and limitations of each method, the team will be able to identify key components that will factor into the later design considerations section.

2.2 Existing Solutions

There are several devices in existence that are designed to deliver controlled odors to a test subject in MRI testing environments with elements of quantification or evacuation included. Some have been developed with human testing in mind, while others are dedicated to animal testing. The level of control and quantification vary between devices, as well as the types of stimuli delivered.

2.2.1 Systems Used in Research

2.2.1.1 Odor Delivery for MRI Testing

Research groups have made many strides in odor delivery and quantification systems, some of which even including methods for evacuation. For example, a university research group in Brussels produced a computer controlled and automated delivery system with the purpose of

delivering odors to human test subjects in a 3-Tesla MRI to create an olfactory response. The system setup can be viewed in Figure 4. The equipment used in this system consists of several main components including a compressed air and flow velocity source, flow controls, tubing, a subject interface and odor "lubrificators," which are described later in this section. In order to create a system which did not interfere with the operation of the MRI, all equipment aside from the subject interface tubing and mask was housed outside of the MRI room. This system could utilize either an oxygen air tank or a hospital HVAC system to push pure air through the system at a rate of 15 L/min. The flow of air was then manipulated to pass through one of the five inert nylon tube branches: four tubes of which led to an oil lubrificator, and one led directly to the human participant to deliver pure air. The direction of flow was controlled by solenoid valves and a flowmeter. These five nylon tube branches then met inside the MRI room and were all connected to a 30 mm Teflon tube, which then led to the test subject. A removable medical mask was used to cover the subject's nose and deliver the odor. An evacuation system used to purge the odor from the MRI bore was not included in this setup, since the system was designed to be used with the same set of four odors, thus reducing the need for contamination prevention. Instead, this system was designed with the purpose of being compact, portable, inexpensive, and easy to replicate. It also contained a comprehensive user interface, in which a LabVIEW program could be modified to adjust the operation of tests.[28]
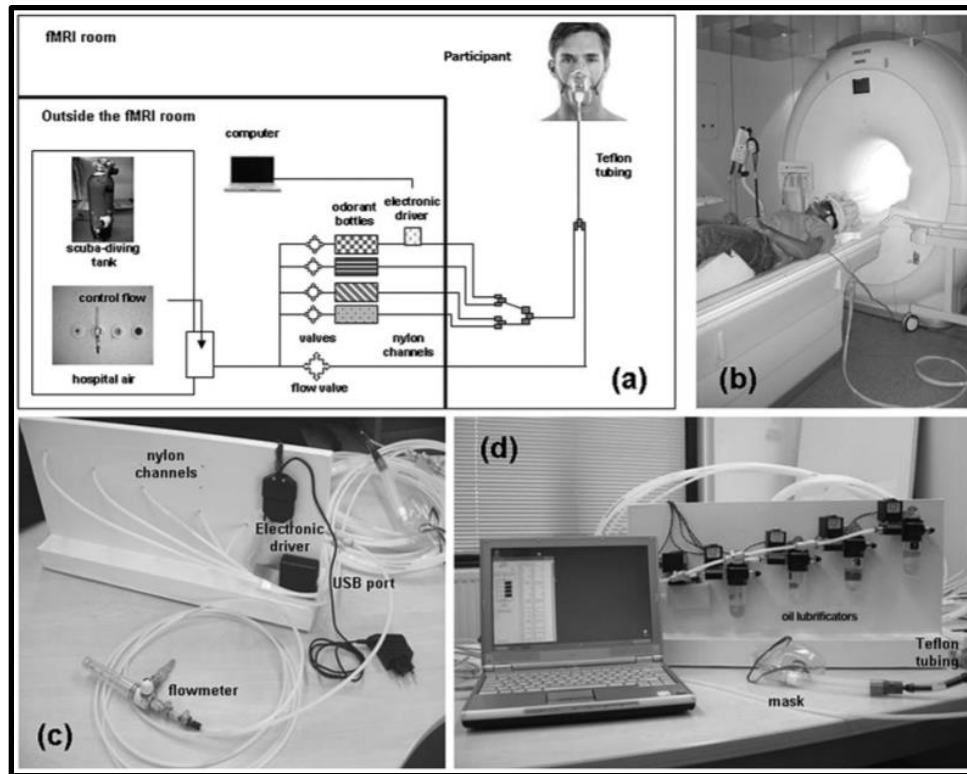
Figure 4: Laboratory setup of computer automated odor delivery device. [28]

The test also included the use of auditory signals sent to the test subject, which allowed the delivery of odor to be synchronized with the breathing rate of the test subject, leading to optimal patterns of odor delivery. This was done by providing the participant with headphones which delivered a sound indicating when it was appropriate for the person to breathe in or breathe out. The odors were released one second before the person was instructed to breathe in. This control of the test subject's respiration is beneficial to the precise and timely delivery of odor. If odor was delivered to the subject while they were exhaling, they would not perceive the full effect of the odor, and the corresponding neuroimaging results would be associated with error. This is a level of control which is not possible with animal subjects due to the lack of control over respiration. A concern with this method of respiration control among human test subjects is that introducing auditory stimulation could provide a confounding factor in the data

collected on the brain's activity. Also, forcing a breathing pattern on the test subject might cause them to focus on breathing and therefore not represent the normal functionality of the brain.[28]

The test setup for the validation of this device included the delivery of four odors: lemon, lavender, banana, and rose to two male test subjects. Each run of testing was made up of seven alternating periods of odor delivery and pure air delivery lasting for thirty seconds each, which can be seen in Figure 5. During the period of odor delivery, six odor samples were randomly chosen from a pool of four odor types in the odor bank and were delivered with a duration of two seconds per stimuli. The system would then deliver pure air to ensure that the subjects would experience a noticeable change in their neuroimaging scans. This testing procedure was repeated four times, each with a different permutation of the set four odors.[28]
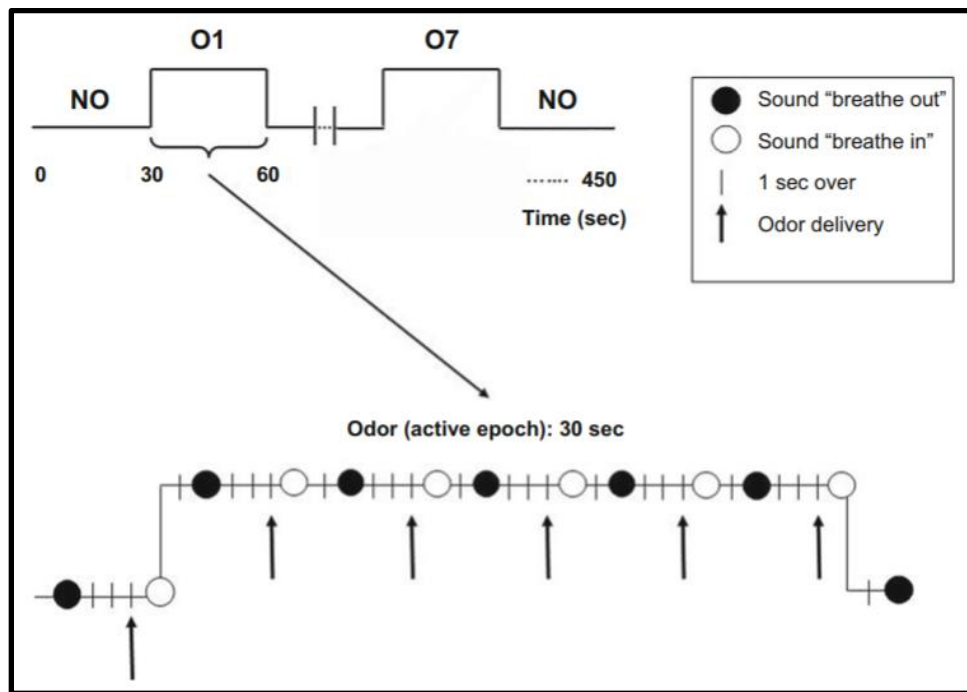
Figure 5: Diagram of odor delivery phases. [28]

The oil "lubrificators" in the design were used to aerosolize and introduce the four odors into the airstream. The four odors were diluted using mineral oil at a concentration of ten percent

and were prepared in 5 mL samples. These odors were kept constant throughout the entire testing

sequence and were kept in their own dedicated lubrificators. One concern with using repeated

odors for the whole duration of these tests is the possibility of odor habituation among the human

test subjects, thereby limiting the effects of the odors on the olfactory response. Residue in the

tubes is also a possible problem. While the lubrificators where cleaned between tests, the tubes

were not causing the possibility of contamination in the case of using multiple odors in one tube.

Therefore, Teflon throughout the entire system is a better solution as it does not retain odor

residue on the sides of the tubes.[28] This system was proven to perform as expected and was able

to activate olfactory sections of the brain, as shown in Figure 6.
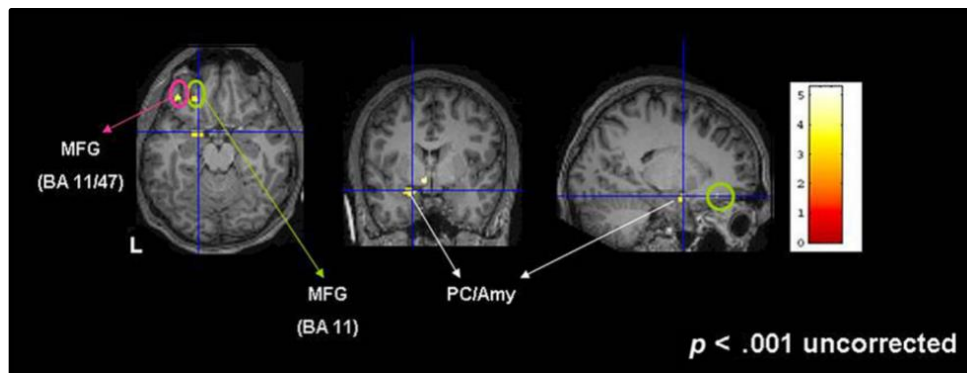
Figure 6: Activation of olfactory regions of the brain as a result of odor delivery. [28]

2.2.1.2 Smoke Delivery for MRI Testing

A second example of a comprehensive stimuli delivery system was developed with the

purpose of delivering smoke to a test subject in an MRI. Smoke is generally prepared for

delivery in a much different method than odors are typically treated and is comprised of

particulate matter rather than volatile organic compounds. Smoke is a challenging stimulus to use

due its tendency to become stale quickly. Becoming stale refers to the fact that it cannot be prepared in advance and then stored away for use at a later date. Smoke must therefore be produced at the time of delivery. Additionally, the particulate matter of smoke sticks to many surfaces and causes contamination which requires constant cleaning. Therefore, an effective evacuation unit is crucial. In addition to these issues, production of smoke is difficult in an airstream due to the low flow threshold at which smoke can be extinguished.[29]

To address these challenges, the team developed a system which contained many of the same components as mentioned in previous studies. A representation of this device can be seen in Figure 7. This device utilized an aquarium pump to push air through the system at a rate of 0.8 L/min. The air was first filtered through an activated charcoal filter, and then a high efficiency particulate arresting filter, to catch any particles expelled from the initial filter. Three solenoid valves were then used to control the flow of air, and two flow meters were used to measure this flow. A combination of polytetrafluoroethylene (PTFE) tubing, glass vials, and Teflon tubing were used to guide the flow of air. Teflon was used at the end of the system, due to its low retention rate of aerosolized compounds.[29]
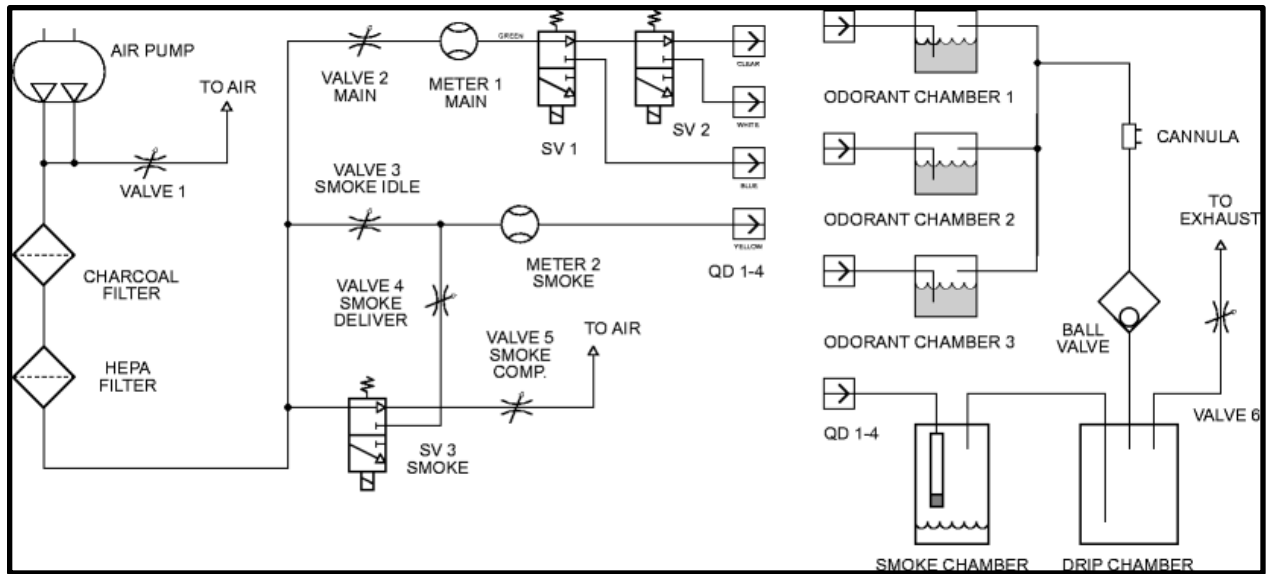
Figure 7: Wiring schematic of a smoke delivery system for an MRI. [29]

There are two main directions of flow. One path directs flow to three different odorant chambers which would then converge into one tube and be delivered to the cannula and the test subject. The second path directed flow to the smoke chamber. Cigarettes were extinguished when the flow rate passing through the flame was lower than 0.25 L/min. Therefore, a flow of 0.3 L/min was maintained through this path and increased to 0.5 L/min at the delivery point to the subject. The smoke chamber contained a lit cigarette and a small pool of water at the base to ensure safety. After the air flowed through the smoke chamber and received concentrated particulate matter from the cigarette, the air then traveled to a drip chamber, which had two points of exit. To deliver this smoke to the test subject, the smoke traveled through a smoke switch. This component was made up of two glass funnels placed together to form a seal and contained a PTFE ball. The ball provided a pressure seal and only allowed smoke to pass through to the cannula when the flow rate into the switch was 0.5 L/min or higher.[29]

This system was designed for human test subjects with the purpose of studying the effects of smoke inhalation on normal brain processing and be seen in Figure 8. It was successful at

delivering both smoke and odor volatiles to the test subject although contamination was determined to be an issue, similar to the design discussed in the previous section. The same odors were used throughout testing and the tubing that would be interacting with the odors for the longest length was made of PTFE. Only at the end of the system, when separate odor tubes converged to be delivered to the cannula, was the tubing made up of Teflon. In order to limit contamination of the odor volatiles on the tubing, the use of Teflon throughout the system would be beneficial.[29]
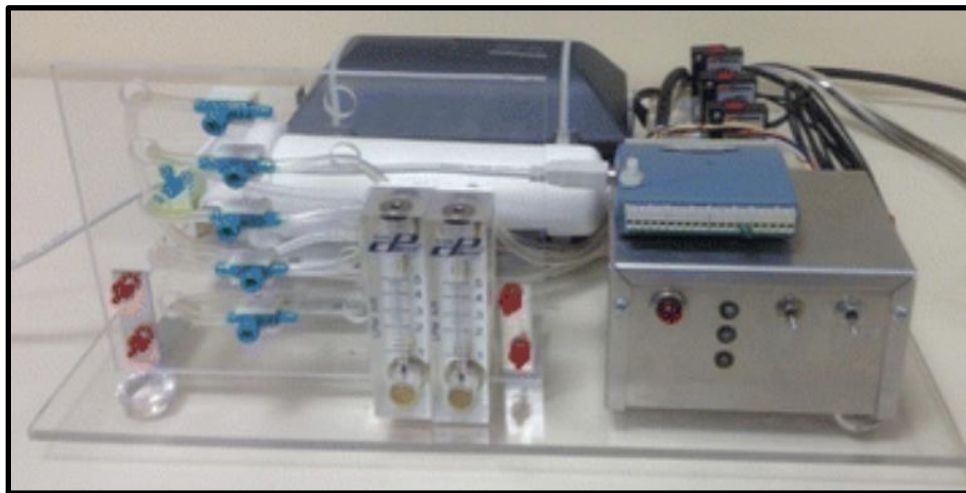
Figure 8: Smoke machine and odor volatile delivery system. [29]

2.2.1.3 Hood Method Delivery System

In a report by the Swinburne Institute of Technology in Australia, an odor delivery system for humans was discussed that differed dramatically from the two previously discussed. The apparatus was referred to as the "hood system" by the Institute and consisted of four main components: an air pump with a flow rate regulator, an aromatiser, an oxygen therapy hood, and an exhaust fan, shown in Figure 9. In the experimental set-up, an odorless carrier gas, in this case air, was continuously forced from the air pump through the regulator device at a known, constant

flow rate. The flow rate was pre-determined by measuring the exact breathing rate of the human volunteers so that the air being pumped was enough to support breathing yet not so forceful as to hinder natural respiration. Essential oils stored in the aromatiser were then vaporized in a known amount and introduced to the carrier stream forming a measurable concentration of air and odor. This combination was then removed through an attached plastic tube through an odor inlet valve to an oxygen therapy hood fitted around the human volunteer's head. The hood consisted of a transparent, vinyl covering affixed to a ring that fit snugly around the volunteer's neck with surgical latex trim. After the volunteer breathed in the air-odor mixture, an exhaust fan removed the expired air at the same rate as the incoming stream. Thus, in a small compartment with a known flow rate and odor concentration, the researchers were able to roughly measure the amounts of stimuli each volunteer was being exposed to and the correlating olfactory responses.[30]
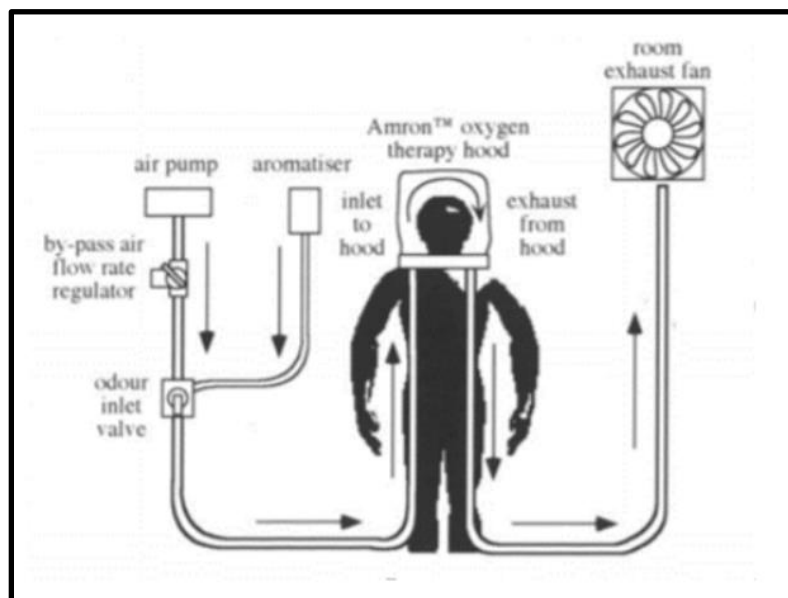
Figure 9: A schematic from the Swinburne Institute of Technology depicting the hood system on a human volunteer. [30]

This system was capable of direct stimuli delivery to the volunteers as well as easy setup and maintenance due to the limited number of components and simple design. However, the hood system did not fully quantify the precise number of odor molecules being introduced into the test subject's system. In the last decade, researchers have worked to eliminate this issue through the implementation of photoionization detectors (PIDs) into their stimuli delivery systems. These PIDs are capable of measuring the concentration of volatile compounds indiscriminately, and, when paired with a chromatography column, can identify concentrations of specific compounds.[31] PIDs are discussed in more detail in Section 2.2.4.1.

2.2.1.4 Time Varying Odor Delivery Method

In a 2016 study, researchers utilizing this PID technology developed a system to present time varying odor stimuli to test subjects. In their experimental set-up, solenoid valves were used to control air flow through one of six glass bubbler vials containing undiluted, liquid odors. Once the carrier air stream was saturated with an odor, it was twice passed through a 10x dilution process to bring the final odor concentration down to 1%. This dilution process entailed the use of additional solenoid valves that released streams of filtered air at 5 L/min to dilute the odor saturated gas. With this process complete, the 1% odor saturated gas was then delivered to the test subject in pseudo-random pulses to mimic the varying nature of natural odor introduction. Throughout the system, flow meters (Kurz Instruments, 490 I-S) were used to measure air flow rate and upon exit of the system, a PID (Aurora scientific, 200B miniPID) was used to characterize the concentration of odor.[32] Components of the system can be seen in Figure 10.
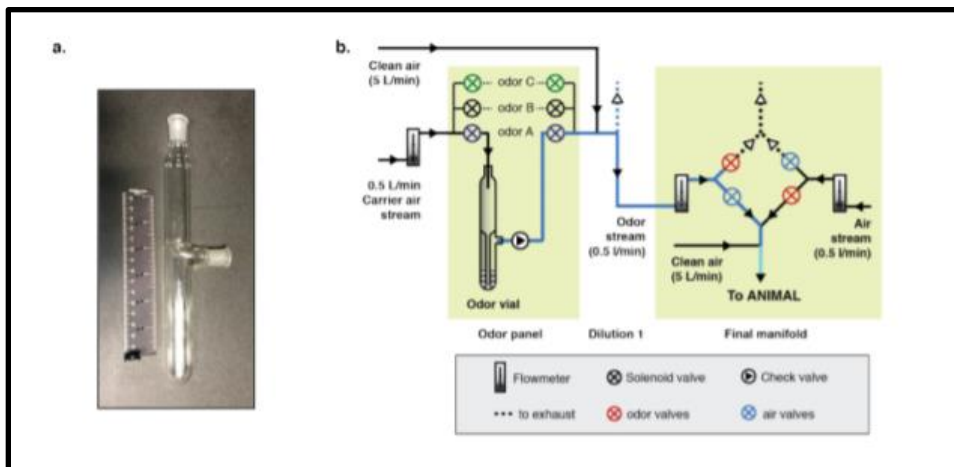
Figure 10: Glass bubbler vials containing undiluted, liquid odors are shown on the left and the solenoid valve schematic is depicted on the right.[32]

To reduce the effect of pressure transients during the dilution process, a low starting flow rate of 0.5 L/min was used. However, fast airflow kinetics were needed for timely delivery of the stimuli to the test subject. Thus, the dilution air streams utilized high flow rates of 5 L/min. To further aid in quick and accurate stimuli delivery, the researchers used short lengths of tubing between the solenoid valves, narrow diameter tubing, and a small distance between the exit of the system and the animal's nostrils.[32]

2.2.1.5 Immersive Odor Delivery System

Another system with a different research purpose but very similar components was the "Brain and Behavioral Laboratory – Immersive System" or BBL-IS built by a team of Swiss scientists and pictured in Figure 11. This system utilized an external air compressor to send a carrier stream of gas to an array of 32 computer-controlled solenoid valves. Before it reached these valves, it passed through two sets of charcoal filters to prevent external contaminants and a flow meter that measures the flow rate. Once the carrier stream reached the solenoid valve array, the operator could select which valve to open and allow the gas to travel through a limiter and on

to the odor bank. This odor bank consisted of a set of glass vials filled with odor-soaked tampons

that were able to evaporate and fill the vial with the odor. The carrier gas then entered the

specified vial flushing out the odor, which traveled along the tube to the cannula attached to the

subject's nose. The cannula and nasal prongs were carefully sized so as not to obstruct natural

breathing, and once the expired air was breathed out, an evacuation system routed it out of the

testing area. In this study, the evacuation unit consisted of two components, a main extraction

module situated above the subject's head and a second smaller unit attached next to the subject's

neck. This combined approach allowed for greater accuracy in removal of confounding odors. To

measure the amount of stimuli being presented to the subject, a PID (miniPID 200B, Aurora

Scientific Inc.) was attached to the exit of the cannula.[33]
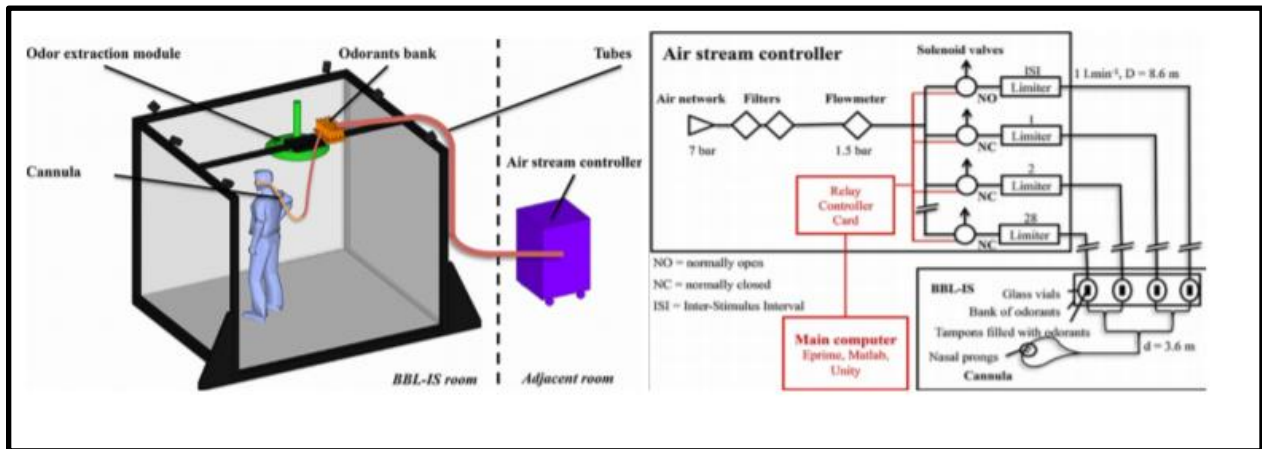
Figure 11: A schematic of the BBL-IS is diagrammed on the left and a schematic of the air stream controller is detailed on the right.[33]

While this odor delivery system and the time varying system mentioned previously allow

for accurate, precise, and controllable stimuli introduction, they are quite costly with PID units

ranging from $1,000 to $4,500.

2.2.2 Commercially Available Systems

In addition to evaluating the usage of odor delivery systems used in research, the team also wanted to analyze commercially available systems. The team found one device in particular that allows for the precise control of odors and costs roughly $13,000, which is manufactured by Aurora and seen in Figure 12. The device consists of a modular design which allows the user to choose the number of vials for testing, with the options of 4, 8 and 12. The manufacturer's specifications also boast that it can be used with "any substance that produces an odor." Each vial has a capacity of 75 mL but requires headspace towards the top. Depending on the odor, the stimulus can be delivered for up to thirty minutes. Solenoid valves are used to choose between odors and are controlled using software to open and close in milliseconds. There is a delay between activation of the solenoid and delivery of the odor, however, as the purge time depends on the length of the tubing.[34]

This system provides many advantages when applied to awake animal neuroimaging. For example, the already assembled device provides a fast and easy interface with the test operator. However, the air supply is not included in the purchased device and would need to be purchased by the operator separately. Additionally, the modular design of this product is limited to 12 odor vials. The device can also be coupled with the Aurora MiniPID to analyze the composition of the odor.[34]
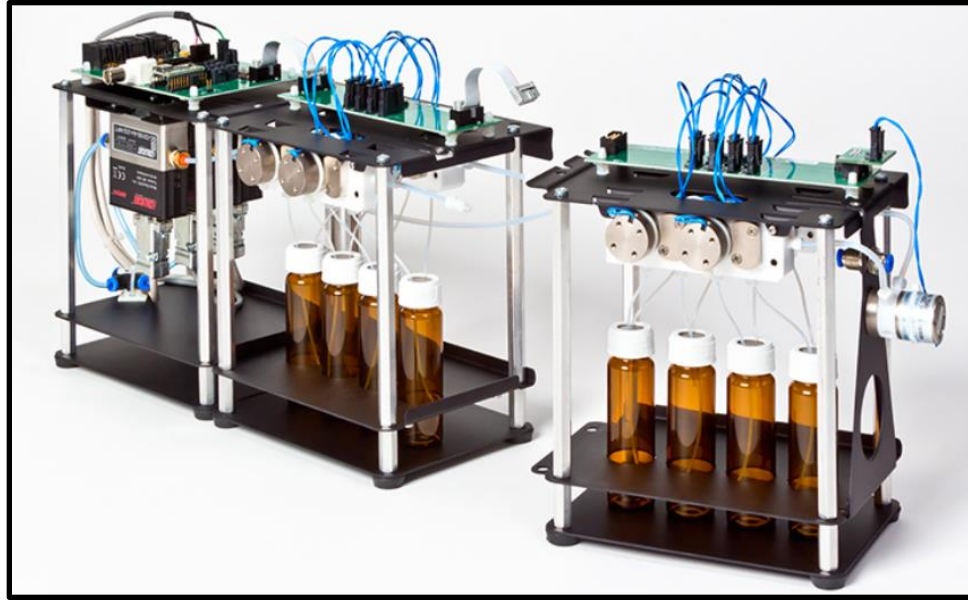
Figure 12: Aurora modular odor bank setup. [34]

While this commercially available system, and those constructed for research purposes in earlier sections, are capable of delivering and quantifying or evacuating odor to some extent, none of these systems are capable of all three. For this reason, the team also wanted to analyze components that were capable of performing these tasks individually.

2.2.3 Delivery Systems

In addition to the delivery mechanisms detailed in sections 2.2.1.1 to 2.2.1.5, odor delivery systems do exist on the market, with only a handful produced to suit the needs of a research environment.

One of the few devices designed to function in this capacity is the Stimulus Delivery System (SDS100) manufactured by Biopac Systems Incorporated, seen in Figure 13. The unit is composed of a stainless-steel box that houses an odor bank at its base containing eight scented liquids. Compressed air is then used to carry the scent up to a horizontal array of four miniature fans that are able to disperse the aroma three to six meters in front of the unit. To aid in precise

control, the SDS100 can be connected via USB cable to a computer and controlled remotely by various software packages.[35]

Figure 13: External casing of the Stimulus Delivery System on the left and inner components on the right. [35]

Benefits associated with this system include ease of use, and portability which combine to make it an attractive option for undergraduate labs. Although the amount of liquid atomized can be measured allowing some degree of quantification, the exact concentration of airborne stimuli exiting the system is unknown. This makes it difficult to establish exactly how much of a stimulus is needed to register an effect in a specimen's neural pathway. Additionally, diffusing odor into a closed or semi-enclosed room impairs the reproducibility of the experiment as the airflow of a room can never be kept exactly the same. In order to accurately measure the effect of an odor-based stimulus, researchers needed to develop a system that directly presents a specific concentration of odor to a test subject's olfactory system.

2.2.4 Quantification

2.2.4.1 Methods of Quantification

While many solutions exist for delivery of stimuli, methods of quantifying odors are still in the developmental stages of research. Although there are several chemical approaches to analyze the makeup and concentration of molecules that represent odors, no widely used standard exists to relate scents with their molecular composition. To complicate matters more, many studies incorporate several different methods of quantifying odor.[36] Current methods for defining an odor's molecular properties include the use of sensors and variations of gas chromatography.

The technique of gas chromatography, like all other forms of chromatography, requires two phases, a stationary and mobile phase, to analyze the quality and quantity of compounds in a mixture. This technique is extremely versatile as it can be utilized with several different detectors depending on the sample being tested. These instruments can also analyze a broad range of volatile and thermally stable samples, which make them useful for many different research applications.[37] An example of a gas chromatography set up is shown in Figure 14.
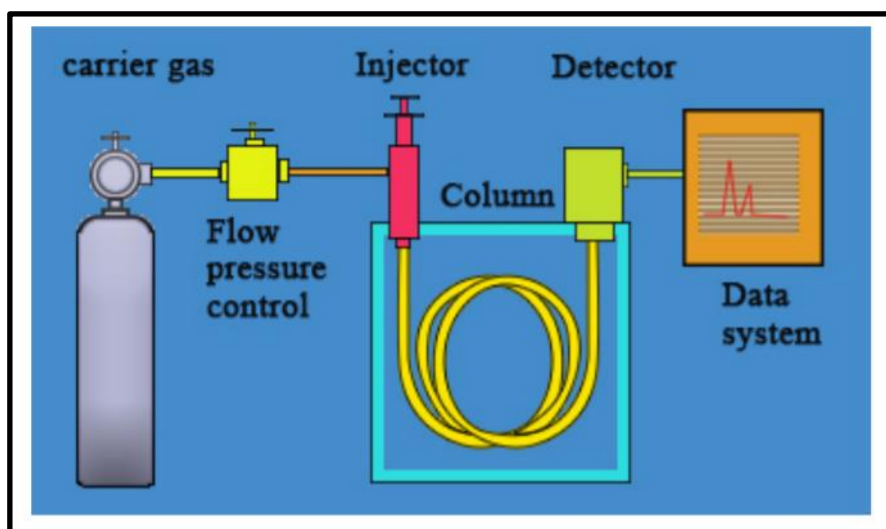
Figure 14: The general components of a gas chromatograph, including the carrier phase, the column, and the detector.[38]

Unlike other forms of chromatography where the mobile phase is a liquid, gas chromatography utilizes a carrier comprised of an inert gas such as helium, argon, or nitrogen to move the compound through the various segments of the instrument. This mobile phase first travels through the stationary phase, which is represented by the central column in Figure 14. The stationary phase can be either gas-solid chromatography (GSC) or gas-liquid chromatography (GLC). A GSC is a solid adsorbent and the GLC is a liquid or an inert support.[38] As the carrier gas and analyte mixture enter this column, the compound is vaporized and separated at a rate dependent on its reaction with the stationary phase. If the reaction is strong, the compound is retained in the column for a longer duration of time. Retention rate is a major determining factor of the quality of separation. A device with a high column temperature, high solubility in the mobile phase, and a compound with a low boiling point will have a lower retention rate and therefore pass though the column more quickly. After the mixture is separated, it passes through a detector. The different types of gas chromatography detectors are shown in Table 1, the most common of which are mass spectrometry (MS), flame ionization detectors (FID) and photoionization detectors (PID).[38]

Table 1: Detectors Used with Gas Chromatography [38]

Type of Detector	Applicable Samples	Detection Limit
Mass Spectrometer (MS)	Tunable for any sample	.25 to 100 pg
Flame Ionization (FID)	Hydrocarbons	1 pg/s
Thermal Conductivity (TCD)	Universal	500 pg/ml
Electron-Capture (ECD)	Halogenated hydrocarbons	5 fg/s
Atomic Emission (AED)	Element-selective	1 pg
Chemiluminescence (CS)	Oxidizing reagent	Dark current of PMT
Photoionization (PID)	Vapor and gaseous Compounds	.002 to .02 µg/L

Mass spectrometry is a type of gas chromatography in which the masses of the compounds are scanned continuously. The sample enters the inlet of the mass spectrometer after exiting the gas chromatography column and is then ionized and broken up by an electron impact ion source.[39] The ions are then subjected to electrostatic repulsion and enter a mass analyzer where they are sorted by their mass to charge ratio. Mass spectrometry instruments are beneficial because the results are immediate and can be used to identify substances that are not completely separated. However, because samples tend to thermally degrade before detection and are destroyed by fragmentation, they typically cannot be analyzed more than once.[40]

This method of analyzing odor samples was utilized in a 2017 study in which the aroma composition, aroma-active compounds, and sensory attributions of cherry wines were analyzed. This study sought to discover the differences and similarities between three price ranges of wines, and a total of forty-eight compounds were analyzed using gas chromatography-mass spectrometry, sensory analysis, solid-phase micro-extraction (SPME), and quantitative analysis of aroma compounds. These compounds were first extracted using SPME, then separated in a gas

chromatograph and detected using a 5973C mass selective detector (mass spectrometer). The volatiles in these compounds were quantified through the comparison of retention indices, molecular weights, and mass fragmentation patterns. In addition, a professional panel of six people then performed sensory analysis on the three sets of wine samples, rating the aromas against a set of discussed standards. Mass spectrometry used in this test was effective and practical, due to the need to determine the molecular weight of each compound.[41]

A flame ionization detector (FID) measures the concentration of organic species in a gas stream and is one of the most frequently used detectors in gas chromatography. In this method, the samples interact with a hydrogen flame after exiting the column and undergo chemical decomposition due to the high temperature. A high-impedance picometer then measures the current carried by the ions and electrons in the sample and monitors the sample's elution. This method is beneficial because it is unaffected by flow rate, water, or non-combustible gases, and therefore has high sensitivity. However, a flame is required for operation and the sample is also destroyed so the analysis cannot be repeated.[42]

This method of detection was incorporated, along with others, in a study dedicated to developing a precise method of isolating, identifying and quantifying volatile compounds in pear juice. GC-FID, HS-SPME, GC-MS were all used to quantify these volatile organic compounds and served different purposes within this novel quantification method. HS-SPME was used to adsorb pear juice volatiles, GC-MS identified the molecular weights and composition of the volatiles and, finally, gas chromatography with a flame ionization detector was incorporated to quantify these volatile organic compounds. Sensory evaluation with trained panelists was again used to score four different juices. Twenty-six volatile compounds were successfully extracted, isolated, and quantified as a result of these methods. However, GC-FID also destroys the

analyzed compounds during analysis and is therefore not a reliable method for procedures requiring quantification at multiple times.[42]

Photoionization detectors (PIDs) are another form of gas chromatography, which use chemiluminescence spectroscopy to detect gas and vapors, specifically volatile organic compounds (VOCs). These PIDs consist of ultraviolet lights that emit photons into an enclosed chamber. Inside the chamber, volatile compounds absorb the photons and release electrons once a certain amount of energy has been attained. The current generated by these ions can then be measured to calculate the concentration of volatile compounds in parts per million (ppm). By itself, the PID can only measure the total concentration of all volatile compounds in the chamber and not the specific compounds that are present. When paired with a chromatography column, each type of compound can be analyzed and recorded. This method is also very portable, which makes it ideal for use in research. However, it is difficult to detect molecules of a small molecular weight.[43]

A study into the use of PIDs for detecting odor pollutants compared its use to that of GCMS and GC-FID. PID use in research is rapidly growing, due to its portability and increased accuracy when compared to GC-FID instruments. The benefits of these detectors lie in the fact that they leave the compounds intact, therefore allowing multiple scans.[31]

Olfactometry is also a method of classifying an odor, commonly used with food aroma quality. Odor intensity is subjective and is determined based on human perception; therefore, a method to quantify the impact that these odors have on humans has been developed through olfactometry. Aspects of olfactometry include time-intensity, dilution analysis, and detection frequency. Time-intensity analysis uses trained humans who smell an odor continuously and record their perceived odor intensity while adding a verbal descriptor such as "sweet" or

"corky."[44] This method depends on human perception and feedback, and therefore is not useful for odor quantification when no human interaction with the odor is involved.

Lastly, an electronic nose is a method of machine olfaction, not directly associated with gas chromatography. It incorporates an array of sensors and a technique of pattern recognition to identify the chemical makeup of odors.[45] Electronic noses incorporate sensors that can detect specific compounds and therefore are designed to meet the needs of specific research. For example, an electronic nose was created with the design of detecting and classifying human body odor. This electronic nose incorporated an array of metal oxide sensors to detect volatile organic compounds in a human's sweat and used software to recognize and analyze this sensory data. The effectiveness of these sensors is inhibited by humidity, which skews sensory data. The researchers rectified this noise by designing software to accommodate the variances. The result of the study was an electronic nose that was capable of detecting a human's armpit body odor and even recognizing specific people when their sent was mixed with other confounding odors. Electronic noses are great tools for detecting one specific type of odor because they can be designed with a specific purpose in mind and can incorporate appropriate sensors. However, these instruments are not as valuable in studies where the composition of odors varies because sensors are not universal in the odors that they can detect. Therefore, the odor being quantified would need to be known before designing the nose. Electronic noses with the capacity to detect a wide range of odors do exist but are significantly more expensive than noses designed for identifying a single odor.[46]

These odor quantification methods are commonly used in conjunction with one another as each method has its own benefits and limitations. When used together, the strengths of these techniques meet the needs of a study, however no one standard combination of these instruments

exists. Additionally, the combined use of these instruments adds to the overall cost of research experiments.[42]

2.2.4.2 Distinctions Between Odor and Particulate Matter

Odor is the team's primary vehicle for stimuli delivery; however, future tests will likely incorporate particulate matter, based off of the information gained from meetings with the CCNI research group, as compiled in Appendix A: Meetings and Interviews with the CCNI. Therefore, it is important to understand both of these categories of stimuli as well as their different methods of quantification.

The majority of odors are volatile organic compounds (VOCs). VOCs can be manmade or naturally occurring organic chemicals that vaporize at a low temperature. As a consequence, odorants are nonionic compounds with molecular weights of less than 300 grams per mole.[47] To be smelled, the chemical compound of an odor must be converted into a vapor and the odor must be volatile and detectable by the olfactory system. For a compound to be detected by air-breathing animals it needs to be volatile at ambient temperature.[48]

When compared to odor, particulate matter is composed of larger particles and is generally attributed to air pollution rather than smell. Particulate matter (PM) is the mixture of solids and liquids found in the air in the form of particles or liquid droplets. It is a combination of many types of pollutants and each particle can be defined as a small, discrete object. Particles vary in size and some are visible to the naked eye such as smoke, dust, and dirt due to their dark color and large dimensions. However, other particles are only visible through use of an electron microscope. Particulate matter varies widely in size and can be made up of hundreds of separate chemicals. The two main categories of these particles are PM10 and PM2.5, which classifies the

particulate matter by size. PM10 is inhalable due to its average size of 10 micrometers. PM2.5 is a fine particle of about 2.5 micrometers and is typically the most harmful if inhaled.[49]

Particulate matter can be measured by several methods such as light scattering photometers and optical particle counters. Light scattering photometers measure the mass of particles per volume of air using a nozzle or cyclone to limit the size of particles that are quantified. These instruments give an output of micrograms per cubic meter.[50] Optical particle, or laser, counters are another method of measuring PM and are instruments with multiple channels used to filter the different particle sizes before analysis. However, neither of these methods analyze the chemical composition of these particles.[51]

2.2.5 Evacuation Systems

2.2.5.1 Overview

Following each phase of delivery and quantification within an odor delivery system, the testing area must be completely evacuated. An evacuation, or scavenger, system is responsible for collecting and removing gaseous matter from an enclosed space. Traditionally, these systems are used to remove excess anesthetic from patient breathing systems during exhalation. The system also acts to ensure that the anesthesia and stimuli that are administered to a subject do not escape into the facility's air supply. This safety measure is especially critical due to the standards set in place by the National Institute for Occupational Safety and Health (NIOSH). These standards mandate that general anesthesia exposure levels cannot exceed a certain limit and can be viewed in Table 2.[52] Isoflurane, which is used by the CCNI, should not be allowed exceed 2 ppm within the workspace during an 8-hour time weighted average. Furthermore, anesthesia and stimuli administration to a rat is typically performed through a nose cone, as opposed to

intubation in human patients. This type of delivery further increases the risk of gas escape and exposure.[53]

Table 2: Various Anesthetic Substances and their Maximum Exposure Levels [52]

Substance	Permitted Maxima in ppm as 8 hr TWA
N_2O	25
Isoflurane	2
Enflurane	2
Halothane	2

Evacuation systems are most commonly used for anesthesia but have also been modified for use in odor delivery, as the two processes are very similar. Evacuation systems typically consist of four individual systems that work in unison, each of which are diagrammed in Figure 15. The first system is the collecting system, which comes in direct contact with the breathing system. The vapor then travels along a transfer system that typically consists of a collection of tubing. Following the transfer system, the vapor passes through a receiving and disposal system that either utilizes an active or passive method of filtration.[54]
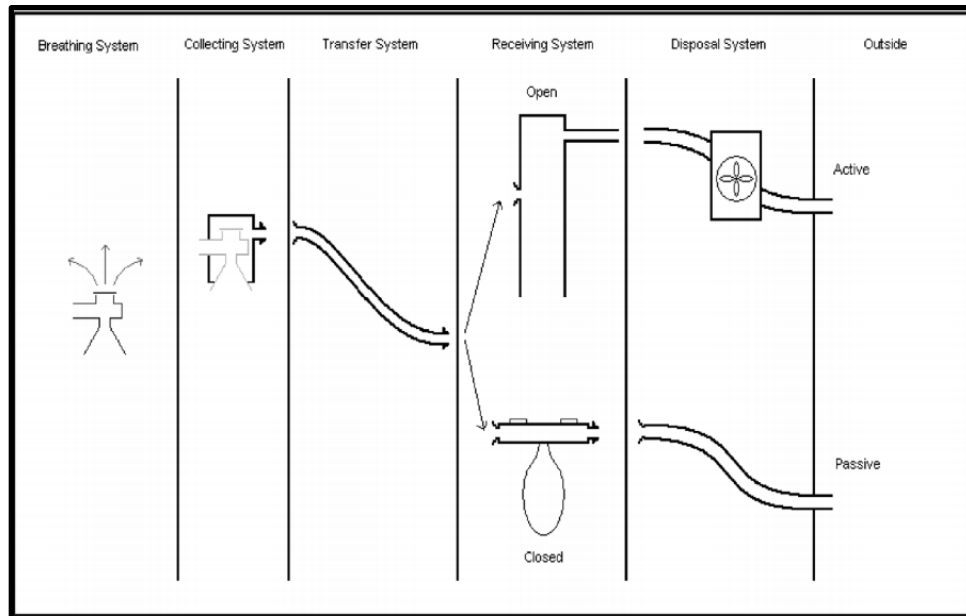
Figure 15: A typical scavenging system and its components. These components are the collecting system, the transfer system, the receiving system, and the disposal system. The system connects to the outside of the facility at the far right.[55]

2.2.5.2 Passive System

A passive system uses the general air circulation system of the facility and as a result does not need to be constantly adjusted. Passive systems are ducted to the exterior of the facility through a window or a pipe that leads to the outside. Passive systems are advantageous because they are inexpensive and have simple functionality. However, due to pressure and gravity, the exit port outside the building must be at a height below the delivery system, which could limit its effectiveness in certain areas. Passive systems, when utilized with animal subjects such as rats, are typically coupled with a process known as charcoal filtration. This process involves the movement of vapors through a charcoal canister filter, which is able to separate halogenated anesthetics.[55] The CCNI would not be able to administer a passive system because there is no window in the testing area and no exit port outside the building and as a result uses an active system instead, which is facilitated by a vacuum.

Active systems utilize vacuum suction to evacuate odor and anesthesia. Such systems tend to operate more smoothly and provide increased evacuation especially without intubation.[56] One such active system is showcased in a 2007 experiment conducted by a group of researchers at American University, in which odor is transmitted to rats that are housed in a closed environment. Air is ventilated into the environment and exhausted out by way of a fan.[57] A similar exhaust system is present in a 2004 report by Cold Spring Harbor Laboratory, which utilized an exhaust fan that ran constantly during the 20 second odor delivery phase.[58] This type of system is practical for the purposes of ambient odor testing as it allows for a fresh stream of odor to be delivered through the housing. However, such large fans would not fare well in a more direct approach such as odor transmitted via a nose cone to a rat housed in a relatively small space. For more finite and easily controllable evacuation of odor stimuli, other methods of scavenging exist.

In a far more invasive procedure, researchers affiliated with the Division of Biological and Biomedical Sciences at Emory University utilized a tracheal cannula to test orthonasal and retronasal odor stimulation in rats. During orthonasal stimulation, odor was suctioned in through the rat's nostrils at a rate of 500 mL/min by means of a vacuum attached to the tracheal cannula.[59] The vacuum utilized here acted primarily as a testing mechanism, but also served to evacuate odor from the rat.

In another similar study, the Health Science Center at Syracuse, New York, administered tests on frogs in order to quantify their inherent and imposed mucosal activity patterns. This test was also invasive as it involved the usage of two valves whose components entered the frog's naris. The odor delivery system is shown as Valve A depicted in Figure 16, while the vacuum

scavenging system is shown as Valve B.[60] The scavenging systems of the two aforementioned tests are advantageous because they provide a steady stream of stimuli to pass through the animal. However, they are impractical due to the fact that they require surgery to be conducted on the animal.
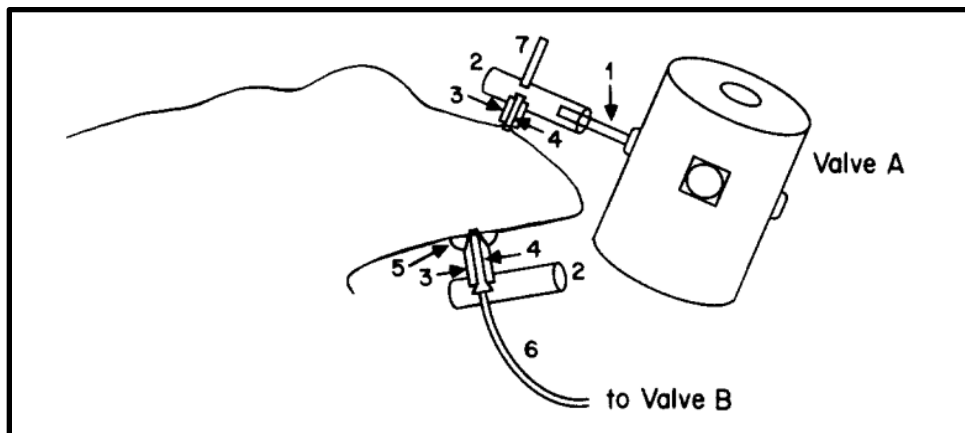
Figure 16: Odor delivery and evacuation system installed on a frog. The delivery system is shown as Valve A and the scavenging system is shown as Valve B.[60]

Anesthesia scavenging, as mentioned earlier, has more documentation than the scavenging of odors, and various companies have created scavenging systems for use in animal testing. For example, Harvard Apparatus designed a Fluovac system that incorporated delivery and scavenging of anesthesia to rats and mice into one system. It consisted of an anesthesia pump that connected to another pump, from which the delivery and scavenging tubes emanated from. The system was self-contained, however it was mainly beneficial to labs that did not possess any type of vacuum or ventilation system of their own, which is not the case for the CCNI.[61]

Other types of anesthetic scavenging involve scavenging hoods that bear a resemblance to MRI holders. A study by the Department of Surgery at the Chinese University of Hong Kong

describes one such scavenging hood, which was constructed out of a plastic food box. A rubber bordered hole was cut into the side to create space for the rat's head. Two additional holes were created to allow for the anesthetic supply line and the vacuum pump to feed through which can be seen as (a) and (b) respectively as seen in Figure 17. The vacuum pump was set to suction gases at a rate of 1.5 L/min and directed the gas outside the facility through an opening in a nearby window. It is important to note here that the anesthetic supply line, which also pumped air at a rate of 1.5 L/min, was designed to strictly encapsulate one-way flow in order to prevent any backlogging of old gas.[62] The advantages of this type of procedure include the fact that supply odor and anesthesia would be contained within the plastic food box. Since the entry supply line is partitioned from the box by means of a unidirectional valve, evacuation would be the only means for the gas to escape. Therefore, there is very little risk of exposure in such a system and gas can be evacuated completely. This type of system is very similar to the CCNI's current system because the MRI rat holder is similar to the plastic food box below.
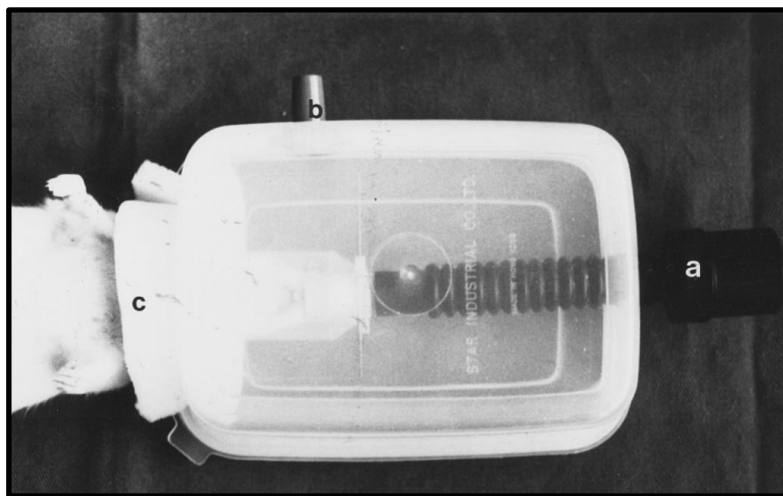
Figure 17: A scavenging hood designed for usage in anesthetic delivery to rodents.[62]

Clearly, there is a need for a device which can combine a robust and adjustable stimuli delivery system with a precise stimuli strength quantification procedure, and can then evacuate the stimuli without accruing an exorbitant cost.

The aforementioned fields of research were delved into after the initial meeting with the client. The following sections will detail the outcomes of that initial meeting and establish the standards for the design to follow in the undertaking of a novel odor delivery and quantification system.

3. Project Strategy

3.1 Initial Client Statement

Upon initial contact with our client, the CCNI, the team was tasked with developing a comprehensive odor delivery system to aid in awake animal MR imaging. The system would need to incorporate three main components including a method of stimuli delivery, a quantification scheme, and an evacuation strategy. These design parameters provided by the CCNI are outlined in the client statement below:

"Design an odor delivery system for an MRI subject holder that enables the measurable and repeatable delivery of odor during MR imaging regimes."

3.2 Stakeholders

Pertaining to this project, there are several vested stakeholders each with distinct objectives that must be satisfied in order to attain success. These stakeholders can be divided into three primary groups: the designers, the clients, and the users, which are represented in Figure 18 below.
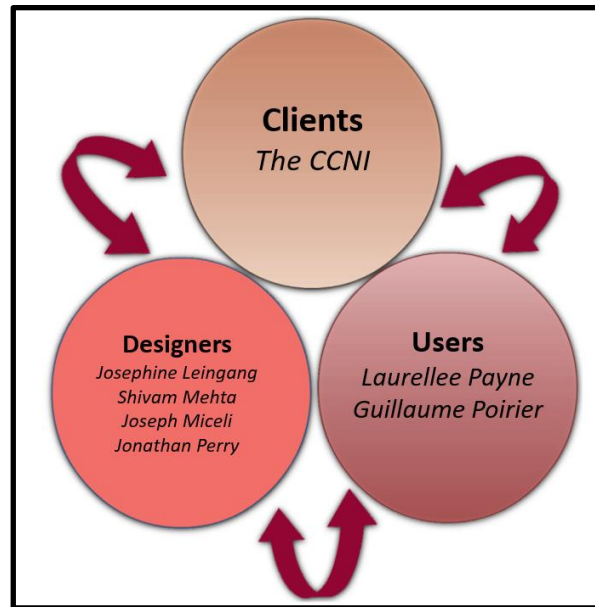
Figure 18: A vested stakeholder diagram created by the team.

The designers for this project perform the creation, testing, and prototyping of a viable stimuli delivery system. This role is filled by the design team, composed of Josephine Leingang, Shivam Mehta, Joseph Miceli, and Jonathan Perry. The clients of the device are the CCNI, who are providing the project and design needs and objectives. The success of this project may have the result of spurring interest amongst researchers desiring a similar device, and this group of people may act as secondary clientele in the future. Lastly, the users of the system are the test designers and test operators in charge of experiments utilizing this device. For the CCNI specifically, these roles will be filled by Laurellee Payne and Doctor Guillaume Poirier. Through meetings and discussions between the aforementioned stakeholders, the initial objectives and design constraints were developed. Following these sessions, the initial objectives and design constraints were further analyzed.

3.3 Initial Objectives

To better define the needs of the clients and inform design decisions, several objectives were drafted. These objectives were outlined following the initial client meeting with the CCNI. Table 3 organizes the objectives into five primary categories including the three main system components coupled with the ease of use and cost efficiency associated with the project. Taking the client's feedback into consideration, the objectives were organized qualitatively and listed in order of descending importance. At a later stage of the design process, these objectives were further analyzed and given quantitative weights. It was determined that the most important priority of the project is to establish a reliable and reproducible stimuli delivery system since successful completion of the other objectives is contingent upon a working method of stimuli delivery. Once this milestone has been attained, a way to accurately quantify the concentration of stimuli being delivered into the test subject's system will be necessary to correlate stimuli and brain activity. Additionally, quantification will be needed following evacuation, our third objective, to ensure all of the stimuli has been removed and will not impact future stimuli introduction.

Ease of use is another important consideration, as this system's effectiveness will be greatly reduced if the users cannot operate the system correctly. The importance of each objective was ranked by each vested stakeholder, in pairwise comparison charts located in Appendix B: Pairwise Comparisons.

Table 3: The Primary Objectives Drafted by the Team

Primary Objective	Description
Delivery	Reliably and reproducibly deliver stimuli to a test subject located within the bore of an MRI machine
Quantification	Accurately measure and quantify the concentration of stimuli being delivered into the subject's system
Evacuation	Safely and effectively remove stimuli from the device and testing environment after delivery sequences
Ease of Use	Device setup and usage must be efficient and intuitive
Cost Effectiveness	The benefits of researching, developing, and prototyping the system must outweigh the associated costs

3.4 Constraints

When considering the design of any device, it is necessary to take into account the absolute limits given for each parameter of the design. After further correspondence with the clients at the CCNI, the team was able to identify necessary constraints in order to complete a satisfactory design. Table 4 identifies the most important design constraints taken into consideration:

Constraints		Description
Logistic	Time	The device must be completed by the end of the allotted project schedule, which would be D-Term of WPI's undergraduate schedule
	Cost	The creation and testing of the system cannot exceed the allotted costs for the group, which would be $1,000
Integrative	Magnetic Compatibility	The device must not be comprised of components that would be negatively affected by the electromagnetism associated with the testing environment, if it is to be used in close proximity to the MRI
	Restraint Compatibility	The device must be able to accommodate for the client's testing procedure, specifically the unique restraint system used for awake animal neuroimaging
	Operational Compatibility	The device must integrate with the client's current testing environment and subject preparation procedures

3.5 Final Objectives

After the team's second meeting with the CCNI and further research into the topics at hand, the team was able to modify the initial objectives to create a more comprehensive list of final objectives. In Table 5, delivery, quantification, evacuation, ease of use, and cost effectiveness are listed as primary objectives in hierarchical order beginning with the most

crucial aspect of the system. Secondary objectives were then established to further clarify and guide the design of the overall system. In terms of the delivery method, fine-tuned needs include a quick response time to increase accuracy, a variable flow rate to provide flexibility during testing, and a multitude of different odors to choose from. Additionally, the system must be able to deliver anesthesia and stimuli concurrently to provide a baseline for testing. Under the primary objective of quantification, secondary objectives include stimuli delivery measurements to quantify the concentration of stimuli exiting the system and post-evacuation measurements to verify that all of the previous stimuli have been removed. During both of these objectives, accuracy and precision will be crucial to provide exact and reliable data. The last primary system objective of evacuation will entail effective removal of the stimuli from the holding area to reduce confounding factors and routing out of the facility to limit the users' exposure to the stimuli. Throughout the fulfillment of the three primary system objectives, the overall project objectives of cost effectiveness and ease of use will also be critical. Under ease of use, secondary objectives were established including operational simplicity, safety, adjustability, and scalability. Lastly, cost effectiveness was broken up into an analysis on value and the lifetime of the design components.

Table 5: Comprehensive List of Secondary Objectives

Primary Objective: Delivery	
Secondary Objective	**Description**
Stimuli Variability - Type	The device should be able to account for multiple stimuli types, including gaseous odors sources, liquid odor sources, vapors, and fine particulate matter
Stimuli Variability - Number	The system should allow for the introduction of multiple stimuli during a single delivery sequence
Flow Rate Variability	The test operators should be able to change the flow rate of the system during use
Anesthesia Incorporation	The device should be able to deliver both stimuli and anesthesia, concurrently if the test operators decide that it is necessary for a procedure
Response Time	The system should be able to deliver stimuli to the test subject within 30 seconds of being activated by a test operator

Primary Objective: Quantification	
Secondary Objective	**Description**
Accuracy	The technique used for quantifying stimuli must meet the client's need for reliable measurements that are an accurate representation of the amounts of stimuli being experienced by the subject
Precision	The technique used for quantification should provide reproducible measurements that offer precise readings throughout the lifetime of the device
Delivery Measurement	The device should be measuring the amounts of stimuli that the subject will be exposed to with each round of delivery
Evacuation Measurement	The system should also be measuring the amounts of stimuli that is removed during evacuation to ensure that there is minimal contamination

Primary Objective: Evacuation	
Secondary Objective	**Description**
Effective Removal	The device must be able to remove a substantial amount of previous test stimuli from the system before the introduction of other stimuli
Limited Exposure	The device should ensure that the test operators are not exposed to an unsafe amount of stimulus or anesthesia
Limited Contamination	The device must be resistant to the contamination of stimuli either through unexpected mixing or ineffective removal of a previous stimulus

Primary Objective: Ease of Use	
Secondary Objective	**Description**
Simplicity	The device should be easily constructed and operated by a technician or reliably automated
Scalability	The device must be capable of accommodating the number of stimuli required without involving a high degree of user interference
Adjustability	The device should be capable of allowing the operator to manipulate the amount of stimulus exposed to the subject and the rate of delivery for different testing sequences
Size	The bulk of the system should not disrupt the current workflow in the testing environment
Safety	The device should not jeopardize the safety of the test operators, subjects, or any other party that may be involved with its use. Safety includes not exposing any party to unnecessary amounts of stimulus, pressure, or dangerous device components

Primary Objective: Cost Effectiveness	
Secondary Objective	**Description**
Value	The usefulness of the device should not be exceeded by the cost of creating the device
Lifetime	The system should be built to last for multiple different test sequences at variable frequencies of use for around 4 years before failure or component replacement

3.6 Revised Client Statement

After meeting with the CCNI and iteratively revising and further clarifying their needs, the team was able to refine the initial client statement. The core concept of the initial client statement remained, however, and would need to be explained and clarified further. Additionally, select client goals were re-categorized as wants, rather than needs, to help clarify which of the design parameters were most important. These reach goals included allowing the design to accommodate for multiple stimuli type (namely odor, particulate matter, and vapors), adjusting flow rates for different stimuli in the same experimental suite, and automating the system to reduce human error. The team will need to incorporate several design parameters into the delivery system including adjustable flow, improved response time, decreased distance between the stimuli storage unit and the subject, and variable number of stimuli that are able to be dispensed. Furthermore, the team decided to focus the client statement on the three main initial objectives, which are delivery, quantification, and evacuation.

The foremost project goal is to create a reliable odor delivery device. The second goal, which stems from the foremost project goal, is a reliable and precise quantification system. Within the system, the concentration of odor or particulate matter will need to be measured both during stimuli delivery and after evacuation to provide reproducible and accurate measurements. Lastly, an efficient evacuation system is necessary to prevent confounding stimuli from affecting the results. Evacuation was not mentioned in the initial client statement, and therefore is also added to the revised client statement. The team's final client statement now reads:

"Design, characterize, and create an odor delivery system for an MRI subject holder that is

capable of enabling the precise delivery of more than 3 odors with adjustable odor strengths

during MR imaging regimes with a maximum input delivery delay of 30 seconds, and a reliable

evacuation system utilizing HEPA and activated charcoal filters to reduce confounding factors

and safely remove stimuli."

3.7 Project Approach

The project approach is split into three different approaches in the following sections. The three approaches are time management, design, and financial.

3.7.1 Time Management Approach

To aid in time management, a Gantt Chart was created at the end of A term for the purpose of guiding the design portions of the project. This ensured that tasks were completed and revised on a timely manner. The Gantt chart can be found in Appendix C: Gantt Charts and included a detailed outline of tasks and due dates for B, C, and D term. Design team meetings were held several times a week to facilitate constant forward progress. Meetings with the advisors were held on a weekly basis to present the findings of the week. Additionally, meetings with the clients at the CCNI were scheduled about twice a month to inform the CCNI on the team's progress as well as to update the design of the odor delivery system.

3.7.2 Design Approach

Through research of existing delivery and quantification systems, the team was able to identify both effective and ineffective designs, which informed the initial ideas of the final device. The objectives and constraints outlined above were considered when developing these ideas.

3.7.3 Financial Approach

As outlined by the MQP budget found on the MQP syllabus, each student is allowed $250 to spend on the project. Since the team is comprised of four members, the total budget is $1000. Of the $1000, $100 is set aside for common supplies, while the remaining $900 is used for project cost.

4. Design Process

Following the project strategy element of the project, the team was able to combine the objectives and constraints of the project and utilize these parameters to create a block diagram of the device, which can be seen in Figure 19. The block diagram was constructed as a general, high-level view of the final design which mainly took into consideration the objectives and functions of each component. The essential areas of the final design will include a power source, a carrier air source, an odor bank, a method of airflow control, and the interface with the subject. Each of these areas will include multiple components and parts which will be outlined later. The device will also have a computer interface which enables the user to start and stop the test, control evacuation, and view readouts. After creating the block diagram, the team created comprehensive lists of the needs and wants of the design and the functions and specifications of the components in order to move the design from the block diagram to an initial design.
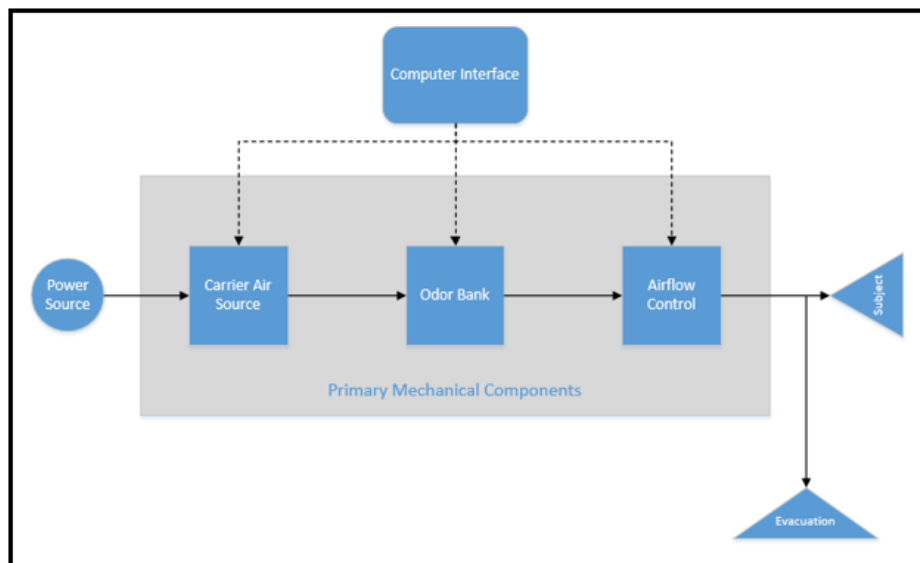
Figure 19: Block diagram of the device created by the team.

4.1 Needs Analysis

After determining the primary and secondary objectives based on the client statement, the team began to analyze the needs and wants of the client. The purpose of this aspect of the design

process is to separate design objectives by their importance and to gain a better understanding of different points of focus for the group. When performing this analysis, a need is defined as a design component that is necessary to complete a successful project that is capable of satisfying the client's statement. A want, on the other hand, is defined as a design component that is not required for completion of a successful project, but would offer improved functionality, or would satisfy objectives that the client deemed as less important. Table 6 lists the needs and wants identified by the project team and their respective descriptions.

Table 6: Design Needs and Wants

Needs	Description
Odor Delivery	The ability of the system to reliably deliver odor stimuli
Quantification During Delivery	The ability of the system to quantify the amount of stimulus being delivered to the subject
Odor Quantification Precision	The ability of the system to reproducibly quantify the amount of odor in the system
Odor Evacuation	The ability of the system to remove stimuli from the system before a subsequent round of stimuli delivery is started
MRI Compatibility	The ability of the system to function without negatively impacting the operation of the MRI magnet or associated devices
Subject Restraint Compatibility	The ability of the system to integrate with the client's current subject restraint system
Operational Compatibility	The ability of the system to be easily integrated with the client's current testing sequence

	The ability of the system to integrate the
Compatibility with Anesthetic	client's current system for isoflurane delivery

Wants	Description
Multiple Stimuli Types	The ability of the system to deliver, quantify, and evacuate different types of stimuli, including particulate matter
Multiple Stimuli Number	The ability of the system to deliver multiple stimuli in conjunction with one another
Odor Quantification Accuracy	The ability of the system to reliably report the amounts of stimuli being delivered to the subject
Quantification After Evacuation	The ability of the system to detect the amounts of stimuli that are still present in the system after evacuation
Interface with Future Quantification Method	The ability of the system to incorporate a more accurate and expensive quantification system for future testing sequences
Variation in Flow Rate	The ability of the system to have an adjusted flow rate during a single test
Automation	The ability of the system to function with little to no human interaction
System Response Time	The ability of the system to deliver stimuli to the subject after a minimal delay time
Maintenance	The ability of the system to be easily cared for either by being robust enough to maximize operation time before failure, or by having easily replaceable components

4.1.1 Design Needs Discussion

The needs of this project, as defined by the group, include several components that would be needed to satisfy the objectives and constraints of the system. For example, compatibility with the client's current system for undertaking experimental procedures was determined to be one of the primary constraints by the project team. In order to satisfy these constraints, the group considered the components that they would be translated to and identified these aspects as needs of the system. These needs were listed as compatibilities with four aspects of the client's current system: their experimental procedure, MRI, anesthesia delivery mechanism, and subject restraint system. Additional needs were drawn from objectives and included the ability of the system to provide mechanisms for delivery, evacuation, subject stimuli quantification, and precision in quantification. The client had determined that these objectives were of utmost importance for their purposes, and the team reflected those decisions in this analysis.

4.1.2 Design Wants Discussion

The wants of the team's design were drawn from less important secondary objectives, and from meetings with the client where alternative ideas were discussed. An increase in the number of stimuli that could be used in the system was an objective that was less integral to the completion of the design than others and was therefore defined as a want. Other wants that were determined in the same manner include accuracy in odor quantification, quantification after evacuation, variable flow rate, and a shortened system delay time. Wants such as the ability to deliver multiple stimuli type were identified from meetings between the client and the project team where the future of the device was discussed. The ability to accommodate multiple stimuli types was determined to be helpful for the longevity of the design, when project teams in the

future might want to use the device for delivery of non-odor stimuli including particulate matter for pollution experiments. Improved quantification accuracy and the ability to interface with more reliable systems were deemed less important for the current needs of the client, although they expressed the possibility of needing those objectives met for future experiments. Additionally, automation and ease of maintenance were recognized by the client as advantageous design additions, but not integral to the success of their experimental procedures.

4.2 Design Functions and Specifications

In order to create a successful system, six main functions were established with corresponding specifications. These specifications guided the design process and helped to ensure that the system satisfies all of the client's objectives and pre-determined constraints. The first four functions comprise the delivery aspect of the system and include gas carrier source, stimuli storage, control method, and component connections. In order to effectively deliver the stimuli from the odor bank to the test subject, a carrier gas source is required. This gas source must be able to reliably and safely force pressurized air into the system with the required mass flow rate. According to the CCNI, the mass flow rate within the system must be approximately 0.8 L/min to allow for sufficient odor delivery yet prevent asphyxiation. In addition, the gas source must be able to incorporate delivery of anesthesia to the subject with a flow rate between 0.5 and 1.5 L/min. Lastly, the gas source must allow for incremental increases in flow to mitigate the effects of stimuli desensitization.

Another crucial function of the system is odor storage. In order for this system to be used safely, the odor storage unit must be composed of a fully sealed container. By eliminating leaks, contamination will be prevented both to the stimuli from outside sources and to the test operators

from the stimuli. In addition, the odor storage units must allow for simple replacement and cleaning. This will mitigate the risk of contamination when reusing storage units and give test operators the chance to easily switch stimuli in and out between test regimens. Another specification to incorporate into the design of this component is a transparent exterior to allow the test operators to view the stimuli inside the storage unit and its interaction with the carrier gas. The final design specification is to build at least three odor storage units as requested by the client.

Two more design functions pivotal in the design of this stimuli delivery system is the stimuli control method and component connections. For the stimuli control method, there must be a system start time under 30 seconds and a less than 1 second response time when prompted to open or close. These specifications are necessary to building a nimble and responsive system that will allow for accurate correlation between stimuli introduction and neural activity. In addition, the component connections must be made of a durable, non-stick material that is easy to clean and resistant to kinking.

In addition to the delivery aspect of the system, there are several other design functions including stimulus quantification system, stimulus evacuation system, and test subject interface. In terms of the stimulus quantification system, the method used must provide at minimum, a qualitative analysis of the concentration of stimuli being delivered to the test subject. Moreover, the cost of the quantification method cannot exceed the group's budget. When considering methods of evacuation, specifications provided by the CCNI include a 90% evacuation of the MRI bore, safe deposit outside of the MRI facility, and little to no backflow. Lastly, when designing the test subject interface, the apparatus used must be stable, fit within the restraint

device, possess a non-porous surface, and allow for effective stimuli delivery. The functions and

specifications can be found in Table 7.

Table 7: Design Functions and Specifications

Function	Specifications
Stimulus Storage	-Avoid contamination -Allow for a minimum of 3 stimuli -Easy and efficient stimuli switching
Flow/Carrier Gas Source	-Anesthesia flow rate of 0.5 – 1.5 L/min -Stimulus flow rate of 0.8 L/min -Short, intense bursts of odor stimuli are more desirable than prolonged exposure -Incremental intensity increases -Prevents backflow
Control Method	-Start time delay of less than 30 seconds -Near instantaneous response time for control method (solenoids, valves, switches)
Component Connections	-Connections should be non-stick (preventing stimuli from attaching themselves) -Resistance to kinks and knots -Easily cleaned -Durable (high mechanical strength)
Stimulus Quantification System	-Inexpensive -Precision more important than accuracy -Relative measurements are acceptable for the design -Include addition for more accurate system in the future
Stimulus Evacuation System	-At least 90% stimulus evacuation between delivery periods -Safely deposit the waste gases outside the testing environment -Prevents backflow
Test Subject Interface	-Fits within the subject restraint system and MRI machine -Compatible with the MRI -Stable attachment to restraint system or MRI -Accurately delivers stimuli to the subject

4.3 Conceptual Design Phase

After determining the functions and specifications that are required to comprise a successful design, the group worked towards identifying different elements and means that were capable of fulfilling these functions. For each mean that was identified, advantages and disadvantages were then discussed, which led to a comparison matrix rating each of the means by their theoretical ability to accomplish the design objectives while abiding by the constraints. Figure 20 shows a general graphical representation of the system's design concepts. The following sections discuss each of these phases in greater detail.
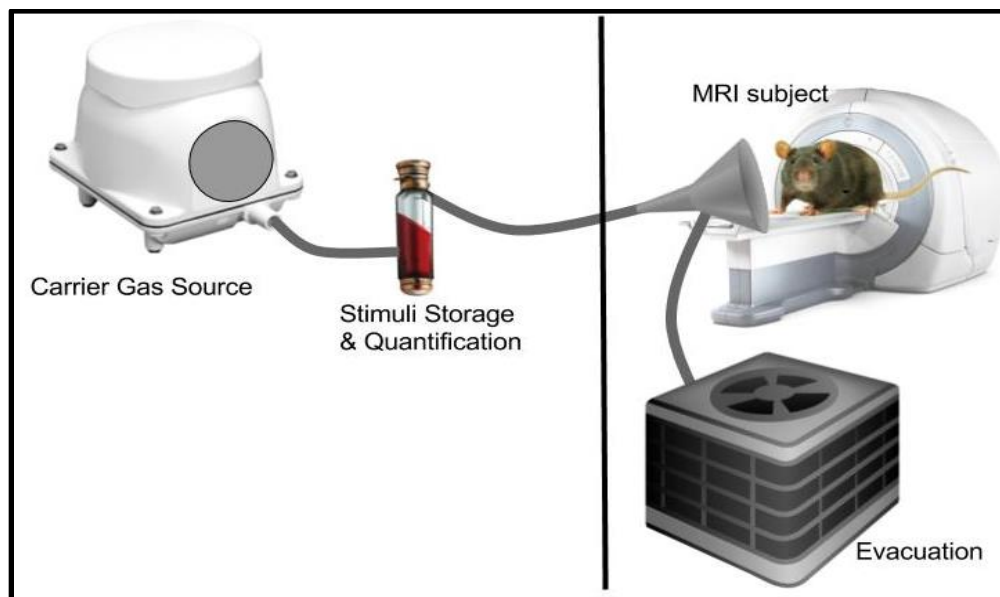
Figure 20: A graphical representation of the design concepts. The leftmost image is a representation of a carrier gas source, which pushes air to the stimulus storage, depicted by the red vial. Odorized air is then sent to the MRI subject in the MRI room, and is later evacuated by the vacuum.

4.3.1 Design Elements: Brainstorming Means

As the initial step in the conceptual design phase, the team first considered all of the elements that any design must contain in order to satisfy the needs of the client. These elements

were then organized by the order in which they needed to be considered to build a successful design and are outlined in Table 8. Elements that were deemed dependent on others were given a lower score, in this case, a larger number, while elements that were independent of others were given a score of 1, since they needed to be considered before the dependent elements.

Table 8: Design Elements

Design Element	Order to be Considered
Stimulus Storage	1
Flow/Carrier Gas Source	1
Control Method	1
Component Connections	1
Stimulus Quantification System	1
Stimulus Evacuation System	1
Test Subject Interface	1
Overarching Structure of the Device	2
Number of Stimulus Storage Containers	2
Component Control Mechanism	3
Power Source	4

Each of these design elements were integral to the success of the design, and in turn affected the design means that were to be considered later in the process. The method for storing

stimuli was considered a primary element in the design of the team's device since the storage

method would dictate the overall structure of the device in addition to the method for accessing

and manipulating the stimuli. The carrier gas source, the method for controlling the stimuli, and

the connections linking all of the device components were identified as primary design elements

for the same reasons. The systems used for quantification and evacuation of the stimuli were also

integral to the design of the final device and affected the structure of the system. The interface of

the system with the test subject was intrinsically linked with the component connections and also

affected the layout of the design, which prompted its selection as another primary design

element. The remainder of the elements were defined as secondary, tertiary, and quaternary

depending on their roles in the final design. For example, the structure of the device and the

number of storage containers were dependent on several of the primary design elements

including the method for stimuli storage and the component connections. The mechanism used to

control aspects of the device was in turn dependent on them, followed by the power source used

to run the system.

For each of the primary design elements, means for accomplishing those elements were

devised by the design team and compiled in Tables 9 and 10, shown below.

Table 9: Design Means 1

Element:	Stimulus Storage	Flow/Carrier Gas Source	Control Method	Component Connections
Means:	-Individual Vials -Holding Chambers -Plastic Bag	-Aquarium Pump -Vacuum Pump -Compressor -Fan -Passive Air	-Solenoids -Manual Switch -None	-Flexible Tubing -Direct Connections -Rigid Piping

Element:	Stimulus Quantification System	Stimulus Evacuation System	Test Subject Interface
Means:	-PIDs -Mass Spectrometry -FIDs -Electronic Nose -Optical PM Detector -Dilution Factors	-Forced Air Evacuation -Forced Water Evacuation -Vacuum Evacuation -Passive Air	-Existing Nose Cone -Redesigned Nose Cone -Tubing Alone -Hood Method

The following section explores all of the means identified for each element and identifies their strengths and weaknesses in terms of design function.

4.3.2 Evaluation of Design Element Means

Stimulus Storage

In order to hold stimuli prior to testing and release it in a controlled, measurable manner, a stimuli storage unit must be evaluated for implementation into the system design. The most widely used storage form in similar devices is a glass vial. By adding an inlet and outlet through the top of the vial, a carrier gas can be pushed through the inlet down through a tube and bubbled through the stimuli in liquid form to impregnate the gas. This method is relatively simple yet is an effective way to transform a liquid stimulus into a gaseous form. A primary advantage of this method is the limited contamination as each stimulus will be given a separate vial and dedicated tubing to deliver the stimuli to the test subject. A few other benefits include easy cleaning due to the properties of the glass which adds a degree of reusability to the system and cuts down in long term operational costs. Lastly, the glass vials allow for quick and easy replacement which will enable the operators to switch through a large number of stimuli if need be. However, several

disadvantages include the fragility of the glass which could lead to breakage, the limited number

of stimuli that can be stored in each vial, and the potential need for customized lids.

Table 11: Pros and Cons of Individual Vials

Individual Vials	
Pros	**Cons**
-Vials can be cleaned easily -Stimuli can be switched quickly and efficiently -Reduces contamination between stimuli	-Personalized vials would be expensive -Difficult to replace after breaking -Limits the amounts of stimuli that can be introduced to the airstream

By using a cubical holding chamber as a vessel for stimuli, a larger volume of stimuli can

be stored allowing for longer testing regimes. The test set-up for these holding chambers would

be very similar to that of the vials with one input and one output as well as tubing that would

push carrier gas through the liquid stimuli and out the exit. In addition to a considerably larger

amount of stimulus being stored, this method would allow for multiple gaseous stimuli to be

combined if there were multiple cells in the bottom of the holding chamber filled with different

stimuli. One major disadvantage of this system is the possibility of contamination. Since multiple

stimuli would be in the same chamber, this could result in cross-contamination when mixing is

not desired. Additionally, this chamber would be much harder to clean as it does not have a

removable lid and would make it much harder to quickly change stimuli in and out.

Table 12: Pros and Cons of a Holding Chamber

Holding Chamber	
Pros	**Cons**
-Capable of holding a large amount of stimuli -Capable of mixing multiple stimuli	-Susceptible to contamination -Difficult to clean -Difficult to switch stimuli without introducing contaminants

This idea was inspired by the pharmaceutical industry's disposable bio-bags that allow for one-time usage and disposal for maximum cleanliness and mobility. For this application, a ziplock bag would be used to store the stimuli and would have an inlet and outlet punched into the top of the bag. A sealant would be used to close any gaps around these holes and gas would flow through the bag in the same manner as the vial and holding chamber method. A clear advantage of this system is the unmatched cleanliness as each bag would be sterilized before use and disposed of after testing, eliminating any chance of contamination. Additionally, these bags would be low cost and very simple to switch in and out. However, several significant drawbacks exist. The first major disadvantage of this system is that the bags are vulnerable to puncture and may burst releasing their contents and exposing the operators to the stimuli. Another drawback is that the bags may not be thick enough to fully contain the smell of the stimuli which could pose a risk to the test operators. One last minor disadvantage is that the bags would need to be replaced frequently which would be an added cost over time, albeit a small one.

Table 13: Pros and Cons of Plastic Bags

Plastic Bag	
Pros	**Cons**
-New sterile bag each time limiting contamination from re-use -Stimuli can be swapped quickly	-If the bags are disposed of after each use, costs can accrue over time -Bags are susceptible to being punctured or burst -Odor may leak from bags

Flow/Carrier Gas Source

The current system used by the CCNI incorporates an aquarium pump to carry anesthesia to the subject interface. Aquarium pumps are designed to take filtered ambient air and pump it into a fish tank, helping with circulation of water and therefore assisting the water filtration system. There are a wide variety of pumps on the market which can be easily purchased online or in stores. This allows for an extensive selection of pumps for use in the design of this project. Some, but not all of these pumps have the option to adjust the flow rate of delivered air. While others have only one set flow rate. In this project the flow rate of the air would be controlled using a flow meter. These instruments are also designed to be unobtrusive in a family home, and some incorporate multiple muffler systems to ensure the pump is quiet. However, over time the precision and quality of these pumps degrade. Depending on the brand and model, these pumps can last anywhere for months to years. After this time, they lack efficiency in flow delivery and sound muffling. While these devices are the lowest cost option for flow control, they would also need to be replaced more frequently.[63]

Table 14: Pros and Cons for Aquarium Pump

Aquarium Pump	
Pros	**Cons**
-Low cost -Easily replaceable -Many models to choose from -Quiet -Adjustable flow rates in some models	-Flow rates are imprecise -Wear over time -Need to be replaced frequently

Vacuum pumps create a pressure differential in the inlet and outlet by evacuating air from a closed system. There are two main methods of vacuum pumps: capture pumps and transfer pumps. Transfer Pumps cause motion in gas molecules by either kinetic momentum exchange or positive displacement. Kinetic pumps are able to have high compression ratios at low pressures. They normally incorporate a blade system or vapor to motivate molecules to travel toward the outlet and are normally not sealed volumes. Positive displacement pumps incorporate a closed system and typically trap a volume of air to move it toward the outlet. Capture pumps use chemical reactions within a vacuum to capture gas molecules on the vacuum surfaces. Vacuum pumps can also be wet or dry depending on the amount of liquid or oil exposed to the expelled air. Some pumps use oil or water to lubricate the systems and therefore, this liquid can contaminate the air. Dry pumps do not incorporate lubrication and instead rely on tight tolerances. Use of these devices could cause safety concerns for the subject interface. If there is a problem with the pump, it could create a partial vacuum abound the subject's breathing zone and therefore lead to suffocation. A vacuum pump could also provide low or high-pressure zones in the tubing of the system and cause damage or wear to the device. A vacuum pump would also

need to be placed between the rat and the components of the system. Therefore, it would not be able to bubble air through a vial.[64]

Table 15: Pros and Cons of Vacuum Pump

Vacuum Pump	
Pros	**Cons**
-Allows for suction of air	-Vacuum must be placed at the end of the tubing rather than the beginning of the system -Could create high pressure zones that would damage the tubing in the event of device failure

Compressors convert power to potential energy stored in compressed air. They take in filtered air and store it in a tank until the pressure of the packed air reaches a target value. Then the compressor shuts off and the air is stored until needed, at which point the energy stored in the air can be used for several applications. In this project, the air pressure would be controlled using an air regulator and a flow meter to create an outlet flow of a desired velocity. As the air leaves the tank, pressure within decreases and the compressor activates again to add more air and reach the target pressure again.

There are two main types of compressors: positive displacement and dynamic displacement. Like the vacuum pumps detailed above, positive displacement compressors use a closed system where the volume of the trapped air decreases, causing compression. Dynamic displacements incorporate a rotary component which uses kinetic energy and centrifugal force which accelerates and then decelerates air, pressurizing it. Compressors can also operate as wet or dry devices, meaning that some use lubrication to lower friction in moving parts and some do not. Those incorporating lubrication can result in liquid contamination of the compressed air.

These devices are quite durable and long lasting. However, they tend to be larger than the above mentions pumps and would be bulky on the operation table at the CCNI. Compressors can also be uncomfortably loud during operation due to the mechanics of the instrument and the resulting vibrations.[65]

Table 16: Pros and Cons of a Compressor

Compressor	
Pros	**Cons**
-Includes filtration system -Industrial grade for increased durability	-Operation produces loud noises and vibrations -More expensive than other methods -May potentially leak oil into air flow

A fan is another option to create flow in a system. These devices are widely used as temperature regulators and are used abundantly in electronics. Fans operate by powering a motor which then rotate a shaft connected to fan blades. These blade cause motion in the air. Fans are easy to replace or repair due to their low cost of materials and abundance of uses in other applications. Most fans have adjustability in speed controlled by a difference of voltage applied to the motor. However, these devices create turbulent flow and could result in backflow throughout the system. Fans produce a small pressure differential and therefore may not supply enough pressure to create our target flow rate. They also do not normally come equipped with air filters and can be bulky and loud.[66]

Table 17: Pros and Cons of a Fan

Fan	
Pros	**Cons**
-Cheaper than other methods -Provides adjustable velocities	-Produce only a small pressure differential -Can result in backflow -Certain fans produce loud noises -Circulates unfiltered air

Relying on the natural air flow of the room to push air to the subject interface is another potential option. This design choice would result in zero added cost and would add simplicity in the number of devices used in the system. However, this method provides no reliable method to deliver odor and could not be repeatable or precise.

Table 18: Pros and Cons of Passive Air

Passive Air	
Pros	**Cons**
-No added cost -No additional components	-Imprecise control of airflow -Pressure gradients are not strong enough to carry stimuli reliably

Directional Control Method

Solenoid valves are on or off switches which are controlled by an electric current through a solenoid. There are two main types: two-port and three-port valves. Two port valves alternate between two states and are either on or off. Three port switches have one input and can alternate between two different outputs or a closed condition. Solenoid valves have an activation time of five to ten milliseconds and therefore can be automatically controlled with an improved response

times. This control option is more complex than the alternatives because it is controlled

electronically, and this valve requires a microcontroller and relay to operate. These devices are

priced in the same range as durable manual valves, therefore, cost is not a significant concern.

Additionally, these devices may not be used in the confines of the MRI room due to it

electromechanical function.[67]

Table 19: Pros and Cons of Solenoids

Solenoids	
Pros	**Cons**
-Instantaneous response time -Automatically controlled -Durable -Reliable	-Must be operated with a relay and microcontroller -Cannot operate in an MRI testing environment

Manual switches, such as a ball valves, are purely mechanical devices and are therefore

simpler for use in design. They are also widely available on the market and low cost, making

replacement of parts an easy task. If made of nonmagnetic materials, for example plastic, these

valves would be compatible with the MRI room and could be used near the subject interface to

control flow. However, these devices lack synchronization, and therefore complicate the user

interface of the device. If there are multiple switches that need to activate at the same time, the

operator would need to plan ahead and coordinate their controls.[68]

Table 20: Pros and Cons of Manual Switches

Manual Switches	
Pros	**Cons**
-Low cost -Easily replaced -No microcontroller is needed -Compatible with use in an MRI environment	-Cannot be synchronized with one another or timed precisely without the use of an additional component

The final option for flow directional control involves using only the pressure controls from the compressor or pump to dictate the flow and exclude an additional device like a solenoid valve or manual valve. While this allows for a much simpler design because of the use of fewer parts, the device would not achieve the desired level of precision needed to accomplish the client's needs. This would also lack a method to control flow direction to the different odor vials.

Table 21: Pros and Cons of No Flow Controller

None	
Pros	**Cons**
-No extra cost in the design	-No precise control of flow

Component Connections

One type of material that the team considered using for component connections was the broad category of flexible tubing, which can be comprised of many different materials, with a correspondingly wide range of mechanical and material properties. Materials with strong elastic properties are capable of greater deformations before failure when compared to less flexible materials. Some examples of common flexible tubing materials include Nylon 6, polypropylene, and silicone tubing, which each have their own advantages and drawbacks. For example, silicone

tubing has the highest reported percent elongation before failure of the three choices, with an elongation percentage between 570 and 795%. Polypropylene has the highest tensile strength of the three, which makes it the strongest of the choices, and Nylon 6 is the most durable choice with higher heat distortion temperatures and specific gravity. These materials are all reported by their manufacturers to not possess an inherent odor.[69] With any of these materials, proper contamination prevention is a primary concern. Additionally, as the length of the tubing is increased through operator manipulation, stimulus delivery is affected and must be monitored accordingly. The advantages and disadvantages of flexible tubing are detailed in Table 22.[70]

Table 22: Pros and Cons of Flexible Tubing

Flexible Tubing	
Pros	**Cons**
-Flexible enough to move through testing environment unencumbered -Can be made from wide variety of materials	-Certain materials are prone to contamination -Some materials are more porous than others -Can be difficult to thoroughly clean -As the length of tubing increases, the delivery time for stimulus also increases

The category of rigid piping encapsulates stiffer materials which come with the disadvantage of providing limited flexibility. Piping materials are also extremely varied and include hard plastics, metals, and metal alloys. Common piping materials include stainless steel, extruded aluminum, and PVC and related synthetic polymers. As a single entity, these materials are stiffer and therefore offer a smaller level of compliance than the option of flexible tubing, but they regularly provide higher levels of mechanical strength. Due to the lack of compliance, the options for rigid piping are prone to limited assembly orientations during construction of the

device. When considering the client's current testing environment, the presence of copper ports ranging in area from roughly 330 mm^2 to 500 mm^2 as the only opening to the MRI room greatly limits the diameter of piping that can be used. Additionally, the distance from the ports to the opening of the MRI bore establish the minimum dimensions of the piping, with obstructions in the room's path adding to the total distance and complexity of the connections. The pros and cons of using rigid piping as the component connections are summarized in Table 23.

Table 23: Pros and Cons of Rigid Piping

Rigid Piping	
Pros	**Cons**
-Can be constructed from a wide number of materials -Good mechanical strength would result in less frequent mechanical failures	-Rigidity would result in limited construction orientations -Larger piping might not be able to fit within the bounds of the testing environment

Direct connections in the terms of this project are defined as continuous links between the device components. This method would certainly minimize the space that stimuli would have to travel before being exposed to the subject, which in turn would minimize the error caused by adhesion, preemptively exiting the system, and flow inconsistencies. Additionally, direct connections would minimize the operating time of the system. However, in order for direct connections to be utilized in the team's system, it would have to be placed entirely in the MRI room. For this placement to be feasible, the entire system would have to be compatible with the MRI, which would prevent the use of solenoids and other electromagnetic systems. Table 24 summarizes the advantages and limitations of direct connections as the link between device components.

Table 24: Pros and Cons of Direct Connections

Direct Connections	
Pros	**Cons**
-Delivery time is minimized -Less space to travel through would result in less possibilities for contamination	-Lack of flexibility would result in limited use -Direct connections would result in a rigid structure that could only work in a single orientation -Construction/deconstruction of the device would likely be more difficult

Stimulus Quantification System

Photoionization detectors are gas chromatography detectors with a range up to 15,000ppm. These battery powered devices are very accurate and portable and also include an option for wireless communication. They are used widely in odor experiments and are thoroughly documented allowing CCNI test designers to model their own tests after others. However, these detectors are in the price range of $4,000 and above. They also require the use of a Gas Chromatograph (GC), a device used for separating and analyzing vaporized compounds that costs approximately $5,000. Having a GC would complicate the design and add unnecessary maintenance, cost, and size restrictions. GC are large and could not comfortably fit on the preparation table.[43]

Table 25: Pros and Cons of PIDs

PIDs	
Pros	**Cons**
-Compact -Portable -Well-defined use in odor experimentation -Accurate quantification	-Expensive system (~$2,000 or more) -Gas chromatograph is needed for detection

A mass spectrometer is a gas chromatography detector which measures complex mixtures by their mass to charge ratio. They are extremely accurate and possess up to a nanogram of sensitivity. This device can be used to analyze a large variety of stimuli and is, therefore, a versatile option for detection. However, these devices do depend on gas chromatography and are large in size as well as cost, which can exceed $3000. Due to the large size, this unit would not be able to be set-up on the available space of the preparation table outside the MRI room.[40]

Table 26: Pros and Cons of Mass Spectrometer

Mass Spectrometer	
Pros	**Cons**
-Accurately describes the masses of each component -Can be used for odor and particulate matter -High in accuracy and precision	-Expensive system (~$3,000 or more) -Bulky system, size might be disruptive to the client's working environment -Gas chromatograph is needed for detection

Flame Ionization Detectors are an accurate solution to the quantification element. They are robust and durable and can withstand both time and heavy usage. They are also small in size and would be able to fit on the preparation table of the CCNI. However, these devices are not commercially available and therefore would be difficult to replace parts in case of failing parts.

FIDs require individual sources of hydrogen gas and filtered air. There is also the added safety concern of including a design element with a flame to the overall device as it is possible for an ignition failure. This device depends on the use first of a gas chromatograph.[42]

Table 27: Pros and Cons of FIDs

FIDs	
Pros	**Cons**
-Accurate quantification -Small device -Robust, linear, and stable	-Expensive system -Includes a flame which could pose a potential safety risk -Gas chromatograph is needed for detection

Electronic noses have been used with success in the field of olfactory research. They are beneficial to experiments where the odors and testing variables are defined and consistent throughout the test. For example, testing the strength of body odor for different people. This experiment measures the same type of compound each time. Electronic noses are accurate to the scale of (CITE) and are small devices, normally the size of a coin. These sensors also are independent of gas chromatographs which is a large benefit, because this absence decreases the complexity, cost, and degree of maintenance of the device. However, electronic noses must be designed with a certain experiment in mind and are therefore not as useful for a device that will be used for a wide variety of tests and stimuli. Currently, there are no commercially available and universal electronic nose is on the market.[45]

Table 28: Pros and Cons of Electric Nose

Electric Nose	
Pros	**Cons**
-Accurate with a specific set of compounds -Does not require a gas chromatograph	-Does not detect a universal array of odors -Must be customized for each experiment -No commercially available electronic nose that suits the needs of the client

Optical Particulate Matter Detectors (OPMDs) are useful when analyzing the amount of pollution in an area and are used mostly in government data collection. Due to their wide use, these devices are available from many vendors, however, these detectors only analyze the size of a particle and do not analyze the type of compound being detected. Thus they can only be used as a supplemental device in testing and not for primary odor detection and identification.[51]

Table 29: Pros and Cons of Optical PM Detectors

Optical PM Detectors	
Pros	**Cons**
-Ideal for classifying particulate matter -Accurate and precise measurements	-Only capable of quantifying the size of the particulate matter -Cannot determine the type of particle detected

An alternative method of quantifying the stimuli delivered to the subject that was considered by the group involved estimating the amounts of stimuli by using dilution factors. With this method, the concentration of stimuli in the stimulus storage container would be assumed at 100%, and the rest of the system would be assumed to contain 100% air. The concentration of the target stimulus being delivered to the subject can then be estimated by calculating the amount that it has been diluted. This dilution factor can be calculated using the

volumetric flow rates of the air and stimulus streams, with variations in flow rate resulting in changes in the final concentration of stimulus being delivered.

This method of quantifying stimuli delivery adds no additional cost to the design and is dependent on well-defined flow dynamics for accurate measurements. Additionally, this method acts as an estimation of the amounts of stimuli being delivered to the test subject, not a quantification of the amount actually being delivered. For this reason, estimation using dilution factors is less accurate than the other methods discussed previously but is believed to be within the realm of accuracy desired by the client. The pros and cons for this method are summarized in Table 30.

Table 30: Pros and Cons of Dilution Factor Estimations

Dilution Factor Estimations	
Pros	**Cons**
-Adds no cost to the design -Accurate enough to satisfy the client's needs -No additional components are required	-Not as accurate as most other methods -Relies on mass flow rates through the device for calculations which could result in inaccurate readings for ill-defined flow dynamics

Stimulus Evacuation System

A forced evacuation system would be beneficial as it would be able to integrate components that are already built into the system, such as the pump. In such an application, air would be forced through the system via the pump until exiting the device later downstream. Therefore, a forced evacuation system would only require incorporation of an exit valve. Other than this, evacuation in this method would ultimately depend on the number and location of the carrier gas sources. If using a single pump, the entire system would need to be evacuated

simultaneously for complete removal of odor. If multiple sources and pumps were used, each

pump could be activated separately to evacuate its respective odor vial and tubing system. The

largest issue in this application would be the potential for air to be forced towards the subject,

which could cause discomfort and produce confounding variables.

Table 31: Pros and Cons of Forced Evacuation System

Forced Evacuation System	
Pros	**Cons**
-Simple system for evacuation -Utilizes existing pumps for directing airflow	-Evacuation would depend on the number and location of carrier gas sources -Using one source would result in the entire system being open for this method to work -Otherwise, multiple sources would need to be used -Air could be forced towards the subject causing discomfort

Another type of evacuation system could utilize water, or another type of aqueous

solution, to flush the components and tubing of the device. Water is more efficient at trapping

odor volatiles than air is and would therefore be a more complete evacuation agent. However, for

this evacuation system to be implemented into the design, a water source and pump would need

to be incorporated into the system as well as a collection system for the water. Furthermore,

water would need to be completely cleared from the system before additional tests could be run

and therefore this type of system would require a secondary phase evacuation to remove leftover

water droplets. Furthermore, water has the potential for damaging electronic components and

water also may be forced toward the subject which would cause discomfort and include

confounding variables.

Table 32: Pros and Cons of Forced Water Evacuation

Forced Water Evacuation	
Pros	**Cons**
-Water would act as a better conduit than air for certain materials -Water is more efficient at trapping odor volatiles than air is	-Requires a water source and pump -Water would need to be entirely cleared from the system before running new tests -Water might damage certain components, particularly electrical -Water may be forced towards the subject, causing discomfort

A heating, ventilation and air conditioning (HVAC) evacuation system would be advantageous as it could function separately of the carrier gas source allowing fresh air to be pumped to the test subject while stimuli are vacuumed out of the system. The vacuum used would be the in-lab HVAC system and therefore would not require any additional materials. Furthermore, vacuum suction throughout the device could be selected through the control valves. However, suctioning too much air may cause discomfort for the test subject or even asphyxiation if not carefully monitored.

Table 33: Pros and Cons of Vacuum Evacuation

Vacuum Evacuation	
Pros	**Cons**
-Allows for inflow of fresh air and outflow of stimuli -Capable of integration with the client's HVAC system -Vacuum suction can be controlled through valves	-Suctioning air away from subject can cause discomfort -Malfunctions could cause subject suffocation

A passive evacuation system would be beneficial because there is no added cost to its incorporation as no additional materials or manufacturing would be required. The device would only need to be opened up to allow fresh, ambient air to flush it out. This passive system would need to rely on gravity and pressure, however, which would be unreliable and make it difficult to replicate evacuation procedures consistently. Furthermore, passive systems rely, in part, on the exhalation of the subject to direct airflow. Due to the small respiratory capacity of the test subject, this will not sufficiently purge the system.

Table 34: Pros and Cons of Passive Air

Passive Air	
Pros	**Cons**
-No cost -No associated materials or manufacturing	-Dependencies on gravity and pressure create unreliable controls -Subject exhalation would likely not be strong enough to direct airflow -Does not accurately remove odor -Long purge times

Test Subject Interface

By using the nose cone that the client is currently utilizing in their experimental

procedures, the team would have the advantages of saving money, time, and materials.

Additionally, the test operators have used this nose cone design before, which would translate to

comfortability with the system and relative ease of use. However, the system was crudely

manufactured, which translates to poorly defined mechanical properties and dimensions, thus

making it more difficult to account for in system models and in actual use. Table 35 lists the pros

and cons associated with using the existing nose cone.

Table 35: Pros and Cons of Existing Nose Cone

Existing Nose Cone	
Pros	**Cons**
-Pre-made -Zero cost -Lab technicians are comfortable using it	-Frequent use has caused some degradation -Properties are ill-defined

By using a newly manufactured nose cone, the team would have the advantages of

customizing the interface to limit the amounts of stimuli that are lost to the environment. In

addition, the new design will have well-documented dimensions that the client could use to make

repairs or additions in the future with minimal hassle. The associated disadvantages include the

time, cost, and materials associated with constructing a new nose cone. Additionally, the nose

cone will have to be manufactured to interface with multiple subject sizes. Table 36 highlights

the advantages and disadvantages associated with using a new nose cone in the final design.

Table 36: Pros and Cons of Redesigned Nose Cone

Redesigned Nose Cone	
Pros	**Cons**
-Can be custom built for the client's needs -Can minimize stimulus lost to the environment -Can minimize turbulent flow around subject	-Requires construction -Will have to work for different sized subjects

Using tubing alone to interface with the subjects would minimize the cost associated with construction and would also have the added benefit of being easier to characterize in terms of flow than adding a subsequent shaped structure. The limitations include a large amount of empty space between the subject and the stimuli, thus leading to a larger amount of inaccuracies. Additionally, the stream emanating from the tubing may produce more turbulent flow than the other methods, which could frighten the subjects and introduce more error to the delivery system. Evacuation through the tubing would also be difficult for the same reasons listed for delivery. The pros and cons of using tubing alone as the subject interface are summarized in Table 37.

Table 37: Pros and Cons of Tubing Alone

Tubing Alone	
Pros	**Cons**
-Limits construction and expenses -Flow to subject can be more easily modeled	-Using only tubing might result in empty space between the device and the subject -May result in more turbulent flow to the subject -May result in stimuli loss to the atmosphere

The hood method introduces the advantages of minimizing the amounts of stimuli lost to the environment and having well-defined flow dynamics, thus eliminating inaccuracies derived from both sources of error. While this method is theoretically the most reliable in terms of delivery and evacuation, the size of the hood would limit its use for the client. By using the client's current MRI, a hood design would likely be too cumbersome and would not fit in the bore of the MRI. Because MRI compatibility is one of the constraints associated with this project, not interfacing with the machine is unacceptable. Table 38 summarizes the advantages and disadvantages associated with utilizing the hood method as the subject interface.

Table 38: Pros and Cons of Hood Method

Hood Method	
Pros	**Cons**
-Minimizes the amount of stimulus lost to the environment -Flow dynamics are well-defined -Minimizes inaccuracies resulting from exposure to the testing environment	-Large size will restrict the testing environment it can be used within -Might not be compatible with an MRI -May disturb test specimen

4.3.3 Quantitative Means Analysis

In addition to exploring the efficacy of each of the suggested design means qualitatively in the previous section, the team also wanted to analyze each possible mean in a more objective manner. This goal was accomplished by designing a quantitative means analysis matrix, which is located in Appendix E: Quantitative Means Analysis. The matrix utilizes the pairwise comparison charts filled out by the device stakeholders to assign a weight to each of the primary objectives. From there, a rating system was developed by the group for each of the secondary objectives, which can be seen in Appendix D: Rating System for Quantitative Means Analysis.

Using this rating system in conjunction with the weights of each objective, each design mean was analyzed objectively to gain a quantitative score on its likelihood for success. The matrix highlights the total scores for each of the elements in yellow, and the highest performing components were chosen for testing purposes. In cases where the highest performing mean could not be obtained by the group, the second best performing mean was used for testing.

5. Development and Verification of the Final Design

Following quantitative analysis of the components with the creation of the means matrix, the team was able to determine which parts would best benefit the design. From here, the team was able to brainstorm a number of preliminary designs.

5.1 Preliminary Designs

Of the preliminary designs, the team was able to isolate three unique, preliminary designs that each met the constraints and objectives outlined in Chapter 3. The designs are outlined in the next sections, after which a final design was picked which combines relevant elements and components from each design.

5.1.1 Preliminary Design 1

The first design idea that the team considered is depicted in Figure 21 which exemplifies an approach utilizing a holding chamber.
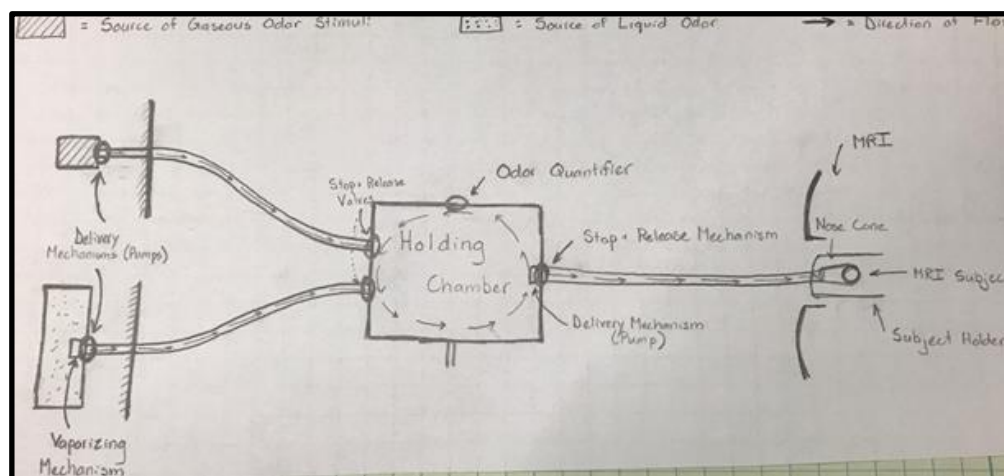
Figure 21: Concept sketch of Design 1.

This design includes two entry ports into the holding chamber. One of the inputs is designed for gaseous odor stimuli storage, while the other is meant for liquid odor stimuli. These

inputs would be loaded with the corresponding stimulus type, and then attached to the pumps connecting the two input sections to the rest of the design. The liquid stimuli input would have a vaporizer attached directly after the pump so that the stimuli could be turned into a gaseous form to be moved throughout the rest of the system. Tubing then connects the inputs with attached pumps to the entry ports of the holding chamber. In the holding chamber, stimuli can accumulate and mix if there are multiple stimuli types being used for a single experimental procedure. Stop and release valves guard the entry and exit points of the holding chamber and are set to block the connections that are not being used. For example, when the stimuli are first entering the system, the output and evacuation ports are closed off by the valves, while the necessary input port is left open.

Within the holding chamber, a quantification system would maintain control of the stop and release valves. The system would be set to a desired amount of stimulus by the test operator and would continuously monitor the holding chamber until that amount is reached. At that point, the valves for the entry points would be set to block access, the valve for the output would be opened, and the attached output pump would be activated to draw the stimulus-saturated air to the next stage of the system. The last portion of the device consists of tubing that would connect to a nose cone that would then interface with the test subject to deliver the stimulus. After each experimental testing suite, or when the test operators determine that it is needed, the system can also be evacuated to reduce contamination. For this process, clean air is moved through the system into the holding chamber in the same method that stimuli would normally undergo. Additionally, a vacuum pump would draw contaminated air from the latter parts of the system and force the stream into the holding chamber. A separate evacuation valve would then be released to allow the contaminated air to evacuate into the surrounding testing environment,

which would then be filtered before leaving the building.

The advantages associated with this design include an accurate quantification system, since stimuli output is dependent on proper quantification, and a robust evacuation system that incorporates the entire device. The addition of several pumping mechanisms to various points in the system provide the advantage of increased manipulation of flow rate. For example, the flow rate of stimulus to the holding chamber can be maximized to shorten the operational time of accruing the proper quantity of stimulus for each test. The additional output pump can then be set to a slower flow rate that would not cause harm or distress to the test subject. Due to the fact that the holding chamber and everything prior to it in this design contain some electro-mechanical component, these portions of the device would need to remain outside of the MRI testing room to avoid compatibility issues. For this reason, the length of tubing connecting the holding chamber to the test subject would cover the distance from the copper entry ports of the MRI testing room to the MRI bore where the test subject would be loaded. Consequently, the risk of tubing issues including pressure drops, changes in flow rate, kinking, and general deformation would increase and could have detrimental effects on the reliability of stimuli delivery to the subject. Other limitations include the possibility of turbulent flow during evacuation due to two pumps drawing different air streams into the same area. This turbulence could result in improper contamination evacuation or in harming the test subject.

5.1.2 Preliminary Design 2

The second design idea, which can be viewed in Figure 22, makes use of a compressor that would deliver a carrier gas to an odor bank composed of four to five odor containing vials. These vials would be custom made and could contain either liquid or gaseous stimuli. Additionally, the vials would be comprised of an inert material such as glass or PTFE to reduce

any odor altering effect on the stimuli. A solenoid valve at the entrance of the odor bank would

control which odor vial the carrier gas would go to and provide quick and precise airflow

kinematics. When the carrier gas enters the odor vials at a known flow rate, it will be held for a

certain amount of time to mix with the odor in a known concentration. Once the odor is

completely mixed, it will be released by another solenoid into a dedicated tube running towards

the test subject nose cone. After testing is complete, the 1st solenoid will switch the carrier gas to

a vial containing no stimuli so fresh air can be pumped into the system purging it of stimuli.

Since there is an opening at the top of the test subject's holding unit, the contaminated gas can be

forced out through there.
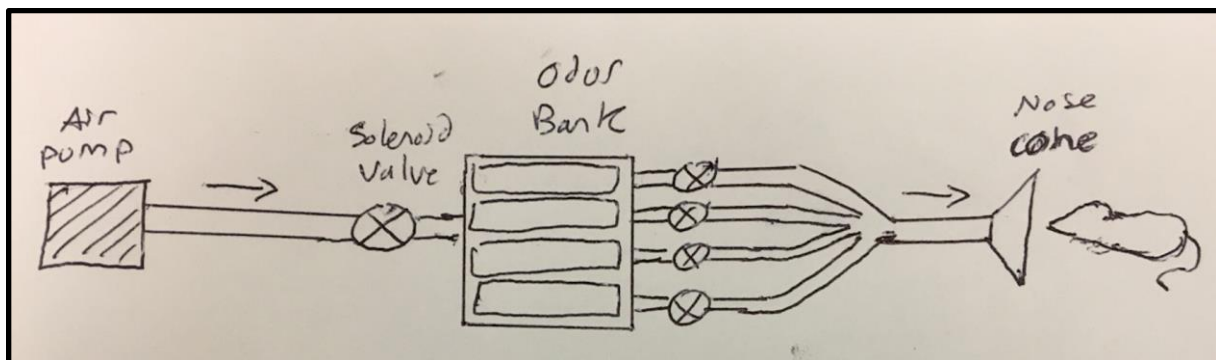
Figure 22: Concept sketch of Design 2.

A few advantages of this system are the modular design, ease of use when switching

stimuli in and out, and dedicated downstream odor lines to prevent contamination. The benefits

of the modular design allow the system to be converted into various configurations for different

types of stimulus testing including liquid, gaseous, and particulate matter stimuli. By simply

switching the odor bank vials to suit the stimuli, the system has unlimited reusability. Other

components that can be switched out include the carrier air source, air flow control mechanisms,

and tubing. Lastly, the system allows for alteration in the future if the CCNI wishes to invest and install a PID.

A potential drawback is that the contaminated gas is let out into the testing facility which could be a concern if testing with potentially deleterious specimens.

5.1.3 Preliminary Design 3

The third design, pictured in Figure 23, focuses primarily on evacuation, while borrowing elements from the first two designs. It is comprised of a pump or compressor which pumps air through the system. The pump is connected to a single tube, which connects into a four-way divider. From the four-way divider, three tubes travel to an odor bank, while the last tube travels all the way through the wall from the testing room to the nose cone in the MRI room. The four tubes each connect to a solenoid directly after the four-way divider, which allows the device to be controllable. From the odor bank, a single tube traverses the gap between the testing room and the MRI room and travels to the nose cone. Prior to the nose cone, the aforementioned single tube connects to the air tube by means of a Y-shaped divider. From the Y-shaped divider, a single tube travels to the nose cone. The nose cone has another outlet which is used for evacuation. The evacuation tube travels from the nose cone to a charcoal filter within the MRI room. Filtered air then travels from the charcoal filter to the inhouse vacuum outside the MRI room.
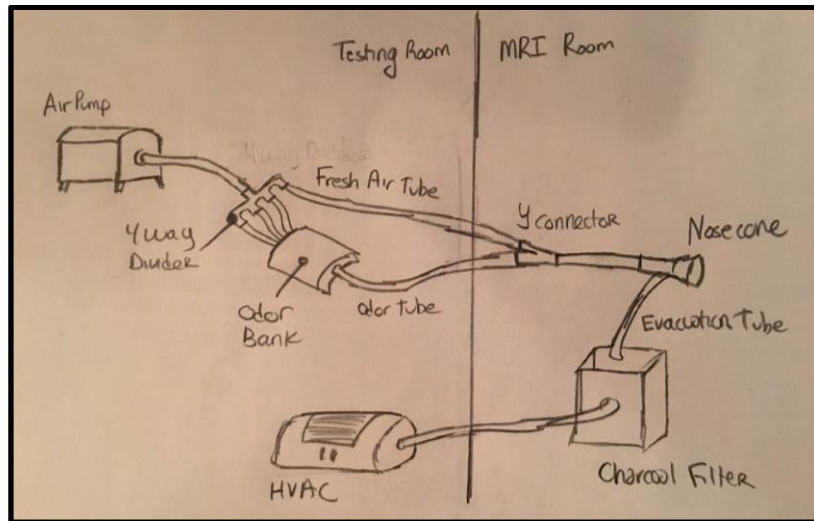
Figure 23: Concept sketch of Design 3.

The benefits of this design are that it can be controllable through the use of solenoids, and also clean air can be filtered through the system at will. Furthermore, the system can be vacuumed, which enables complete evacuation of the system. The system also has a charcoal filter, which will be able to filter out dangerous chemicals that may damage the house vacuum or pose a hazard if pumped outside of the facility. A disadvantage of this system is that the odor could be sent through the Y-connector as well as the nose cone, which could create a buildup of pressure and a loss of odor. Flow calculations may also be made difficult due to the fresh air tubing.

5.1.4 Complete Initial Design

The strengths and weaknesses of preliminary designs one, two, and three were evaluated and outlined. The team then created an initial design, borrowing from the main advantages of each system. A conceptual image of the initial design can be seen in Figure 24.
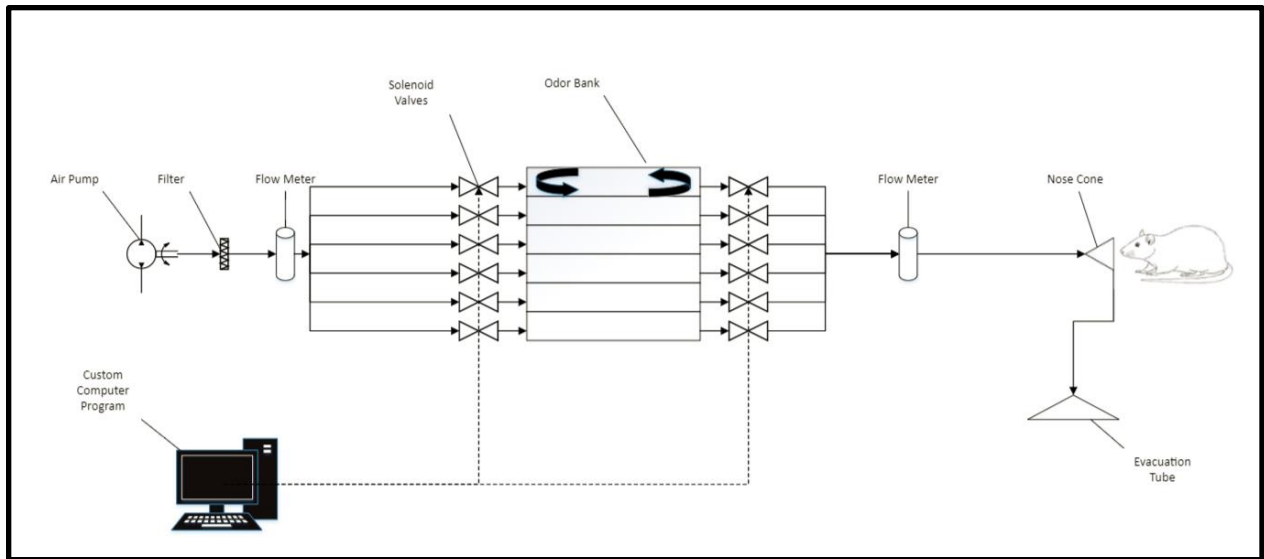
Figure 24: Diagram of the initial design.

This system begins with an industrial grade air pump equipped with a HEPA filter that has 5 outputs built into it. Each output will be connected to a length of tubing that passes through a flowmeter and leads up to a large odor bank. At the entrance to the odor bank, there will be 5 solenoid valves to start and stop the flow of air into separate odor vials loaded into the system. These solenoid valves will be controlled remotely via a computer interface that a technician can operate. Once the carrier gas is let into the odor vial at a known flow rate, it will mix with a known concentration of odor in either liquid or gaseous form. This will allow the computer program to use dilution factors to control the concentration of stimuli that is released. Once the proper amount of mixing has occurred in the vial, a second set of solenoids will release the odor stream to a second flow meter to take a final flow measurement. After the measurement is taken, the odor stream will continue on to the nose cone and the test subject. To evacuate the system, contaminated vials will be taken out of the system and replaced with empty vials so fresh air can purge the tubes. To aid in this process, an additional output will be added to the nose cone connected to a vacuum pump that will provide light suction to remove the contaminated air without asphyxiating the test subject. Benefits of this system include completely separate lines of

air to limit cross-contamination between stimuli, modular design, and precise quantification through odor dilution. Additionally, the added vacuum pump will limit contaminants from entering the test facility and potentially harming any technicians.

5.2 Preliminary Testing

After choosing the initial design, the team initiated a testing phase. The team created testing procedures to validate parts and functional aspects of the design. The following sections describe the various tests that the team conducted.

5.2.1 Part Validation

Before the team began initial testing, the first necessary step was to validate the working condition and accuracy of equipment. The two components analyzed for operational effectiveness where the ball valve and pump. The pump used in tests is the "Whisper 300" model rated for a 1.3 L/min flow rate. To validate this specification, the team connected a foot of tubing to the pump and a flow meter with a range of zero to ten L/min. The pump was then plugged into the wall outlet as a power source and a flow rate of approximately 1.3 L/min was confirmed. The ball valve was then inserted between the pump and flow meter and was turned to the off position. This caused the flowmeter to report zero L/min of flow, therefore validating these components and allowing testing to begin with confidence in the results.

5.2.2 Initial Testing of Odor Delivery

After validating that the selected parts for the project worked as specified, the team then wanted to perform an experiment to further gauge the effectiveness of infusing an airstream with

odor by bubbling air through a liquid odorant. To perform this experiment, the group first selected a team member, referred to in this report as Team Member A, to perform blind odor detection tests. Three odorous compounds were selected initially to be used for this test, mirin, sesame oil, and vinegar .25 mL of each of these compounds was poured into a test vial. The vial was then sealed with a modified cap that had two ports of the same size as the silicone tubing. An input tube and an output tube were both inserted through the cap, with the input tube being submerged into the odorous liquid to initiate bubbling. The output tube was kept closer to the cap to ensure that it would only be allowing an air-odor mixture to be passed through the tubing to the test subject, rather than any of the liquid odorant. The input tube was connected to the aquarium pump used for testing, which has a flow rate of approximately 1.3 L/min as confirmed by initial validation. The longer output tube then led to Team Member A, who was blindfolded to prevent visual identification of the odor source.

When running this test, odor quality and quantity were measured with several parameters. Upon starting the pump and initiating the testing sequence, the test subject was asked to identify the time at which an odor was detected, whether or not they could recognize the scent as familiar, and an attempt at identification of the odor. These three parameters, detection, recognition, and identification, are all characteristics by which odor is measured, with each requiring increased levels of quantity or quality of odor to be achieved. The time of detection was recorded, and then recognition and positive identification were reported as binary true or false qualities. Each odor delivery sequence was run for one minute to give the subject time to process the aroma.

When running this procedure initially, sesame oil was arbitrarily selected as the first compound to test with. Team Member A detected the aroma approximately 5 seconds after the

pump was started, and was able to recognize the odor, but was incapable of correctly identifying it. The second test was run with mirin, and Team Member A reported detecting the odor within two seconds of beginning the procedure but determined that the smell was the same as the first trial. Realizing that there had been contamination at some point in the process, the team decided to halt the testing, and continue with some adaptations.

To remove the chances of contamination affecting the results from this test, the group thoroughly cleaned all of the odor vials that were used previously until they were determined to be odorless. Additionally, the group disposed of the contaminated tubing and selected 5 one-foot portions of fresh silicone tubing to rerun the experiment with. These sections of tubing were shorter compared to those used in the initial testing sequence due solely to the limited amount of silicone tubing for testing. These sections of tubing were each attached to individual vials and the tests were run separately to ensure that no contamination was occurring between samples. The only shared component between each of the tests was the aquarium pump. To further remove error from this procedure, sesame oil was removed as an odorant due to its ability to stick to and contaminate tubing. Additional odor sources were selected to replace the sesame oil with a focus on stimulant diversity to ensure that the results from this test could be applied to a wide variety of odors. Mirin, lemon juice, coffee, hot sauce, and vinegar were selected as the new test odors to incorporate samples of different compositions and aroma qualities. Finally, to establish a more effective control, Team Member A was instructed to perform the test as specified earlier, with the added component of smelling odors directly from the vial to eliminate the effects of bubbling air through an odor source. Each of the same qualities were measured for these samples, which were randomly interspersed between the samples delivered through tubing, with approximately one minute between each test to prevent odor cross-contamination. After all of the tests were

conducted, Team Member A was presented the identities of the odors, in no particular odor, and was asked to match these named compounds with those that they tested with. This second round of identification is commonly used in odor experiments to gauge the accuracy of the test subject's ability to recognize odors.

With the procedure modified accordingly, the test was run again with a greater degree of success. The coffee sample proved too effervescent to be used for the experiment, since it started to bubble through the output tubing, so it was accordingly removed from the testing analysis. Otherwise, the average detection time for the samples bubbled with air was approximately 5 seconds, with detection time for the non-tubing samples being nearly instantaneous. While Team Member A did report that a tubing smell was detected in addition to the test odors, recognition was identical between tubing and non-tubing odors and identification was very similar. The second round of identification yielded the same results for both methods of odor exposure, which demonstrated to the group that odor delivery through bubbling is an effective method with noticeable differences from direct sampling in detection time. The results from this experiment can be viewed in Table 39.

Table 39: Results of Initial Odor Delivery Testing

Sampling Method	Sample	Detection	Recognition	Identification	Identification 2
Bubbled Through	Mirin	8s	Yes	Orange	Vinegar
	Lemon Juice	6s	Yes	Lemon	Lemon
	Hot Sauce	3s	Yes	N/A	Hot Sauce
	Vinegar	4s	No	N/A	Mirin
Directly from Source	Mirin	Immediate	Yes	Apple	Vinegar
	Lemon Juice	Immediate	Yes	Lemon	Lemon
	Hot Sauce	Immediate	Yes	N/A	Hot Sauce
	Vinegar	Immediate	No	N/A	Mirin

5.2.3 Stimuli Container Testing and Stimuli Delivery Testing

In order to properly contain and store the liquid stimuli, different shapes and materials were tested to observe the quality of odor emanating from the output tube and if any odor was detected leaking from the tube. For preliminary testing, 20 mm x 150 mm test tube vials were used due to their compact nature and ease of use. The team decided to test both borosilicate glass for its chemically inert properties and acrylic for its ability to be modified. Both types of vial were capped off with a plastic top that was pressure fit down into the top of the test tube to close it off.

In order to determine if there was any odor leakage outside the vial when the system was running, the team ran 5 trials for each type of vial. For each trial, the normal testing procedure was followed where the aquarium pump was turned on forcing air through an input tube and into the bottom of the vial filled with 25 ml of stimuli. By bubbling air through the stimuli, the carrier gas is effectively saturated with the odor of the stimuli. Once saturated, the air was then forced out of the vial through an output tube that traveled five feet down to a team member's nose (team member A). Another team member (team member B) was stationed right next to the vial itself and was tasked with observing the air quality and if any odor was detected during testing. The measurements recorded from this test include if odor was detected to be running through the system by team member A and if odor was detected escaping the cap of the test tube by team member B. As can be seen from the test results below, the system's odor delivery was proven to be functioning properly by Team Member A while no leakage odor was detected by team member B. This proves that odor impregnation by bubbling is a feasible option for stimuli delivery and borosilicate glass and acrylic vials are suitable containment vessels. The data for these tables can be found in Tables 40 and 41.

Table 40: Borosilicate Glass Leak Test Results

Trial Number	Odor Detected by Team Member A	Odor Detected by Team Member B
1	Yes	No
2	Yes	No
3	Yes	No
4	Yes	No
5	Yes	No

Table 41: Acrylic Leak Test Results

Trial Number	Odor Detected by Team Member A	Odor Detected by Team Member B
1	Yes	No
2	Yes	No
3	Yes	No
4	Yes	No
5	Yes	No

5.2.4 Bubble Testing

During the original testing of the odor infusion process, it was observed that when testing with several substances including coffee, large bubbles would develop, climb the walls of the test tube, and enter the output tube spraying the substance onto the lab bench. As this would contaminate the tubing and potentially harm the test subject, the team looked into ways to mitigate bubble formation and prevents liquid stimuli from entering the output tube.

5.2.4.1 Foam Pad

For this method, the team wanted to see if a porous barrier would be able to form a ceiling over the liquid and prevent bubbles from getting through while still allowing the stimuli saturated gas to enter the output tube. A piece of foam cut in a rectangular shape 70 mm x 45 mm x 15 mm was used in this test and curled around the input tube to prevent gaps. It was then pushed into the test tube with the input tube before coming to rest approximately 1 inch above the liquid. In this test, 25 mL of coffee was used as this produced the most bubbles during the original stimuli testing and represents a worst-case scenario. A normal testing procedure was then run as described in section 5.2.3 and three measurements were taken: the time at which odor was detected by a team member at the output, the time at which the liquid stimuli breached the foam mesh, and the time at which the liquid stimuli entered the output tube. After 5 trials, test

results showed that the foam barrier was breached in under 1 second and liquid stimuli entered the output tubing within 1-2 seconds rendering this bubble prevention method a failure. The setup is shown in Figure 25 and the results from the experiment can be found in Table 42.
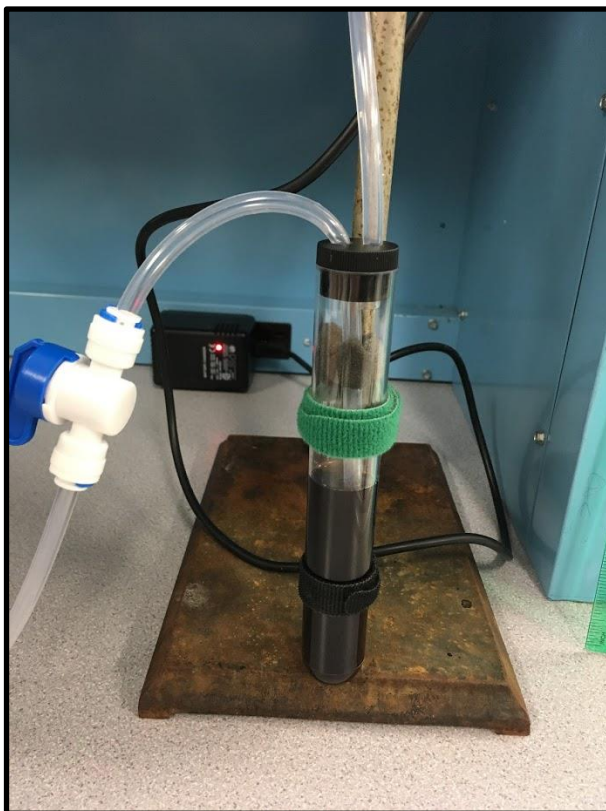
Figure 25: Test setup, with foam inside the vial.

Table 42: Foam Bubble Test Results

Trial Number	Time of Odor Detection (sec)	Time when Top of Foam is Breached (sec)	Time of Stimuli Entry into Output Tube (sec)
1	0.33	0.51	1.02
2	0.41	0.47	0.98
3	0.36	0.41	1.05
4	0.39	0.50	0.90
5	0.32	0.42	0.95
Mean ± SD	**0.36 ± 0.04**	**0.46 ± 0.05**	**0.98 ± 0.06**

5.2.4.2 Steel Wool

Based off of the concept used in the foam pad method of bubble prevention, the team decided to use a different type of porous barrier in the form of steel wool. The experimental setup for this procedure was very similar to the last set up for the foam and can be seen in Figure 26. However, the steel wool had to be prepared by thoroughly washing it before testing as it had soap detergent loaded onto it. Once washed, the steel wool was stretched and wrapped around the input tube before being inserted into the vial 1 inch above the 25 mL of liquid coffee. The test procedure was similar to the foam test in 5.2.5.1. The 3 measurements from the foam test that were noted were the time at which odor was detected by a team member at the output, the time at which the liquid stimuli breached the steel wool, and the time at which the liquid stimuli entered the output tube. Based off of the results, this test was successful in mitigating bubble creation and preventing them from entering the output tube. The sharp edge of the steel fibers effectively sheared the forming bubbles and the liquid only made it up half of the approximately 1-inch height of the steel wool. However, the team member testing the odor quality emanating from the output tube reported that the coffee aroma was completely masked by a potent metallic smell completely founded the odor delivery. Due to this, steel wool was not a viable bubble prevention method. The results from this section can be seen in Table 43.
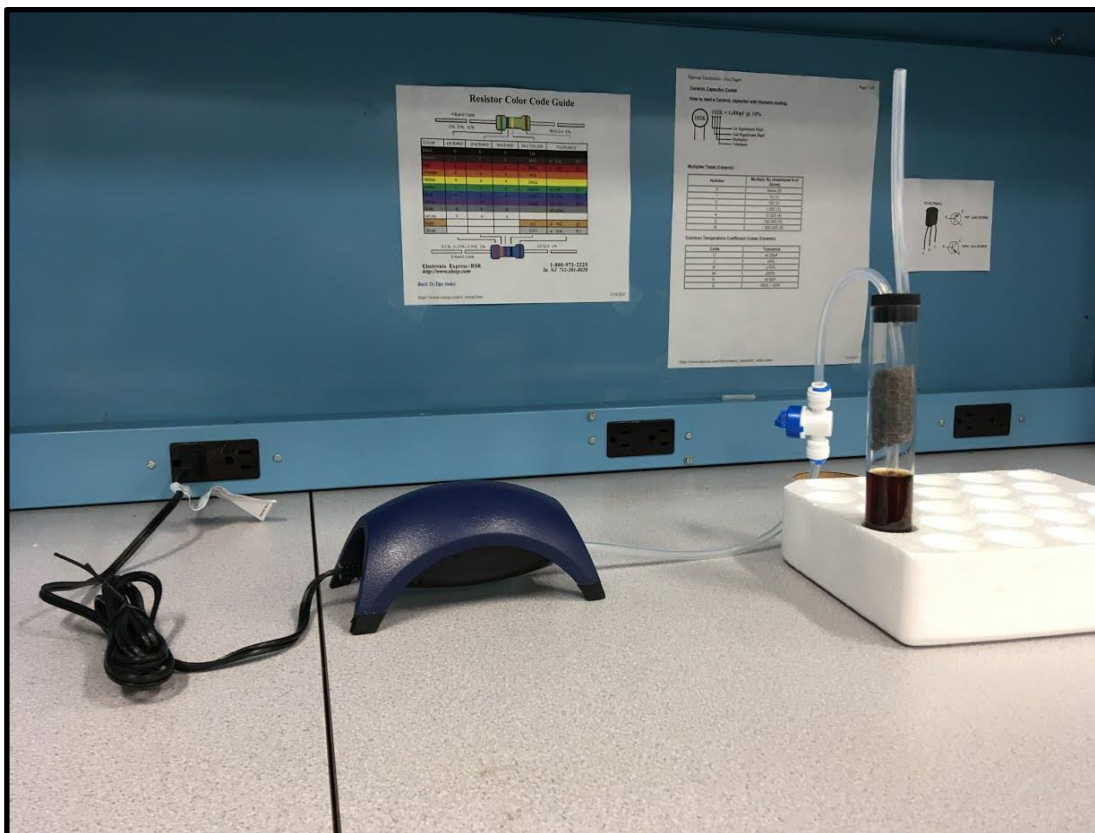
Figure 26: Steel wool test setup. Steel wool can be seen in the vial

.

Table 43: Steel Wool Bubble Trap Results

Trial Number	Time of Odor Detection (sec)	Time when Top of Steel Wool is Breached (sec)	Time of Stimuli Entry into Output Tube (sec)
1	0.45	N/A	N/A
2	0.36	N/A	N/A
3	0.35	N/A	N/A
4	0.41	N/A	N/A
5	0.38	N/A	N/A
Mean ± SD	0.39 ± 0.04	N/A	N/A

5.2.4.3 Vials in Series

Looking for a different approach entirely, the team devised a new method for bubble prevention that did not have a barrier at all but instead used two vials in series to catch spare liquid that may bubble over the top of the first test tube. For the experimental set up, two vials with two holes drilled in the top were set up two inches apart from one another. An input tube was inserted into the first vial that went down to the bottom of the tube to bubble air through the liquid stimuli. A second tube was then used to connect to the second vial allowing for both the air and bubbled stimuli to enter. However, this tube did not go down all the way to the bottom of the second test tubes bottom preventing bubble formation in the second test tube while still collecting overflow and allowing the passage of odor saturated gas to leave by way of another output tube. The setup can be seen in Figure 27. During testing, the team measured if odor could be detected coming from the output tube, the amount of liquid that bubbled over into the second test tube, and the time it took for the first tube to run out of stimuli. Test results can be viewed in table 44. After reviewing the test results, this test was successful in preventing bubble overflow into the final output tube and still allowed odor to be detected at the end of the output tube. However, there is a time limit with this method as once all of the stimuli from the first tube is in the second tube, the carrier gas is no longer being saturated. This should not be a significant issue though as this test was run for 20 minutes, longer than requested by the CCNI's parameters, with stimuli still remaining in the first vial.
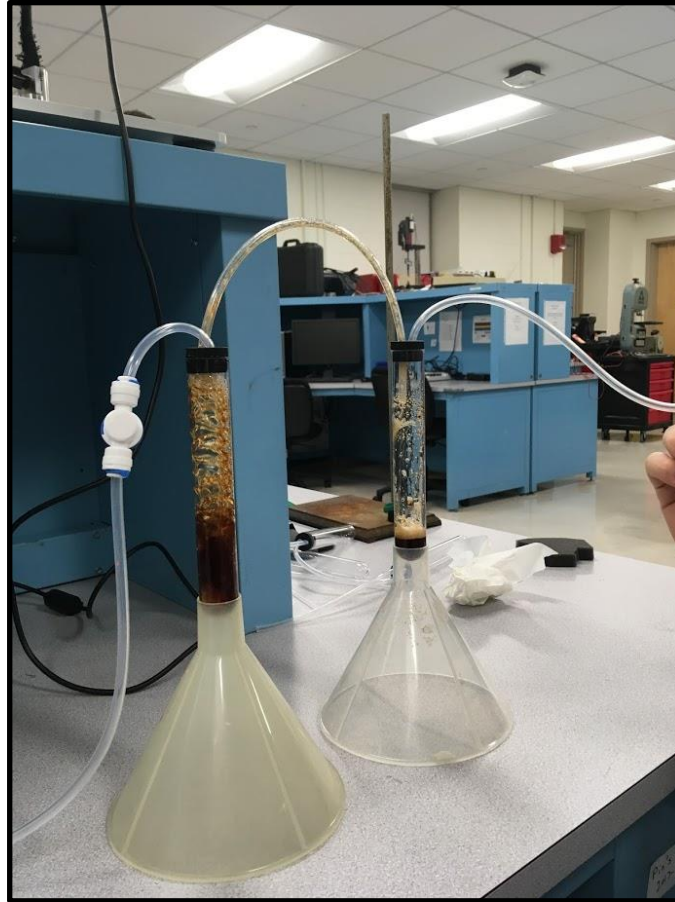
Figure 27: Vials in series setup.

Table 44: Bubble Trap with Vials in Series Results

Trial Number	Time of Odor Detection (sec)	Starting volume of Vial 1 (mL)	Final Volume of Vial 1 @ 20 min (mL)	Time of Stimuli Entry into Output Tube (sec)
1	0.3	25	5	N/A
2	0.3	25	6	N/A
3	0.3	25	5	N/A
4	0.4	25	6	N/A
5	0.3	25	5	N/A
Mean ± SD	0.32 ± 0.04	25 ± 0.00	5.4 ± 0.55	N/A

5.2.4.4 Erlenmeyer Flask

The last test performed by the team for bubble prevention and general stimuli container
shape was to test a variety of different geometries for the container. The most successful
geometry tested was a 250 mL Pyrex Erlenmeyer flask. A normal experimental setup was
followed with one input tube leading to the bottom of the flask and one output tube leading to the
test subject. Upon testing with 25 mL, it was found that the wide shape of the flask mitigated
bubble formation as the liquid and bubbles were pushed to the side of the flask rather than up the
flask. Once this was discovered, the team tested increasing amounts of liquid to determine the
overflow point at which the bubbles would enter the output tube. As can be seen by the results in
table 45, 25 mL of stimuli was able to be contained in the flask for 10 minutes which is when the
test was cut off. However, the 50 mL, 75 mL, and 100 mL all entered the output tube at
approximately 302.0 seconds, 14.6 seconds, and 9.4 seconds respectively. Additionally, it is
interesting to note that while the smell potency increased from 25 mL to 50 mL, it did not
increase from 50 mL to 75 mL or from 75 mL to 100 mL. Overall, this test was extremely
successful at delivering odor to the test subject and preventing bubble formation and entry to the
output tube.

Table 45: 25 mL Erlenmeyer Flask Results

Trial Number	Volume (mL)	Time of Entry into Output Tube (sec)
1	25	N/A
2	25	N/A
3	25	N/A
4	25	N/A
5	25	N/A

Table 46: 50 mL Erlenmeyer Flask Results

Trial Number	Volume (mL)	Time of Entry into Output Tube (sec)
1	50	296
2	50	310
3	50	317
4	50	302
5	50	285
Mean ± SD	**50 ± 0**	**302 ± 12.39**

Table 47: 75 mL Erlenmeyer Flask Results

Trial Number	Volume (mL)	Time of Entry into Output Tube (sec)
1	75	18
2	75	12
3	75	13
4	75	15
5	75	15
Mean ± SD	**50 ± 0**	**14.6 ± 2.30**

Table 48: 100 mL Erlenmeyer Flask Results

Trial Number	Volume (ml)	Time of Entry into Output Tube (sec)
1	100	10
2	100	10
3	100	9
4	100	10
5	100	8
Mean ± SD	**100 ± 0**	**9.4 ± 0.89**

5.2.5 Flow Split 4 Ways

A test was developed to understand the direction of flow within the odor bank. Flow from the pump was divided into four separate outputs and directed into four odor vials, each filled with twenty-five milliliters of water. Ball valves were used to control the flow into each of these four branches. The test setup is displayed in Figure 28.

First, all ball valves except the first were turned to the "off" position and the flow through the first branch was verified using a 0-10 L/min flowmeter to have the same flow as the pump. This was then repeated for the other three branches. Then, all four ball valves were turned to the "on" position and flow through the system was analyzed to understand the flow within the odor bank in the case of mixing multiple odors. The team found that the flow streams from each of the four branches were not equivalent and could not be reliably controlled without adding flow regulators to the system. Therefore, mixtures of odors are not in the scope of this project.
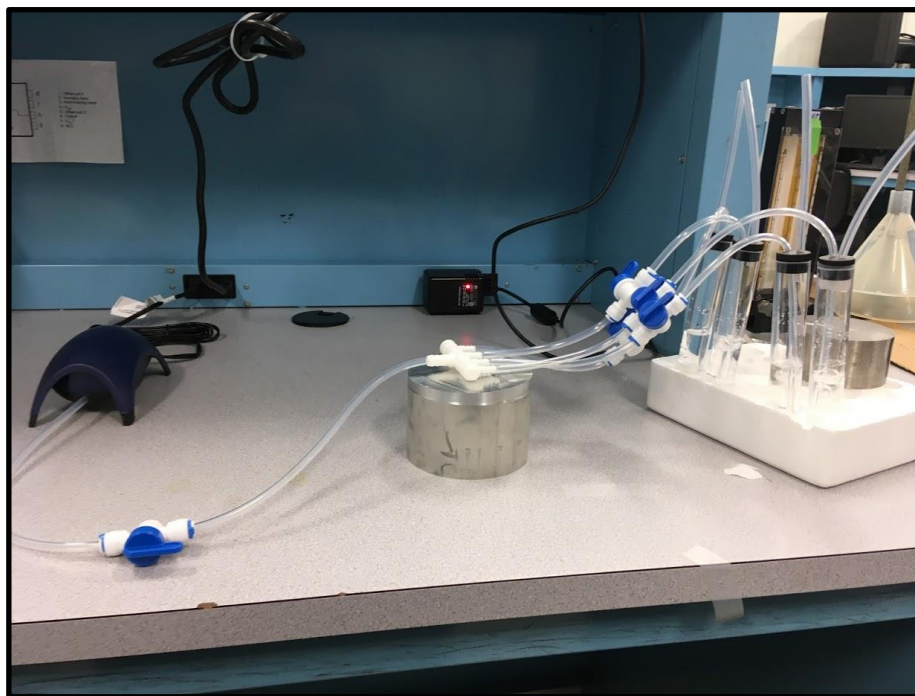
Figure 28: Flow split in four ways setup.

5.2.6 Pressure Drop

To determine the necessary specifications of a final compressor, the team analyzed flow

calculations to understand the pressure necessary at the start of the system. First it is necessary to

understand the type of flow throughout the system. To do this we use Equation 1 to determine

the Reynolds number or Re. The Reynolds number is a unitless value that describes flow systems

and can be calculated by multiplying the velocity of the flowing fluid by the distance through

which it flows, divided by the kinematic viscosity of the fluid.

$$Re = \frac{Vel * L}{v}$$

(1)

Definitions of terms and calculations can be found in Appendix F: Pressure Calculations. The

Reynolds Number allows us to categorize the flow as laminar because it is below 2100.

Therefore, Equation 2, the Darcy-Weisbach equation, can be used to understand the change in

pressure along the tubing. This equation can equate the change in pressure during fluid flow to

the length of flow multiplied by the friction factor of the tubing, one half the density of the fluid,

and the velocity of the flowing fluid squared over the diameter of the tubing.

$$\frac{Change\ in\ Pressure}{L} = f_D * \frac{\rho}{2} * \frac{vel^2}{D}$$

(2)

Because the flow is laminar the Equation 3 can be used to determine the Darcy Friction Factor.

This equation relates the friction factor to 64 divided by the Reynolds number solved from

Equation 1.

$$f_D = \frac{64}{Re}$$

(3)

The velocity is found by determining the flow rate of the flow steam in Equation 4. Where the velocity of a flowing fluid can be calculated as 4/π multiplied by the volumetric flow rate of the fluid divided by the square of the tubing's diameter.

$$Vel = \frac{4 * (Volumetric\ Flow\ Rate)}{\pi * Diameter^2}$$

(4)

Therefore, the initial pressure and be calculated and determined to be 0.0376 psi absolute.

5.2.7 Evacuation Test

To test air pump system evacuation, the team set up the air pump and connected the pump to two vials in series. The vials in series were set up as mentioned earlier, again using 25 mL of coffee liquid stimuli in the first vial. The vials in series were then connected to 27 feet of tubing, which is significant because 27 feet of tubing would be necessary to reach the MRI subject from the team's proposed device location in the CCNI's testing room. To test qualitatively for evacuation, a designated sniffer was put at the end of the 27 feet of tubing. To run the test, the pump was turned on and the sniffer declared when they first detected a scent. This portion of the test is also able to test for the time it takes for odor to travel from the vials to the end of the 27-foot length of tubing. Once the sniffer detected a scent, a stopwatch was clicked on, and odor was run for a duration of 1 minute. During this time, the sniffer was allowed to smell the stimuli once every 5 seconds, to minimize the change of odor fatigue. After the one minute was over, the test operator switched the device configuration from odor delivery mode to evacuation mode. To do so, the vials in series were disconnected from the set up, and the 27 feet of tubing was hooked up directly to the air pump. This ultimately made it so that only fresh air was pumping through

the tubing. At this point, the sniffer was allowed to keep smelling until all trace of odor disappeared. The results can be viewed in Table 49 below.

Table 49: Evacuation Test Results

Test Number	Test Subjects	Time to Odor (s)	Time to Evacuation (s)
1	Member A	12	81
2	Member B	13	103
3	Member A	11	95
4	Member B	20	94
5	Member A	10	49
Mean ± SD	**All**	**13.2 ± 3.96**	**84.4 ± 21.30**

5.2.9 Quantifying Odor Delivery

Another aspect that the group looked into testing was the effectiveness of delivery sequences through a quantifiable procedure. Initially, the team investigated the usage of gas chromatography coupled with PID or FID arrays to measure the amount of odor leaving the system in an effort to model the amount that would be delivered to a test subject. However, the limited availability of this equipment forced the group to investigate other means of analysis. Methods discussed included using a color-changing media solution to bubble odorous air through and analyze the color change for quantification, using a liquid-based odor delivery system to model concentrations and then extrapolation of the gas phase for analysis, and the condensation of gaseous odors at the end of a delivery sequence. After discussing the accuracy of these techniques with respect to their costs and availability, the group decided on an alternative

method to test the device in C Term under the guidance of Professor Marion Emmert. Due to the odor bank, evacuation system, and vials in series, the team's device minimizes the number of parts that interface with the liquid odorant. For that reason, when a delivery process is run, any mass that has been removed from the system can be thought of as volatilizing rather than being transported to a different part of the system. Knowing this information, the amount of odorant volatilized during any given delivery procedure can be thought of as the difference in mass of the system before and after running the delivery procedure. Using this method of quantification, only a mass balance is needed, which eliminates the need to use expensive GC-FIDs or similar equipment for validation. Additionally, by choosing test durations greater than 1 hour to volatilize a noticeable amount of substance, these mass differences can be accurately measured to one hundredth of a gram, which provides more than enough sensitivity requested by the client.

5.3 Final Design and Component Selection

5.3.1 Compressor and Tank Calculations

The first component considered for the final design was the compressor as it is responsible for pushing the flow of air through the control box, odor bank, and to the MRI bore. To choose an appropriate compressor, the team took into account the demands of the system such as test run time, pressure differential needed, and desired flow rate. The required flow rate at the nose cone was initially stated to be between 1.0-1.5 L/min, which is the recommended rate for delivering anesthesia to adult rats.[71] Therefore, the system needed to deliver air within this range, which corresponds to 15.9-23.8 gallons per hour. To generate air flow within this range, a pressure differential is required. Most compressors have very high pressure ratings, with the average being 250 psi, but because this system only requires about 5 psi, the team chose a low capacity compressor. The compressor used is depicted in Figure 29 and is rated for a flow rate of

0.69 CFM (19.54 L/min) at 5 psi, which encompasses the needed pressure for this system. To power the compressor, the team chose a power source which would allow the 12V DC, 11 amp maximum compressor to be powered in series with other devices. The pressure and flow rate of the system was controlled by a regulator and flowmeter.

Figure 29: Image of the compressor that was chosen for the device, and its components.[72]

To analyze the operation of this component, the team performed a test where the compressor was directly connected to the flow and pressure control components which were in turn to the tubing. The team powered the compressor, set the regulator and flowmeter to the target flow rate of 1 L/min, and monitored the consistency of the exit flow rate for approximately ten minutes. The compressor was able to consistently deliver the target flow rate in combination with the flow control system, which made this initial test a success. However, the compressor heated up quickly, which caused the team to reconsider the original plan to run the compressor constantly. Based upon this information, the team decided to incorporate an air tank into the design, which can be viewed in Figure 30.
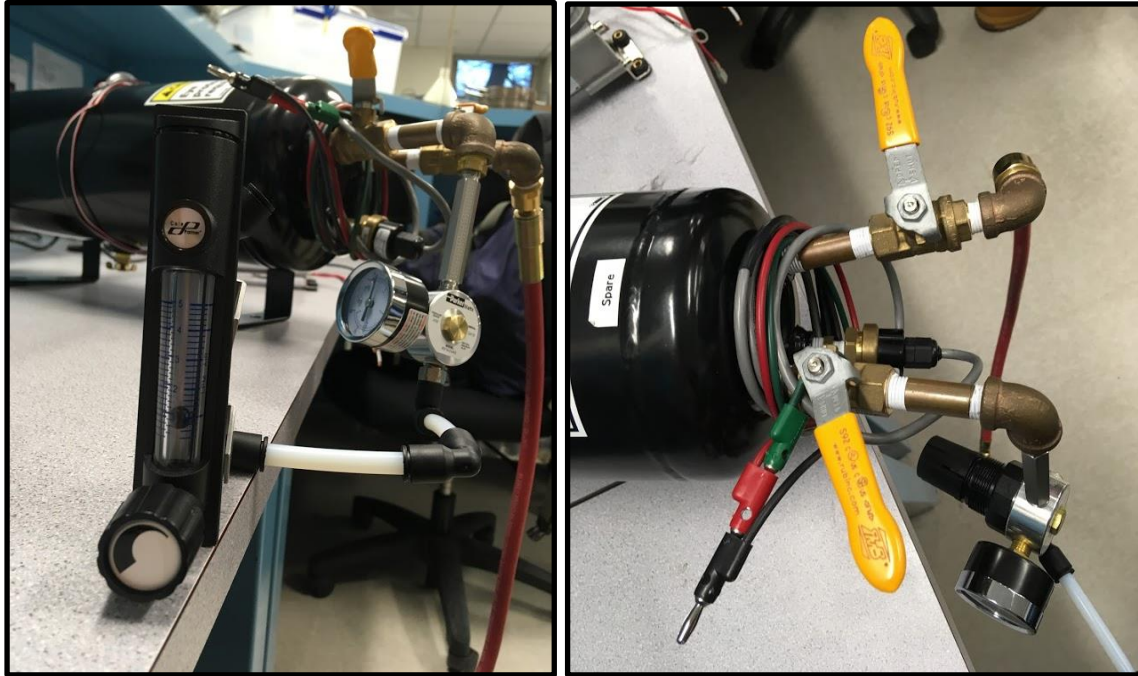
Figure 30: Image of the 1.5-gallon tank, the regulator, and the flowmeter. The rightmost image shows the control handles. With the depicted setup, both the input switch at the top and the output switch at the bottom are set to the OFF position. The leftmost image shows the regulator and flow meter interface with the output tube.

An air tank introduces an energy storage component to this system and allows the compressor to operate only when needed. The tank was connected to the flow controls and a pressure switch which maintained the correct pressure range in the tank at all times. When the tank pressure dropped below a certain value, the compressor would turn on and increase the pressure. When the pressure in the tank reached a maximum pressure in the set range, the compressor would turn off. The chosen compressor was rated for a 9% duty cycle when filling a 1-gallon tank at a pressure of 100 psi. The equation for calculating the duty cycle of a compressor can be seen below where on-time and off-time refer to the amount of time that the compressor was powered on and off, respectively.

Compressor-on-time ÷ (on-time + off-time) = Duty Cycle %

Therefore, according to this compressor's rating, for a test run of one hour at a pressure of 100 psi, the compressor will be on for about 5.4 minutes and will then need 54.6 minutes to cool down completely. The duty cycle is an important value to consider when incorporating a tank in order to preserve the compressor's life.

To verify this duty cycle, the team tested the process of filling up a 1.5-gallon tank borrowed from the Engineering Experimentation Lab at WPI. This 1.5-gallon tank was tested by measuring the period of time needed to fill up the tank as well as the time it took to deplete the tank. To fill the tank, the compressor was connected to a power source and the valve to the tank was opened while the exit valve on the tank was closed. The team filled the tank to a maximum of 100 psi and recorded how long it took to reach four different target pressures: 25 psi, 50 psi, 75 psi and 100 psi. Test results can be seen in Table 50. These results show that the higher the pressure in the tank, the longer it took to fill up to the next target pressure, with every increment of 25 psi taking approximately 20 seconds longer than the previous. The team also noticed that as the tank reached a pressure of around 85 psi, the compressor became louder and seemed to be working harder to fill the tank. After checking the product specifications, it was discovered that at this pressure the compressor used 11 amps rather than 10 amps from the power source. When the compressor reached 100 psi, the compressor was turned off and the valve to the tank was closed. Then the valve to open the tank to the atmosphere was opened and the time needed to return the pressure in the tank back to 0 psi was recorded, as seen in Table 50.

Table 50: Tank Duty Cycle Test Results

Pressure (psi)	Time (seconds)
25	40 sec
50	1 min 30 sec
75	2 min 32 sec
100	3 min 53 sec
Depletion Time:	15 Minutes

5.3.2 Air Regulator and Flow Meter Measurements

To regulate the air flow in the system, the team chose a pressure regulator and flowmeter in series. The regulator had a range of 0-25 psi and performed the majority of the flow controls. The fine tuning of the control was done by the 0.5-5 L/min flow meter.

To validate this control system, the team connected the compressor to the regulator and recorded how well the flow rate could be maintained. The regulator was set to 5 psi and the flow meter to 1 L/min. After running the compressor for ten minutes, the resulting flow remained consistent with the original setting.

The next step was to adapt this flow control system for use with the 1.5-gallon tank and to analyze the information gained in testing to determine the pressure range that must be maintained in the tank to reach the target flow. Although the maximum pressure allowable for the chosen tank was 250 psi, the team decided to limit this to 80 psi based on the increased power draw determined from the initial test described above. Therefore, setting the max pressure to 80 psi served to lower the duty cycle and maintain the condition of the compressor.

The minimum pressure in the tank was determined by a choked flow test. The team filled the tank to 80 psi and opened the valve to the regulator and flowmeter. The flow meter was first opened all the way and then the regulator was calibrated so that the flow rate in the flowmeter

registered below 5 L/min. Then the flowmeter was adjusted so the output flow rate was 1 L/min.

The flowmeter was then monitored to see at what pressure in the tank the flow rate of the

flowmeter changed. We found that the flow was affected when the pressure in the tank fell below

5 psi. These results reflect the fact that the regulator was adjusted to a pressure of 5 psi so that

anything above that pressure in the tank would have motivated a choked flow situation. The team

decided to account for any added error margin to this minimum tank pressure by setting the

target to 20 psi.

To ensure that the pressure regulator and flowmeter can be accessed and adjusted easily

by test operators, a mounting plate was created in CAD, shown in Figure 33. This mounting plate

was then manufactured by laser cutting a 3/16-inch piece of white acrylic and attaching this to a

heavy piece of particle board to certify that the plate would stay upright. The prototype for this

mounting plate is shown in Figure 31.
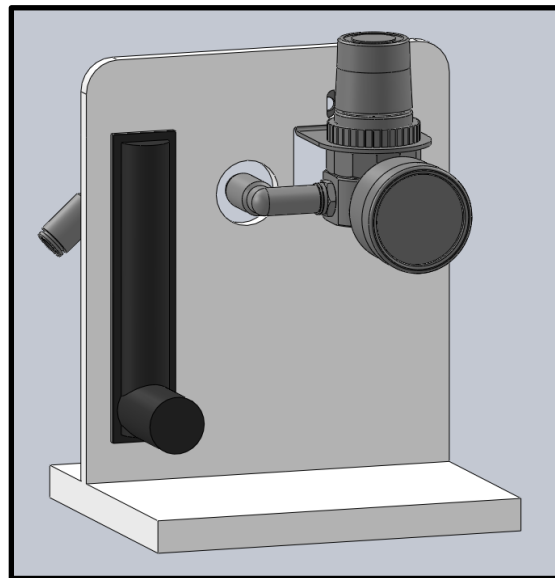
Figure 31: Flow control component mounting plate CAD model.

Figure 32: Flow control component mounting plate prototype. The flow meter is shown on the left and the pressure gauge is shown on the right.

5.3.3 Directional Control

To control the directional flow of the system and guide air from the compressor to the individual vials, the team chose to incorporate electrically controlled solenoid valves. Adding this degree of automation provided a more user-friendly operator interface and provided repeatability for testing.

Five solenoid valves were incorporated in the design; four to direct air flow to the odor bank, and one to direct air directly from the compressor assembly to the nose cone. Tubing from the flowmeter was directed to these five solenoid valves through the use of a one to six straight flow rectangular manifold. Push-to-connect fittings were attached to the one input and to five out of the six outputs in this manifold. The last output was plugged with a threaded cap. After flow was split into five directions, air could then be controlled by the solenoid valves. These solenoids valves are normally closed which means that they allow flow through the valve only when power is supplied. The solenoids are made of brass, weigh approximately 0.295 kg and are designed for

¼ inch NPT push-to-connect fittings. An Arduino Mega microcontroller shown in Figure 33, controls the timing for when each valve is opened. Depending on the information uploaded to the Arduino, it will send a signal to a SainSmart 16-Channel Relay Module, shown in Figure 34, which then powers the desired solenoid valve and opens its channel to allow flow. A wiring schematic for the solenoid valves, microcontroller, and relay module can be found in Figure 35 below. To secure these solenoid valves and electrical components in place, they were incorporated into the design of the control box.
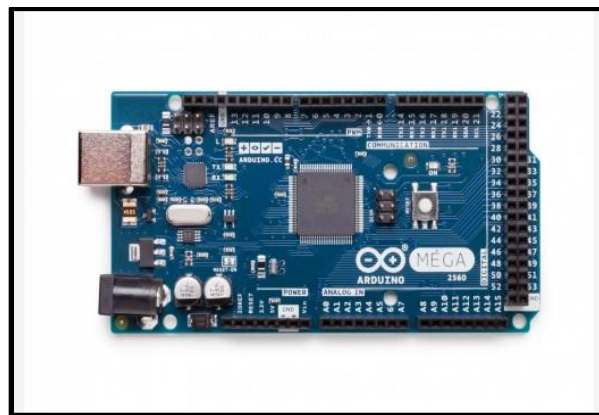
Figure 33: Arduino Mega 2560 Rev3.[73]
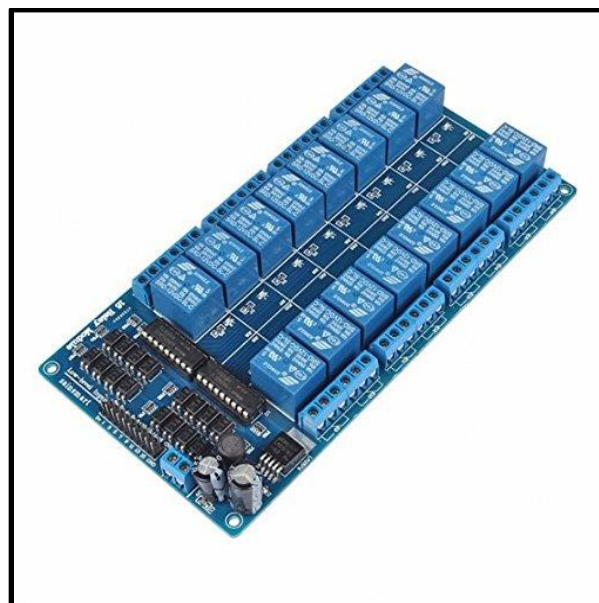
Figure 34: SainSmart 16-Channel Relay Module.[74]
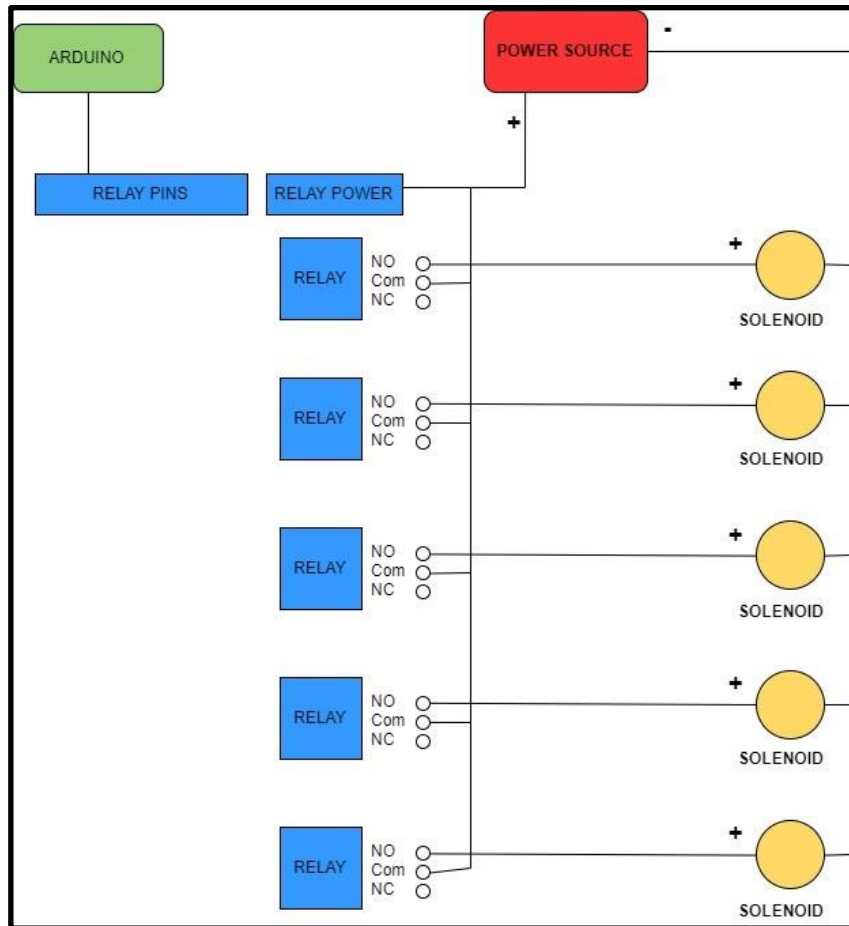
Figure 35: Solenoid valve wiring schematics.

5.3.4 Control Box Design

As mentioned in the previous section, a control box was designed to protect the electronics from contamination and to house all the control components in one convenient location. This box needed to provide sturdy mounting points for the microcontroller and relay board and shield them from any potential harm. Housing these parts in a box also served to shield the wiring from over-handling or from being disconnected and protects the electronics from liquid. The top of this box was attached by two hinges to ensure that the electronics could still be accessed by the operators if needed. To prevent the box from heating up, a fan was also incorporated into the back plate of the control box and ventilation waves were cut into the right-

side plate facing away from the odor bank. A hole was also added on the back panel of the box to allow power and computer interfaces to be connected with the internal components. Two toggle switches, one to turn on the system and the other to start the testing trials, were incorporated into the front panel granting easy access for the operator. Finally, the solenoid valves and tubing manifold were secured on the top of the control box. The connections between these parts should remain unchanged regardless of the testing procedure performed. Therefore, mounting them to the same surface verifies that the tubing connections between them will never be unplugged or damaged. The CAD model for the control box is shown in Figure 36. The final dimensions for this component are 8 inches by 11 inches by 3 inches.
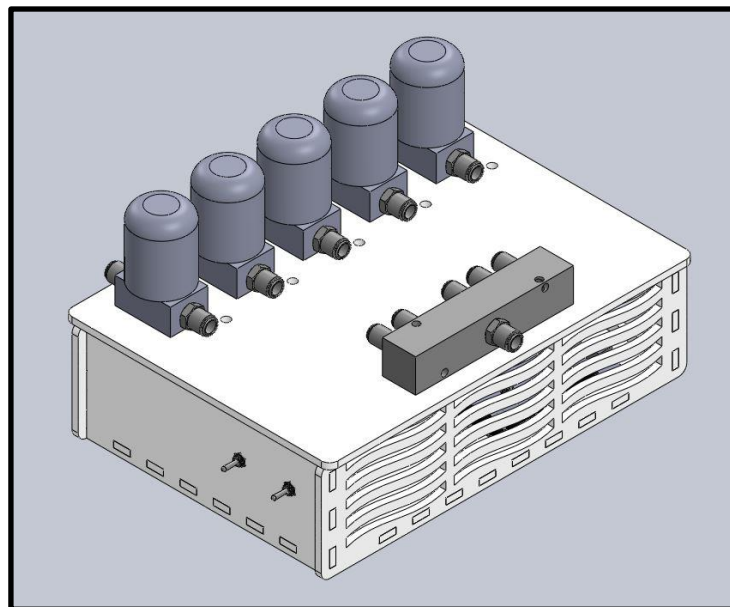
Figure 36:CAD Model of the control box assembly.

5.3.5 Odor Bank Design

For stimuli storage and containment, an odor bank was designed and prototyped. In accordance with the design parameters, the odor bank was developed to accommodate up to four

different stimuli for use in testing. Additionally, several other factors including ease of use, durability, and weight were taken into consideration when constructing this prototype. For the preliminary design, a 68.5 cm by 32 cm rectangular base was created out of wood with a 13.5 cm high by 4 cm wide piece of wood screwed into it at a 90-degree angle down the centerline to act as a center support. Hexagonal supports situated at the ends of the base secured the center support in place, thus providing added strength and durability. Everbilt brand spring grips were then screwed into the center support at regular intervals of 10 cm to serve as holders for the stimuli vials. Both sides of the center support were equipped with the spring grips so that the vials could be used in series with secondary vials to collect any liquid stimuli that may escape. To provide an easy way to carry the device, a handle was added to the top of the center support completing the design. The finished prototype had final dimensions of 68.5 cm long x 32 cm wide x 13.5 cm high can be viewed in Figures 37 and 38.

Figure 37: Construction of the preliminary odor bank prototype.

Figure 38: Attachment of the spring grips to the odor bank prototype.

Major advantages to this design include sturdy construction and durability as well as portability due to the shape and attached handle. Another benefit of the system is its ease of use due to the spring grips which allow users to quickly secure or remove stimuli vials. Also, the second set of vials provides a safety feature to prevent liquid stimuli from escaping the odor bank and traveling directly to the test subject. Lastly, the device is modular in design and can easily accommodate different sized stimuli containment units such as Erlenmeyer flasks. One major drawback is that the device is quite heavy weighing 2.3 kg due to the wooden construction materials.

Once the prototype was completed, design work on the final device commenced. After analysis of the prototype, the team began by eliminating the issue of weight by changing the construction material from wood to ¼ inch thick white acrylic. This change yielded a new weight of 1.3 kg and also aided in preventing contamination of the odor bank as well as assisting in the cleaning of the device. However, with the introduction of acrylic, much of the center support's strength was lost, so perpendicular ⅛ inch thick clear acrylic supports had to be introduced as

shown in Figure 39. These supports also had the added benefit of compartmentalizing the system

so that each stimuli vial would have its own semi-isolated cell to mitigate the risk of cross-

contamination. Another change that was made on the final device was the removal of the handle

from the center support. Instead, two handles were added to the hexagonal end supports to

maintain the portability of the design.
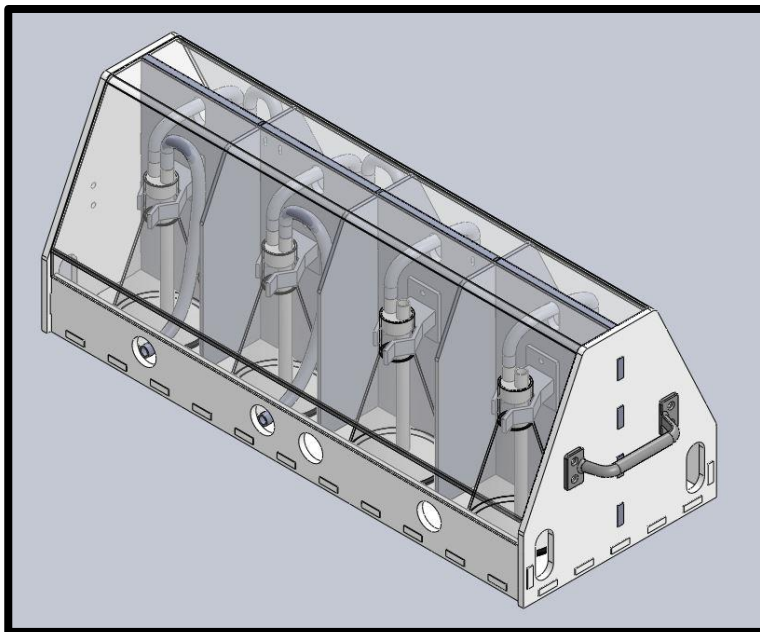
Figure 39: CAD model showing the design of the odor bank with attached Erlenmeyer flasks for reference.

In the event of stimuli overflowing from the containment vials, the team also decided to

add a cover to the center support that would close off the cells and protect the technician. To aid

in stimuli containment in the event of overflow, a lip was added to the edge of the device. Holes

were also placed through this lip to allow the tubing to pass through. These entry holes were cut

in both the lip and hexagonal support to provide the maximum amount of flexibility to the

technician in terms of odor bank orientation with respect to the rest of the system. Lastly, all of

the edges of the device pieces were box-jointed to promote strength and durability during

construction since the acrylic was too thin to allow for screws. Final measurement of the device

yielded dimensions of 8 inches tall by 8 inches wide by 20 inches long and a weight of 1.3 kg

and the device can be seen in Figure 40.
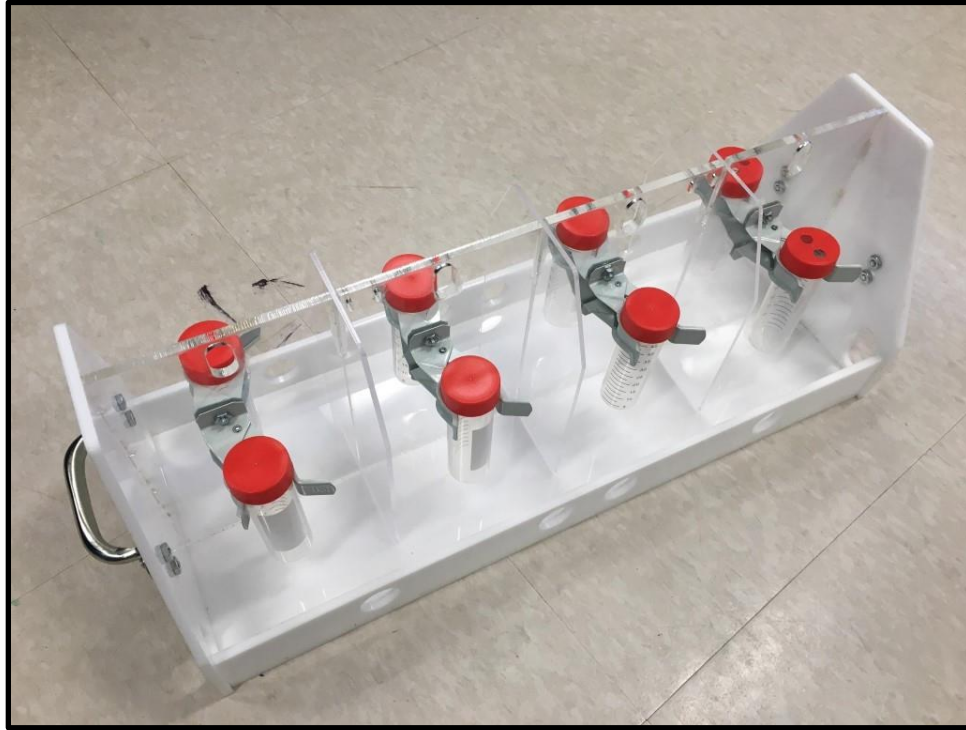
Figure 40: This picture demonstrates the odor bank made from laser-cutting acrylic. Large centrifuge tubes are shown in this image to demonstrate the modular design.

5.3.6 Evacuation Design and Testing

Three tests were run to examine the preliminary evacuation design of an evacuation tube

branching out from the bottom of the nose cone and feeding into an adapter, where a filter and a

vacuum would be housed in series. In order to validate the concept, a prototype was constructed

out of a foam box with dimensions of 10.5-inch x 9 inch x 7.5 inch. The team also created a

makeshift filter out of a small cardboard box, rubber bands, and cloth as seen in Figure 41.

Figure 41: The team's prototype of the filter to house in the adapter, constructed out of cardboard, cloth, and rubber bands.

Two circular holes were cut on both sides of the foam box to function as an input and output. On the input side, a funnel with an end diameter of 4.5 inch was secured. On the tapered end of the funnel, 27 feet of Nylon-6 tubing was attached with a hot glue gun. On the output side, a brushless computer fan with a diameter of 4.5 inches, manufactured by Delta Electronica, Inc., was secured. The computer fan required an input of 12V DC and 1.60 amp which was supplied by an appropriate laptop charger. The completed prototype is shown in Figure 42. As can be seen in the figure, the lid of the adapter was also taped and secured shut to prevent any air leakage.
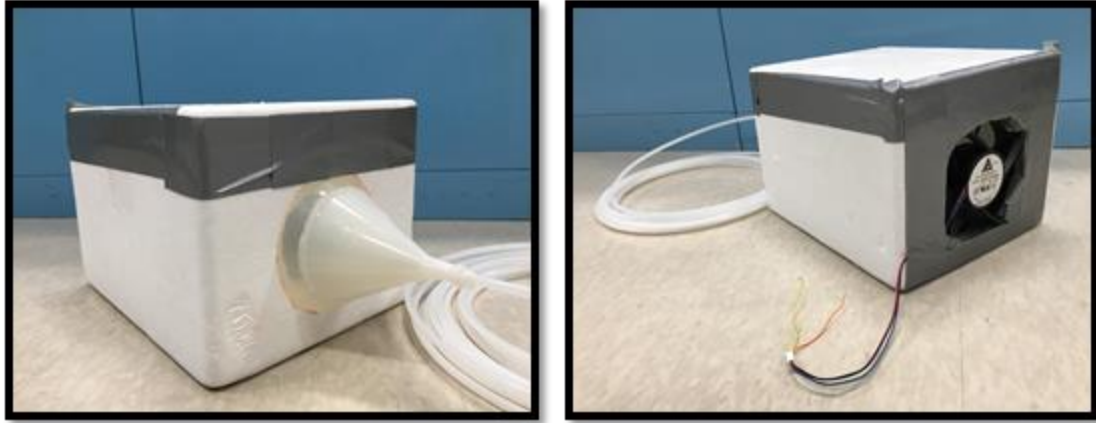
Figure 42: The team's prototype of the adapter. The leftmost image depicts the adapter's input and the rightmost shows the vacuum outlet.

The objective of the first evacuation test was to determine the air suction flow rate created at the end of the Nylon-6 tubing caused by the computer fan. To determine the flow rate, a flowmeter was attached to the open end of the tubing. The knob on the flowmeter was opened all the way to allow for fully unrestricted air flow. The team hypothesized that the suction created by the pressure drop of the fan would elicit a reading from the flow meter, however, when the team powered on the computer fan, the flowmeter displayed a reading of 0 L/min. After running this initial test for several minutes, the team realized that the flow meter was incapable of registering a vacuum flow, and the test was stopped. Therefore, the result of this test was deemed a failure. However, it was noted that the fan was creating a vacuum flow because the team also tested the flow of the fan qualitatively by removing the funnel and sprinkling small pieces of foam in front of the open input hole. The fan was able to pull numerous pieces of small foam into the adapter.

Due to the first test's failure, the team ran a second test in order to test the suction force of the fan. For the second test, the team cut up small pieces of foam and paper and sprinkled the pieces onto the table. The team then attempted to vacuum the pieces up with the tubing, similar

to a vacuum hose. The team hypothesized that the tubing and the suction force from the fan would be able to lift some of the smaller pieces. This test also proved unsuccessful as none of the pieces of paper were observed being vacuumed into the tubing.

The final test that the team ran was an experiment to test the flow rate of the fan itself, to determine at what rate air would be pulled from the rat during a procedure. For this test, the funnel was placed directly before the fan and the flowmeter was attached to the end of the 27-foot section of tubing. The fan was activated, and the flow was measured. This test resulted in a failure as well since the flowmeter did not register any flow caused by the fan. The team determined that this result was likely due to the small cross-sectional area of the tubing as well as the length of tubing. These two factors combined prevented the fan from creating a sufficient pressure differential to allow for a flow rate detectable by the flow meter used. As a result of the three tests outlined above, the team decided that it would be necessary to purchase a vacuum pump for the evacuation system to generate the necessary pressure differential.

5.3.7 Automation and Future Development

Once the device had been fully assembled, the team decided to automate the use of the system, thus minimizing error introduced by the test operator while simultaneously improving the ease of use of the system. Automation will be completed through the addition of several components including the solenoids that were previously validated, a microcontroller and relay module, and a graphical user interface (GUI). The control box detailed earlier in this section will house the Arduino, relay module, and the necessary electrical components to prevent them from being damaged. A fan is included in the control box to circulate air and cool the components. Solenoids located on the top of the control box will determine which of the vials in the holder the airstream will be directed to. When all of these components are connected to a power source, and

the Arduino is loaded with the necessary operating program, the test operator would be able to

connect the system to one of their computers. The control box with the solenoids attached to it

can be seen in Figure 43.

Figure 43: A picture of the top lid of the control panel which holds the solenoids in an array as depicted.

Once connected to a computer, the test operator will be able to load the program and be

presented with a GUI that prompts the user to choose the testing parameters for their experiment.

These parameters might include the number of odors to be presented to the subject, the location

of each odor within the odor bank, the duration that each odor will be presented to the subject,

and the number of times each odor will be presented to the subject. The GUI will be kept simple

to minimize confusion and will print the appropriate messages to prompt the user to choose their

settings. Improper entries for user-settings will be followed by a prompt explaining why the

entry cannot be accepted, followed by a request for more information from the user. Once the

proper information has been loaded into the program by the user, the first toggle switch can be

flipped on the control box to power the system, allowing the compressor to fill the tank up with its initial supply of compressed air. After the tank has been filled, the test operator can then adjust the flow meter and pressure regulator to the desired flow rate and pressure, and the flip the second toggle switch to start the testing procedure loaded into the microcontroller from the program. The Arduino code for the GUI can be found in Appendix XXX.

5.4 Final Device Considerations

After considering the final components needed for the team's initial design as well as the data collected from preliminary tests, the team established a final system design. A conceptual image of the final design can be seen in Figure 44. The reasoning for selection of components for this design is outlined in the sections below.
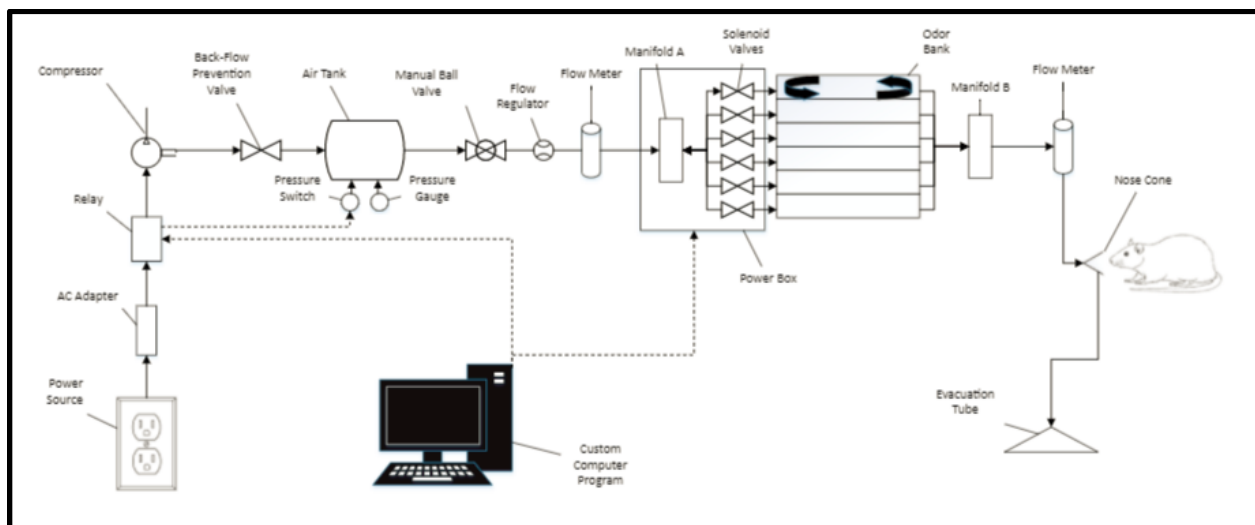
Figure 44: This image depicts the design for the entire system in the form of a Visio model. Every portion of the system from the power source to the test subject is included.

This system begins with a compressor which is connected to a 1.5-gallon tank via a 2-foot long pressurized hose and a backflow prevention valve. This valve ensures that the pressure

stored in the tank does not seep into the hose and return to the compressor. The tank stores the

compressed air produced by the compressor and is connected to the remainder of the system by a

manual ball valve, regulator, and flowmeter. The regulator performs the majority of pressure

control while the flowmeter produces the fine-tuned flow rate. This flow is then delivered to the

control box which contains a one to six rectangular flow manifold and five solenoid valves. A

microcontroller and relay module activate these solenoid valves based on the parameters of a

user-specified test and control the direction of flow to the rest of the system. Four solenoid

valves direct air flow to vials in the odor bank and the remaining solenoid valve delivers fresh air

to the rat. The odor bank contains two vials per stimulus and are connected by a small piece of

PTFE tube. The second vial is meant to catch any liquid that bubbles into the exit tube of the first

vial. A second manifold then joins the flow from the four vials and the source of clean air into

one tube. A second flowmeter then verifies that the desired flow rate has been achieved and is

being directed through the length of tubing that is routed into the MRI room and to the nose cone

of the test subject. Figure 45 shows the CAD model assembly for the device, barring the tubing.
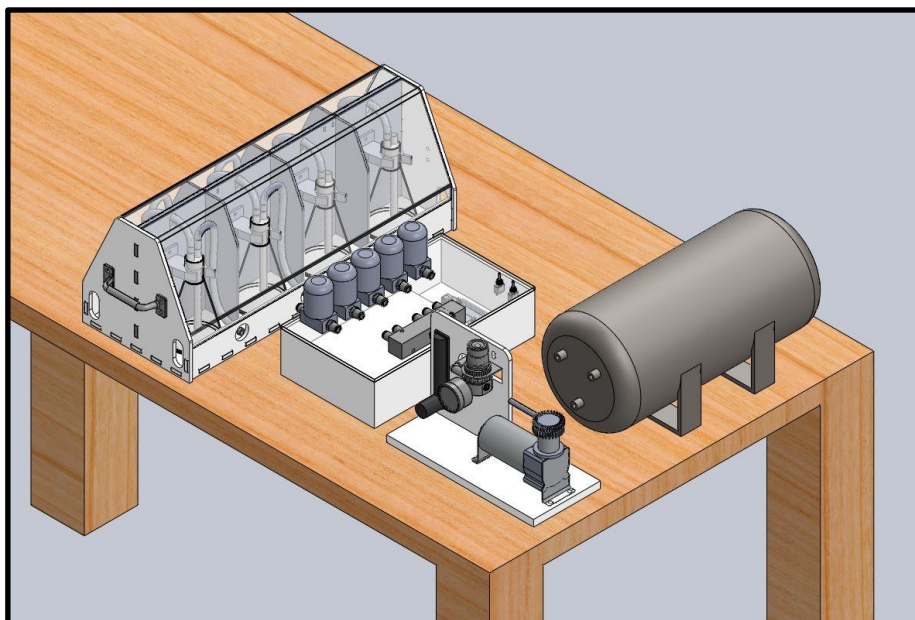
Figure 45: This CAD assembly shows the individual aspects of the final design, without the tubing connecting them.

Once this stimulus has reach the rat, an evacuation system is used to flush old stimuli from the MRI bore. A tube is connected from inside the MRI bore to the testing room and attached to a vacuum pump. A filter is placed before the pump to remove contaminants from the air and to ensure that the evacuated air is safe to breathe.

For quantification purposes, the device will include several odor profiles to assist the test operators in making decisions on system settings. Since the perceived strength of an odor by a subject depends on a multitude of factors, as discussed in Section 5.3.6, it is not feasible to accurately quantify how much of an odor is processed by a subject. To add to this complicated array of variables, even knowing the exact amount of odor reaching a subject does not indicate how the subject perceived such an odor, since different species have different olfactory systems, which can differ at the individual level. Therefore, by providing representative relationships between the factors discussed in previous sections with the amount of odorant volatilized, the device can provide an estimate that fulfills the needs of the client, without introducing the individualized aspect of odor perception.

6. Device Validation and Results

After initial testing of device components and fabricating the final device, testing was required to assess the effectiveness and success of the device. As seen in Table 51, testing methods were categorized based on the primary objective that they were analyzing. Testing and validation procedures and results are discussed in this section while the conclusions drawn from these tests are discussed in the subsequent chapter.

Table 51: Testing Methods for Evaluating Objectives

Primary Objective	Testing Method	Data Collected
Delivery	System Usage Time	Robustness of delivery mechanisms through logged usage time
	Automation Testing	Accuracy of delivery duration
Quantification	Odor Strength Measurements	Measurement of odorant strength dependency on flow rate
Evacuation	System Purge Time Testing	Length of time required to evacuate 27 feet of tubing
	System Smoke Testing	Visual observation of effectiveness of vacuum pump and filter
Ease of Use	Automation Testing	Accuracy of time delay
	User Manual Creation	Collection of points of difficulty, troubleshooting, and general information

6.1 System Usage Time

Throughout the additional testing procedures discussed in this chapter, particularly the odor strength measurement procedures, the team decided to use the final delivery device components. This decision allowed the group to obtain an additional metric both in terms of delivery reliability and ease of use satisfaction. When performing the odor strength testing, the team utilized the tank, compressor, control box, and flow controls system that constitute the final device. All testing sequences combined for a total of approximately 25 hours of usage for these components. After 25 hours of operational usage, the device did not suffer any apparent damage

or decrease in effectiveness. However, minor operational observations and adjustments were made which were then noted in the user manual, located in Appendix I.

6.2 Odor Strength Measurements

Once the bulk of the device was constructed, the team was able to conduct initial quantification testing to provide future users of the device with odor strength behaviors based on numerous factors. As mentioned previously, this testing sequence was devised with the help of Professor Marion Emmert of the WPI Chemical Engineering Department and focused on calculating the difference in mass of the system before and after running a delivery sequence. The change in mass was interpreted as the amount of the odorant that was volatilized and mixed with the running airstream, which would then be detected by the olfactory system of the test subject. The testing procedure involved constructing the main components of the device, including the compressor, tank, pressure gauge, flow meter, odor bank, and the necessary amount of tubing. A representative image of the team's quantification testing procedure can be seen in Figure 46 below.
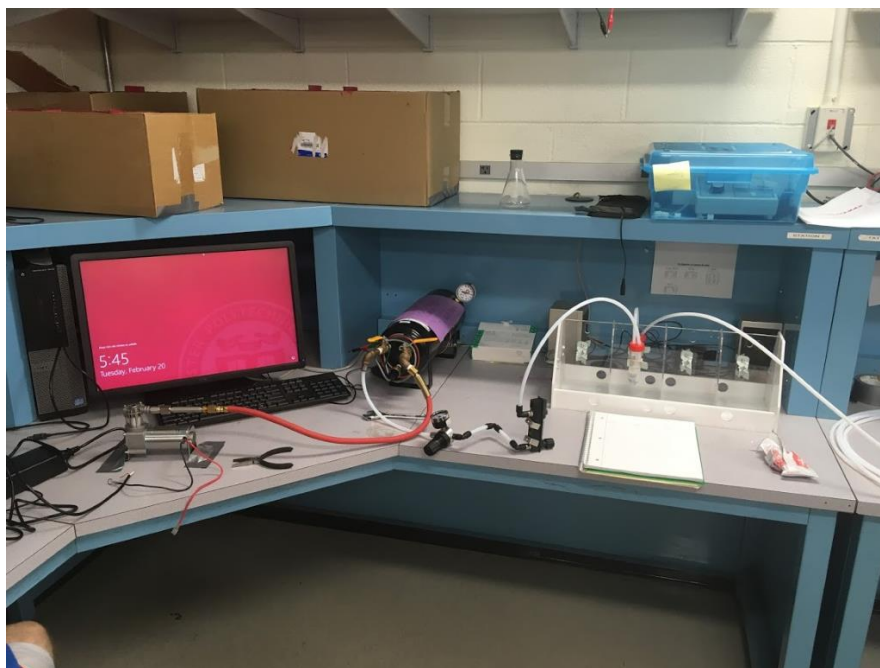
Figure 46: Quantification Test Setup Configuration

To begin testing, the device was constructed as intended with the compressor attached to the input of a tank whose output was regulated with a pressure regulator and flow meter. The regulated air stream was then directed to one of the vials in the odor bank, which was in turn connected to another vial in series to collect any stimuli that may bubble over from the first vial. Finally, a 27-foot piece of tubing was attached to the output of the second vial to mimic the length expected by the client. Once the device was fully constructed, the compressor was turned on to fill up the tank for the first phase of testing. Throughout the experiments, the compressor was manually turned on and off to fill the tank when needed. The rate at which the compressor was activated was determined by both the duty cycle of the compressor, and the output flow rate required by the experiment, as discussed earlier.

Before each test was run, the vial containing the odorant liquid and the vial to which it would bubble into were taken and weighed with the PTFE tubing that connected them. These components were selected since they would be in contact with the odorant and would therefore

be the only aspects of the design that would be exposed to the liquid phase. The device was

designed to prevent the output tubing from contacting the liquid phase of the odorant, and the

PTFE tubing was chosen due to its chemical inertness, thus not trapping any gaseous odorant in

the tubing itself. Additionally, after each experiment was performed, the input tubing was

removed from the liquid source, but remained in the vial for approximately 2 minutes while

expelling air to remove any liquid from that portion of the system. With these design decisions in

place, any difference in mass between the vials and connecting portion of tubing measured

before and after testing was considered to be volatilized. After measuring these portions, the caps

of the vials were hot-glued to prevent any leakage during testing. Once the tests were completed,

the dried glue was easily removed and was therefore not considered when weighing the

components post-experiment.

When designing these experiments, the team opted for a range of substances that

represented different odor threshold levels as reported by the 2nd edition of Odor Thresholds for

Chemicals with Established Health Standards.[75] The selected compounds were amyl acetate,

ethyl acetate, and acetone based on their safety, cost, and availability. Additional compounds

were chosen to extend the range of odor thresholds, but were ultimately not tested due to

budgetary restrictions.[75] These compounds and some of their relevant properties can be seen in

Table 52.

Table 52: This table displays some relevant characteristics for the compounds initially chosen to be used for quantification testing[75]

	N-butyl lactate	Amyl acetate	Ethyl acetate	Acetone	Triethanolamine
Odor Threshold (ppm)	4.9 x 10^{-9}	0.007 – 43	0.09 – 190	0.40 – 11,745	>10
Odor Character	Mild	Banana, etherous	Fruity, sweet, fingernail polish, etherous	Sweet, fruity, etherous	Mild, ammonia
Vapor Pressure (mmHg)	0.4 @ 20 °C	4 @ 20 °C	73 @ 20 °C	198 @ 20 °C	0.008 @ 20 °C
Chemical Family	Ester	Ester	Ester	Ketone	Tertiary amine/triol

To ensure that these experiments were reliable and repeatable, the team identified the main factors that would affect a compound's odor strength. These variables included chemical structure of the compound, vapor pressure of the compound, flow rate of the entering airstream, initial volume of the odorant, the surface area of the odorant exposed to air (which in turn was affected by the shape and capacity of the chosen vials), and the duration of the experiment. In an effort to minimize the variability of some of these factors while measuring the effects of others, initial volume of the substance and the vial shape and capacity were kept constant throughout all tests at 15 mL using a 25 mL centrifuge tube. The compounds chosen varied in chemical structure and vapor pressure as noted in Table 52 to provide distinct relationships between these representative compounds. Both the flow rate and duration of the experiments were altered between trials to determine their effects on the amount volatilized.

The first tests involved running 15 mL of amyl acetate at varying flow rates, specifically 1, 2, 4, and 8 L/min for 1 hour. The resultant data can be found in Table 53 and Figure 47. Then,

ethyl acetate and acetone were run under these same testing conditions. Since acetone and ethyl acetate have much higher evaporation rates than amyl acetate, the 15 mL of each of these substances lasted for only the duration of the 1 L/min test. For this reason, the data for these substances was not reported. Amyl acetate was also experimented with using the same flow rates listed above for a duration of 5 hours, with only the 1 L/min and 2 L/min tests leaving any remaining liquid. These values are included in Table 53 and are graphed alongside the hour-long duration tests in Figure 48.

Table 53: This table displays the amount of amyl acetate depleted after bubbling through it with an airstream of varying volumetric flow rates for varying amounts of time.

	Flow Rate (L/min)	Amount Lost After 1 Hour (g)	Amount Lost After 5 Hours (g)	Mass Flow Rate of Amyl Acetate (g/min)
Amyl Acetate Initial Volume: 15 mL	1	1.40	7.19	0.023
	2	2.76	13.20	0.046
	4	6.31	N/A	0.105
	8	13.18	N/A	0.220
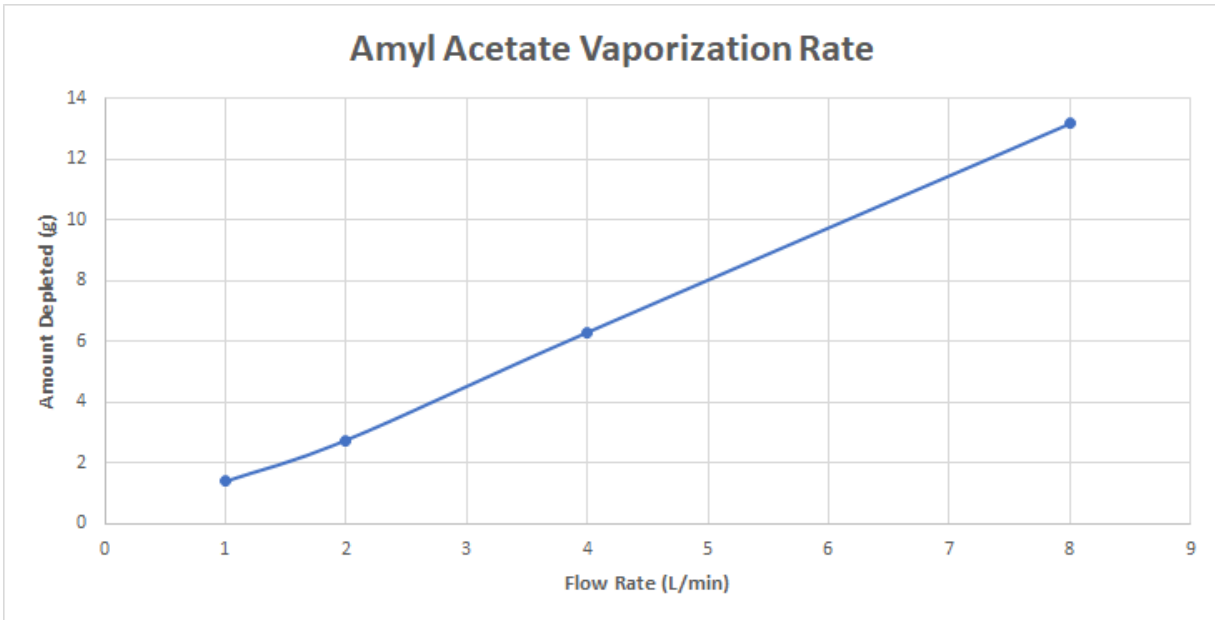
Figure 47: A graph showing the effects of flow rate on the amount of amyl acetate being volatilized and thus depleted from the system
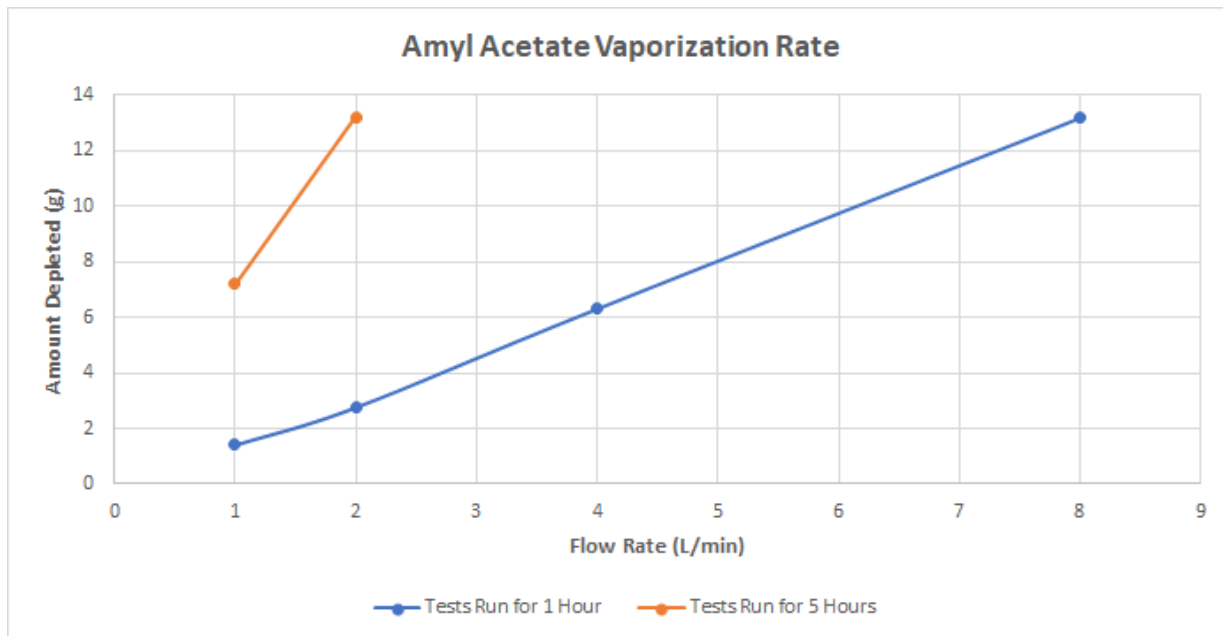
Figure 48: A graph showing the effects of flow rate and flow duration on the amount of amyl acetate volatilized. The blue graphed line shows the effects of flow rate on the amount depleted for tests lasting 1 hour with the orange line representing tests run for 5 hours.

These data showed that for amyl acetate, an increase in delivered airstream flow rate, while duration was kept constant, resulted in an increase in the amount of mass volatilized.

Additionally, the amount of mass volatilized increased when flow rate was kept constant, and the duration of the testing was increased.

After the amyl acetate had been tested for both 1 and 5-hour testing durations, and the acetone and ethyl acetate samples had both evaporated entirely, the team determined that setting a lower time point for testing would yield more data points. Therefore, the team lowered the testing duration to 20 minutes, which was shown to dissipate a measurable amount of amyl acetate at the lowest flow rate of 1 L/min while not evaporating all of the acetone at the highest flow rate of 4 L/min. The rest of the testing variables (initial volume of odorant, odorant selections, vial size and shape, and testing environment) were all kept the same for these new testing procedures. For each odorant at each flow rate, 3 tests were performed to increase statistical power from the initial amyl acetate testing sequences.

The data from these tests can be seen in Figure 49 which graphs the averages for each of the odorants at each tested flow rate.
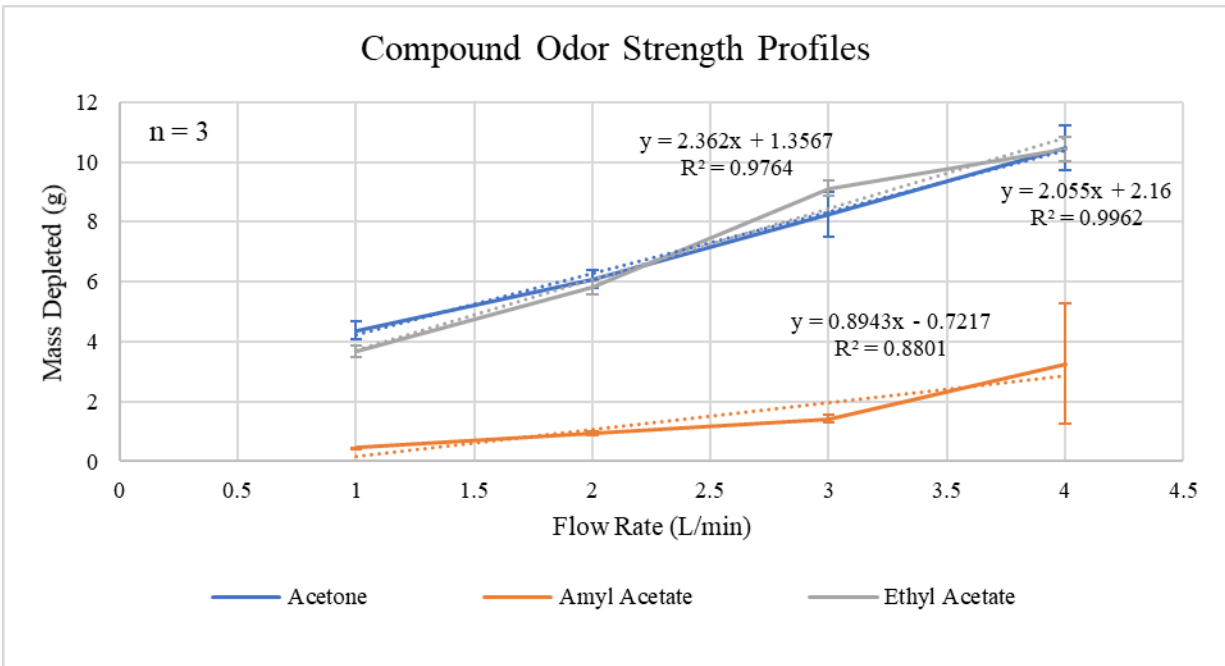
Figure 49: A graph showing the effects of flow rate on mass depletion for all of the odorants tested. Standard deviation bars are shown for each data point (n = 3) and linear trendlines with associated equations are included as well.

Results from the testing show that, for each of the odorants tested, an increase in flow rate corresponded to an increase in the amount of mass depleted from the initial sample volume. Relating mass depletion to volatilization of the substance, this relationship can be used to correspond flow rate to the relative strength of the odor upon delivery to the test subject.

Further testing with different substances will likely yield similar results, with alterations resulting largely from differences in the vapor pressure and the chemical structure of the compounds analyzed.

6.3 System Purge Time Testing

To gain a better understanding of the evacuation time of the system, the team decided to run a purge time test using the equipment offered by the Fire Protection Engineering (FPE) department on campus. The purpose of this test was to pass a gaseous substance through a length

of tubing that would likely be used in the final design and to then calculate the time that it took for that substance to be removed from the tubing as another is pushed through. This type of testing would mimic a forced evacuation sequence and could be used as an approximation to the amount of time that such a sequence would need to be run to minimize odor persistence. Due to the limited availability of odor quantification and gaseous analytic equipment, the team determined that this type of experiment would be the closest approximation available. As was calculated, the maximum distance that the tubing would have to travel in the client's facility is approximately 27 feet. For this reason, 27 feet each of polypropylene and nylon 6 tubing were chosen for testing.

The testing setup was comprised of two gas reservoir sources, one for filtered air, and one for pure nitrogen. Additionally, the system contained a multi-sensor array that was capable of detecting and quantifying oxygen and nitrogen. After 27 feet of both polypropylene and nylon 6 tubing were portioned out, they were connected to the compressed air reservoir on one end and the multi-sensor array on the other end. A mass flow meter was used to ensure that a constant flow rate of 200 cc/min, the maximum allowable flow rate for the delicate sensors, was achieved throughout the testing suite. The mass flow reader and its display are seen in Figure 50.

Figure 50: Mass flow meter and its display, which fluctuated around 200 cc/min. In the image the display reads 199.8 cc/min.

After properly connecting the tubing, air was pumped through the tubing and towards the sensor at a constant rate until a stable level of oxygen was reached. The average oxygen concentration reached was about 20.82%. After stabilization, the tubing was disconnected from the pressurized air source and moved to the nitrogen source. Nitrogen was then forced through the tubing at 20 cc/min until the oxygen sensor read 0.03%, or the allowable error threshold determined for this test. The time at which this concentration of oxygen was measured was considered the purge time. This test was run 10 times for each of the two types of tubing resulting in 20 total tests. The system's display and filter system can be seen in Figure 51.
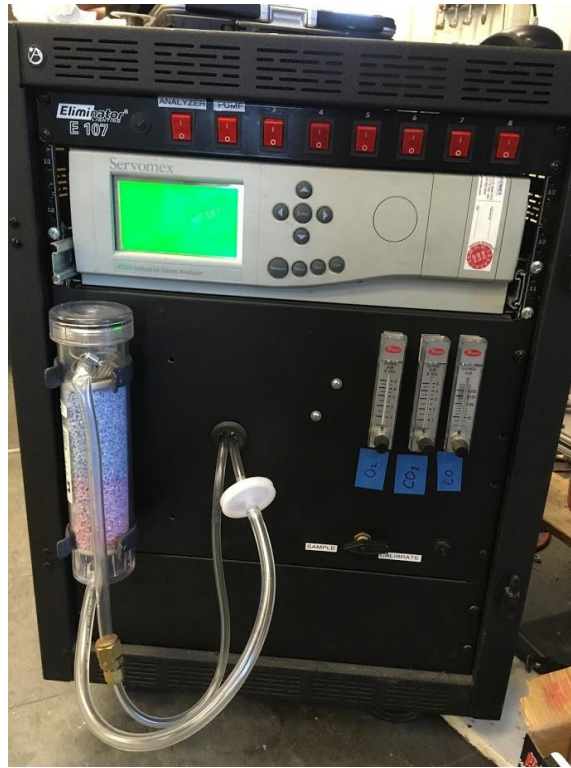
Figure 51: Display and filter aspect of the multi sensor array

The results of this testing showed that the average purge time for the polypropylene

tubing was approximately 65.35 seconds, while the purge time for the nylon 6 tubing was 60.25

seconds. Both of these groups had small standard deviations which informed the group of the

high precision of this test. The differences between the average purge times for the tubing was

likely caused by the minute change in diameter between the two, since the test operator

associated with the FPE department informed the group that flow rate, tube diameter, and tube

length were the largest influencers in purge time. The smaller diameter nylon 6 tubing therefore

had a correspondingly shorter purge time, despite the consistencies between tube length and flow

rate. While this test does not accurately model the chances of odor volatiles adhering to the

tubing walls since VOCs have different mechanics than molecular oxygen, it does provide a

good estimation of the time an evacuation system would need to be run in order to remove all of

the gaseous contaminants. Additionally, the client plans on utilizing a higher flow rate than what was used for this test, something that would likely shorten the purge time. Using Teflon (PTFE) tubing to deliver the odors would also help to minimize tubing contamination, which would give more power to this experiment thus making it a better approximation of the final device. The results for this experiment can be found in Appendix H: Purge Test Results.

6.4 System Smoke Testing

In addition to the purge time testing, the team also tested the evacuation scheme of the device visually through a series of smoke tests. To accomplish these tests, the system was set up normally, with the addition of a smoke generation unit in place of the odor bank. The smoke generation unit consisted of a container wrapped in aluminum foil for heat protection. A cut was made in a side portion and on the lid of the container for tubing attachments, and a burning piece of incense was left inside the container. The air being pumped in from the tank and compressor was left at 5 L/min to ensure that the fire was being supplied with an ample amount of oxygen. The tubing leaving the smoke generation unit then led to a second sealed container which was used as a storage component for the smoke, acting as the environment of the test subject. The tube exiting the second container then led to a custom-built adapter which housed a combined HEPA and activated charcoal filtration unit. Tests were performed to visually evaluate the amount of smoke exiting the adapter during three different conditions. These conditions included an empty adapter (no filter), the adaptor with the filter, and the adapter with the filter and a vacuum pump pulling air through it.

Results from these tests showed that without the filtration system, smoke was visibly able to exit the adapter and was also shown to pool in the second container used to mimic the environment of the test subject. When the filter was added, no smoke was seen exiting the

adapter, but there was still a noticeable amount of smoke pooling in the second container. When the active evacuation system in the form of a vacuum pump was added, the cloud of smoke did not form in the second container, although a stream traveling through was still clear to see. Additionally, there was no smoke seen exiting the adapter or entering the vacuum pump itself.

6.5 Automation Testing

One of the primary objectives of this project was ease of use, which centered on ensuring that the device was usable by the test operators and did not require an extensive knowledge of the system to use it properly. One way in which the team met this objective was by assembling a user manual for usage and troubleshooting, which is discussed in the next sub-section. The other main way in which the team accomplished this objective was by limiting the number of steps required to be completed by the user to operate the system. In order to accomplish this goal, the team automated much of the system processes, allowing the test operator to interact with the system through a few simple steps followed by answering prompts on a user-interface.

As discussed in previous sections, the system is automated through an Arduino-relay system which operates a power switch, a run test switch, and the solenoid switches in the system. When the test operator is prompted for information concerning the test they wish to run, the information is relayed to the Arduino, which then determines the time points to activate the solenoid switches and other components of the system. In order to test this process, the system was run through several trials of entering user input and timed to ensure that the times were accurate. This suite of testing provided insight in both the accuracy of the device automation system and to evaluate whether or not the device accomplished the delay times specified by the client.

After running through the device with user input for delivery and evacuation times and manually timing these points for comparison, the average time difference was determined to be about 0.02 seconds, which is almost certainly due largely to human error. These results demonstrate the reliability and accuracy of the automated delivery and evacuation procedures.

6.6 User Manual Creation

In addition to all of the testing sequences described in this section, a user manual was compiled detailing the purpose of each component, the steps needed to set up the device, the steps taken to operate the device, a bill of parts for replacements, and a troubleshooting section. This manual was designed to allow the client to use the device with a very limited background on the system creation process. The user manual can be found in Appendix I.

7. Discussion

To disseminate the results received from the testing discussed in Chapters 5 and 6, it is necessary to compile the information in a discussion. The following sub-sections detail the analysis of results of each of the areas discussed in previous chapters, with an additional focus on an analysis of the possible impact that this device could have.

7.1 Stimuli Delivery Analysis

The delivery of odor stimuli to the test subject was verified as successful by the design team through testing and analysis. To classify this component of the design as successful, the resulting delivery needed to fulfil the objectives outlined in Section 3.5, Final Objectives. These objectives included allowing for variation in stimulus number and type, flow rate variability, incorporation of anesthesia delivery, and a minimal response time.

Through testing, the team has determined that the device did in fact accomplish the objectives determined through collaboration with the client. The modular design of the odor bank allows for delivery of up to four odors during one experimental procedure, which is more than the three requested by the client and should be substantial enough for any single experiment they would need to run. Testing with several different liquid odorant types and the fact that any vial could be used to hold odorants as long as they fit within the odor bank ensure that a wide variety of odorants can be utilized by the device. Additionally, odor strength quantification testing showed that selected compounds representing a wide range of odor thresholds increase in odor strength during delivery as flow rate is increased, which confirms that this method of odor strength adjustability is valid for a wide variety of odor types. Adjustable flow rates are accomplished by both a coarse and fine method of flow control which are available to the user in the form of a pressure gauge and a flow meter. The automated features of the system allow for

delivery to happen nearly instantaneously, with a 30 second delay used before each test to ensure that the environment is cleared before introducing an odor. Finally, the nose cone designed by the team is large enough to support the addition of a line for anesthesia, as identified by the client, which would allow the client to incorporate their own anesthetic delivery system with the device.

7.2 Quantification Analysis

The final objectives concerning quantification of stimuli included accuracy, precision, and measurement during both delivery and evacuation. Through testing with specific odors, a test operator will be able to estimate the amount of mass depleted during a delivery sequence with a fair amount of accuracy, as long as they know the flow rate and it has been maintained as a constant during the test. While this is not the most accurate method of quantification, the degree of accuracy requested by the client was minimal and mainly consisted of a way of categorizing "strong, average, and weak" scents, which the test operator is capable of doing by comparing delivery flow rates. The precision of the odor strength estimation method used by the team achieved relatively low standard error for most test cases, and included fairly high R-values for linear regression lines, which helps to prove the precision of the mass depletion measurements and their dependency on flow rate. From the statistically significant dependency of mass depletion on flow rate, the team can conclude, that the objectives of accuracy and precision as defined by the clients were accomplished. Additionally, measurements are taken during delivery, but are not taken during evacuation. After speaking with the client several times, this secondary objective was deemed one of the least important for the odor tests that the client is most likely to run. Future testing may require an accurate measurement of odor strength leaving the subject and is certainly something that can be added to future iterations of the device.

7.3 Evacuation Analysis

The objectives involved in proper evacuation included effective removal of stimuli, limited exposure of waste stimuli to the test operators, and limited contamination of the device for subsequent stimuli.

To accomplish these evacuation objectives, an adapter was designed and modeled that could hold a filter. The filter included a dual HEPA and activated charcoal filter that were rated to remove 99% of particles equal to or greater than 0.3 micrometers in size from the air. This specific filter was chosen in order to exceed the client's specification of effectively removing 90% of stimuli between delivery periods. Furthermore, using the filter eliminated the need to deposit waste gases outside the testing environment, as the filter can remove hazardous particles during the evacuation process, which again limits the amount of stimulus that can escape from the system and come into contact with the test operators. Therefore, the system releases evacuated and filtered air directly to testing room. If desired, the exit tubing from the adapter could also be modified to transfer air outside the facility to further reduce the exposure of the test operators to stimuli. To prevent backflow, a vacuum pump was integrated into the evacuation system. The vacuum pump was tested to prevent backflow by vacuuming air at the same flow rate as delivery. This design choice ensures that air travels through the system in one continuous stream up to the evacuation exit tubing, which further reduces the chance of stimuli re-entering the device and creating confounding factors that would affect the test subject's stimuli response. These factors combine to prove that the device did accomplish the objects set forth concerning evacuation of stimuli, as specified by the clients.

7.4 Impact Analysis

After testing, the team looked into all of the ways that the device impacts the world outside of the directly vested stakeholders. The analysis is detailed below, including the various impacts.

7.4.1 Economics

The MRI stimuli delivery system developed by the team has many potential market uses in laboratory, commercial, and clinical settings. Each case could have a profound impact on the economy both directly and indirectly through increased GDP, jobs created, and resulting economic opportunities from related research. The first use case for this device is for stimuli delivery to animals undergoing neuroimaging testing in MRI machines. As this was the original use case given to the team by the project client, the system is specifically design for this purpose and allows for quick, easy, and precise delivery of multiple odorants to measure their effect on neural activity. With this functionality, the system could be sold to research labs across the country focusing on neuroimaging or behavioral response to stimuli. Additionally, the system could be sold for use in scent marketing applications. Scent marketing involves the introduction of certain smells into an environment to stimulate a certain behavior such as buying. By using this system, researchers at a scent marketing company could study the effect that certain stimuli have and develop specific scents for their marketing purposes. Another use case for this system is in MRI imaging regimes at hospitals and doctor's offices. By releasing a pleasant, soothing scent to an anxious or claustrophobic patient entering the bore of an MRI, doctors can potentially ease stress, reduce movement, and provide the patient with a better experience.

With the original cost of development around $1400 and an estimated production cost of $1200 (which could be lowered with the proper manufacturing partner), the unit would need to sell for approximately $2000 to yield a gross profit margin of 40%.[76]

A modification to the system that would make this system far more viable is the addition of a PID to detect and quantify stimuli with extreme accuracy. With this modification, the system would be much easier to sell to labs with rigorous testing requirements and alter the target market to high end labs, hospitals, and companies. With an average PID costing $3000 ($1000-$6000 range), this would drive the cost of unit production up to $4200 and the unit price would need to be adjusted to $7000 to maintain the 40% profit margin.[77][76] A proper market and need analysis would need to be conducted before making this alteration to the device.

7.4.2 Environmental Impact

While production of the MRI Stimuli Delivery System itself is environmentally friendly as it produces little waste and no harmful gases, the production of some of its component materials may be a concern. Many of the components such as the odor bank and the power control box are made of acrylic which can produce harmful waste chemicals and gases in its manufacturing process. Additionally, some of the electrical components may not have environmentally sound manufacturing processes. To reduce the impact of the device, it is recommended to recycle components when they need to be replaced or are being upgraded.

An additional environmental factor to be taken into account is the electricity used by the compressor and power control box. As the system has a small duty cycle for the compressor and testing will only be conducted for a few hours at a time, the electrical use will not be significant and there will be minimal environmental impact.

7.4.3 Societal Influence

This system could have a large societal impact as its usage could improve the lives of many people in various forms. In a direct manner, patients who have anxiety when entering an MRI machine could experience peace of mind and a much more pleasant experience at the hospital by using this system. For example, an estimated 5% of the US population suffers from claustrophobia, which can cause extreme anxiety when affected patients are put in the closed-off MRI system.[78] Calming odors could alleviate some of these anxiety-induced stresses and allow sufferers of these types of anxiety to be imaged properly by these machines. Additionally, people can benefit from this system indirectly by reaping the rewards of the research conducted by neuroimaging labs. For instance, if a lab studying addiction or PTSD was able to use the system and publish groundbreaking research leading to therapeutics, sufferers of those conditions would able to receive the medication and improve their lives.

Another way this system could have a societal impact is if the scent marketing industry transforms the way we shop and function in our everyday lives. By using this system to identify smells that encourage various feelings and activities, scent marketing could be employed in every environment: scents that inspire creativity at school, scents that calm and relax at home, and even scents that stimulate productivity at work.

7.4.4 Political Ramifications

While there are not many direct effects of the creation of this device on politics, through the use of this system, government labs and labs funded by government grants could produce new groundbreaking research that could lead to greater fund allocation and larger grants. This would fuel research in this area and draw new talent into the field in a positive feedback loop.

7.4.5 Ethical Concerns

There are several ethical points that can be brought up with the use of this device. The first concern stems from the use case of this specific project which involves animal testing. While the end goal of the research is to improve human lives, test subjects are forcibly restrained in the bore of the MRI machine and will be exposed to potentially harmful stimuli such as cigarette smoke. Additionally, some stimuli such as fox urine will inspire fear in the test subject and make them extremely uncomfortable and unhappy. These testing methods may raise ethical concerns regarding the use of animals and the mental and physical stresses they will have to endure.

Another concern that may be associated with the device is its use in scent marketing. Due to the nature of scent marketing, some stimuli introduced to an environment may go unnoticed and subliminally influence behavior. For example, if a scent that promotes buying is released at a mall and a person spends more money than they initially intended, it may be seen as a violation of their rights. If used in scent marketing, the appropriate steps must be taken to ensure that these ethical concerns are addressed.

7.4.6 Health and Safety Issues

A health issue that may arise as a result of device usage is the inhalation of potentially dangerous chemicals and odorants. This issue can be made especially apparent if a secure connection between components and tubing becomes loosened or if the evacuation system malfunctions. Such issues will be mitigated by providing a user manual along with the device that warns against the dangers associated with the device. The user manual will advise that the user run a test procedure prior to beginning experimentation. The test procedure will use fresh air from the compressor to test for leaks and malfunctions in the system. The procedure will instruct

the user to switch on the compressor and run a hand over component connections as a qualitative

assessment to feel for loose air flow. Next, the flowmeter will be set to a high flow, which will

allow the user to listen for escaping air. The user manual will also advise the user to move and

transport components carefully to avoid loosening or damaging components. Furthermore, the

device can become dangerous for the MRI subject if the air flow in is too great, or if the

evacuation component suctions air out too rapidly. This scenario was avoided by calculating the

flow rates and pressure differentials of air flow in the system and finding the optimal flow rates

to deliver air to the subject. The flow rate, however, can differ between subjects. Therefore, the

user must exercise their own caution and ensure that the delivery flow rate and the evacuation

flow rate are adequate for the subject.

There are also potential safety issues that may arise from usage of the device. The user

must be aware of areas of the device that may pinch or prod the fingers. The user must also take

care not to touch the compressor during tests as it can become dangerously hot relatively quickly.

To mitigate this danger, the team will design and fashion a cage to insert the compressor in. The

cage will allow the user room to change parts on the compressor but will block the user from

burning themselves. The team will also make sure to keep the components compact on the lifting

tray. Therefore, when a user must move the lifting tray of components from one location to the

other, the user will be able to see most of the ground around them and avoid any potential

hazards. In order to confirm that operators of this device stay as safe as possible, the use of an

IRB or informed consent form would be ideal during training for use of the device.

7.4.7 Manufacturability

This device contains multiple subassemblies that contain both manufactured and

purchased parts. All raw materials and ordered parts can be found in the Bill of Materials section

of the user manual located in Appendix I. The majority of components are purchased and therefore the degree of manufacturing involved with replicating this device is minimal. The methods of manufacturing for components include: laser cutting, cutting, 3D printing, heat treating, drilling and facing.

The first component that included manufactured parts was the flow rate control system. The white, opaque, acrylic mounting plate that houses the pressure regulator and flowmeter was laser cut, the aluminum base was machined using a Bridgeport manual mill, although a drill press could also be used, and all other parts were orders.

The control box, seen in Figure 52 housing was also laser cut from white, opaque acrylic. These pieces were designed in SolidWorks to fit together similarly to a box joint. To assemble these pieces a quick setting solvent glue was used. All other components were purchased and attached to the control box using bolts.
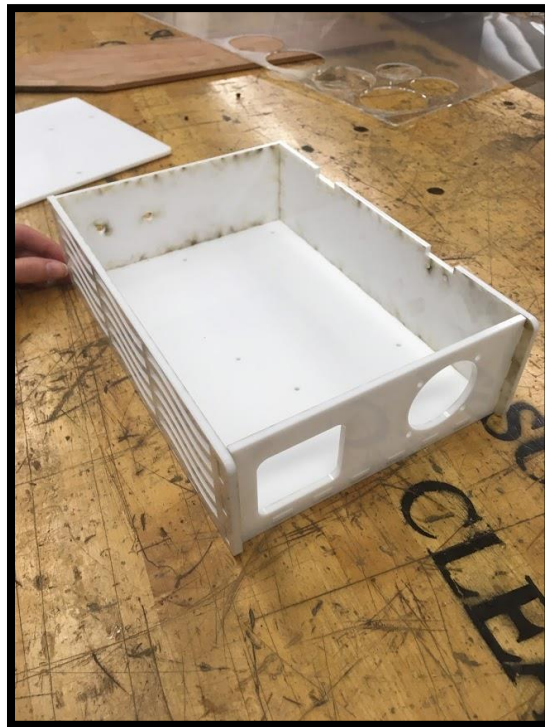
Figure 52: An image showing the manufactured and laser-cut control box

The wiring and tubing were all cut to accommodate the workspace of the CCNI that the team measured during a visit. All wires were soldered together, and heat shrink was used to insulate the exposed wires. To change the wiring of the system, use a sharp edge to cut the heat shrink, expose the wires and use a soldering iron to heat and separate the attached wires.

The odor bank frame was also laser cut and glued together and can be seen in Figure 53. The handles and vial clamps were then bolted to the frame. The caps for the odor vials were 3D printed, and O-rings were inserted in the two top holes of the caps to allow a tight seal around the tubes. These custom-made vial caps can be seen in Figure 54. The odor bank cover was made from two pieces of Lexan polycarbonate and cut to the correct size using a band saw. The two pieces were then heated using a heat gun and bent to the correct angles. These pieces were then glued together, holes were cut for tubing using a Dremel and a handle was bolted to the top. Part of the process of manufacturing the Lexan cover can be seen in Figure 55.

Figure 53: The laser-cut and assembled acrylic odor bank with handles

Figure 54: The custom-made 3D printed centrifuge tube caps with inserted O-rings

Figure 55: This image shows the process of heating and bending the Lexan to form the cover for the odor bank

The test subject interface is composed of purchased components including a Teflon nose cone and tubing. The nose cone was cut and sanded to the correct size using a bandsaw and sandpaper. A hole was then drilled using a hand drill to insert the Teflon tubing and these

components were glued together. A tube holder was 3D printed to secure the nose cone and

tubing in the correct orientation of the nose cone.

The evacuation system was composed of two 3D printed parts that housed the filter and

vacuum pump. The orientation for printing these was important for insuring the strength of the

barbed tubing adapters and support material was used for overhanging parts. An example image

from this printing process can be seen Figure 56. After printing, an O-ring was placed in a

groove of the front piece to ensure a tight seal, the filter was put inside the two parts and they

were bolted together. The vacuum pump was secured to the printed part using rubber bands and

the system was connected to the flexible tubing.
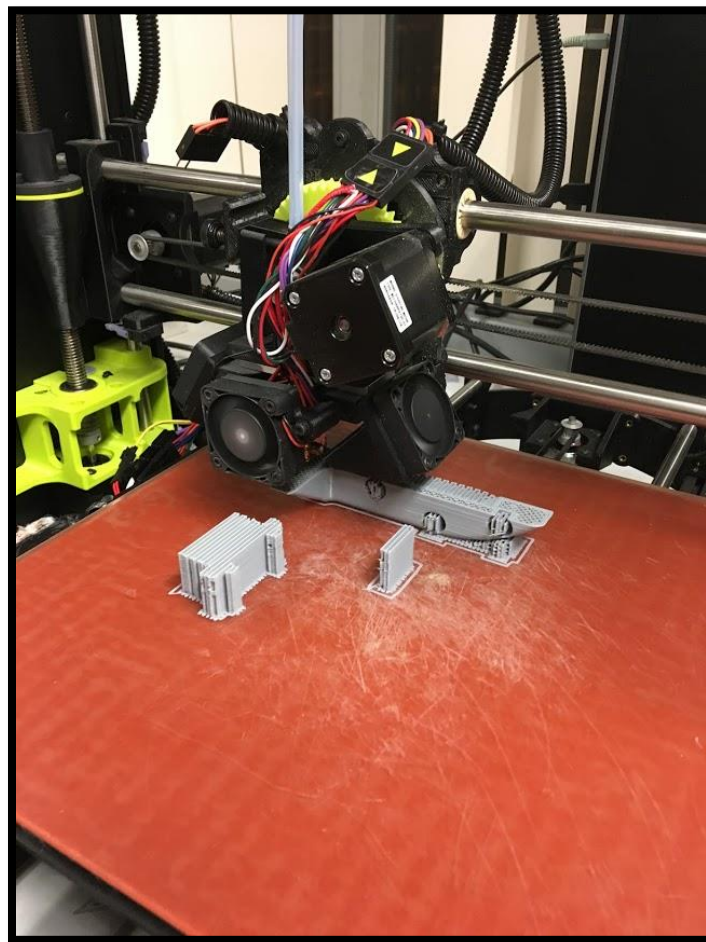
Figure 56: This image shows a representative view of 3D-printing the evacuation adapter

7.4.8 Industry Standards

According to the National Institute for Occupational Safety and Health, the maximum allowable exposure to anesthesia such as isoflurane is 2 parts per million for an eight-hour time weighted average. In other words, a person's exposure to isoflurane must not exceed an average exposure of 2 parts per million over the course of eight hours, a typical work day. In order to meet this industry standard, the team manufactured a state-of-the-art evacuation system complete with a combined HEPA and activated carbon filter and a vacuum pump. This evacuation system pulls air away from the rat and sends it away from the users of the device as well.

Additionally, the design of this device incorporates the isolation of magnetic components from the room containing the MRI, which ensures that the magnetic field created by the imaging machine is not disrupted and that operators are not in danger of components being drawn towards the magnet. All tubing and other materials used within the MRI are properly rated for use in imaging machines, and do not cause artifacts in the resultant data.[79][80]

8. Conclusions and Recommendations

As discussed in the previous chapter, the device created by the team met the objectives defined by the client for this project. In terms of odor delivery, the device is capable of delivering up to four odors per experiment, which exceeds the objective established by the client. Odors can be delivered at flow rates between 1 and 1.5 L/min, which is within the range for rodent breathing rates, as mentioned in previous chapters. Additionally, a visual smoke analysis demonstrated that the evacuation system portion of the device is capable of filtering contaminants from the wasted air, thus reducing confounding factors in the system environment between tests while also maintaining a safer environment for the users. Odor strength quantification testing helped to confirm the relationship between odor strength, represented by mass depletion of the odorant, to flow rate, which established a relationship for test operators to base their odor strength assumptions on. While this method is only semi-quantitative, the level of quantification desired by the client was minimal, with accuracy between tests being more important to them than a high degree of precision. Therefore, by establishing relationships between the odor strengths and flow rates, the team has developed a system that semi-quantitatively estimates odor strength based on user input. Finally, the automated aspect of the device limits user error and allows for an easy to use system which can be modified easily with assistance from the user manual written and compiled by the team.

In conclusion, the team was able to satisfy all of the primary objectives of the clients, while also including some key features that further grant the system usability and effectiveness. In terms of future work, there are many additions and alterations that can be made to the device. For example, if a test operator wanted to use this device for a pollution test where particulate matter is delivered to the test subject instead of odors, they could simply replace the odor bank

with a particulate matter storage device and nebulizer. The remainder of the device could still initiate and perpetuate an airflow for the system, while the new particulate matter system would be added to handle a different stimulus type. Additionally, if higher flow rates are required, the flow controls aspect of the system can be replaced with a flow meter and pressure gauge with different ranges. If these flow rates cannot be achieved with the current tank and compressor system, these can also be changed for different components depending on the needs of the test operators. The device's modular design allows for all of these components to be switched with other components, as long as the proper fittings are used to connect the components to each other and with the PTFE tubing.

Another aspect of the device that could be improved upon includes the level of quantification. While the current device relies on mass depletion estimations to correspond to odor strength, incorporating a more quantitative method such as a GC-FID (gas chromatography – flame ionization detector) could drastically increase accuracy by using direct measurements. Other more accurate quantification devices could be added to points in the system depending on the purpose of the experiment being performed.

These possible improvements and additions would certainly add to the value to the device, making it a versatile and integral stimulus introduction system in the field of MRI technologies.

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Appendix A: Meetings and Interviews with the CCNI

September 11, 2017

The team members and Professors Pins and Sullivan met with the clients at the CCNI to discuss the needs of the project and understand the operations of the CCNI. This meeting was meant to establish this MQP project and meet the test designers and operators who would be influenced by this device.

Meeting Notes:
The CCNI currently has a means of delivering scents, but the test designers and operators could benefit from having more control over the test variables. They want more versatility for delivery mechanisms and would like to look into the possibility of delivering both odor and particulate matter. One concise delivery system is preferred but they are open to multiple systems. The stimuli used in the past have been extracts. Future tests with incorporate exposing the rats to types of stimuli that are difficult to quantify. A way to quantify certain scents, like pup body odor, may not be possible. Reproducible scents can guarantee that the odor makes it to the subject. Odor particles may be sticking to the current delivery system, a yard stick with odor soaked gauze taped to the end, and is not reaching the rats. Other studies that delivered pups' sent placed them in a cage with non scented shavings and inserted a pump to transfer the air. Wood chambers produce volatiles, so an empty chamber of rats would be best. It would be beneficial to understand the dispense rate and quantity of these scents. This might be dependent on flow rate. Does binding of scent over time to the delivery mechanism cause problems? The ability to deliver particulate matter is beneficial to future tests at the CCNI. They want to have the ability to switch between different tests during one test. In the past, they have used aquarium tubing, scented gauze placed in the nose cone, but this method cannot be done remotely. There may need to be a multiple chamber tube prevent taking the rat out of the MRI. There could possibly be a reduced time of stimuli introduction. In the past they have used about 30 seconds. To switch between odors in a test programed or manual switches could be used. The current restraint with bite bar and nose grip cannot be redesigned. The rats used in the tests either awake or anesthetized. It takes about two to three weeks to acclimate a rate to the MRI holder. With this device there is a possibility of allowing for visual stimuli later. The rats are prepared in the procedure room. The anesthesia used for rats is isoflurane.

October 2, 2017

The team members met with Laurelee Pain and Guillaume Poirier to ask more specific questions about the system and understand the needs of the test operator and test designer. Laurelee and Guillaume then showed the experimental procedure and test set up for delivering odors to the test subjects. The team took measurements and pictures of the holding chamber, procedural table, MRI room, MRI bore, and testing room.

Meeting Notes:
The team asked questions about the desired outcome of the project and specifications of the test procedures, shown below.
- The team showed Lauralee and Guillaume the progress made on background research, similar systems (hood system), individual components (solenoid valves, quantification devices), scavenging systems.
  - In the future CCNI will be moving to another location in which the magnet will face the doorway, so that there will be no more need for a long tube.
- Will the e-cigarette vapors be delivered in a different method than the other odor stimuli? Will they still be present/stored in a liquid state and then administered in a gaseous state, as with the other odors?
  - Same way as the links do it. They use an unadulterated e cigarette and insert it into the testing apparatus.
- Will there be experimental setups that require anesthesia or different odors to be administered simultaneously, or will all setups require discrete times of anesthesia and odor delivery separate from one another?
  - It is likely for the odor and the anesthesia to be administered simultaneously.
  - But it does not need to be mixed. Perhaps it could be intermittent flow of odor and anesthesia.
  - The odors will be merged at the specimen, but no earlier than that.
- If delivered discreetly, will evacuation in between delivery rounds be necessary?
- Are there any constraints for flow rate (maximum or minimum) that you require for your experiments?
  - There are not any constraints, but we do not want it to be so max that it is suffocating/blowing past the subject. We also need to account for the distance between the nose and the nosecone. We also need to think about awake animals vs anesthetized animals, breathing slows in the latter.
- Removal Rate: Boundaries for how much of the odor can remain in the system before a new odor is introduced?
- Will flow rate of stimuli need to be adjusted during the imaging sequence, or will it always be required to remain constant?

- ○ Doesn't need to be adjustable during scan, but different flow rates likely for different stimuli, so we need to account for using different flow rates for discrete odors in a single session.
- What particulates will be used for testing?
  - ○ DUST
- What is the target response time for the system?
  - ○ We don't need it to be extremely quick. From computer start to odor delivery to rat: 60 seconds is ok, 30 is great, 15-20 would be excellent.
- What is the purpose of your current research? Is it to identify brain pathways associated with parental bonding?
  - ○ Nutshell – interested in reproductive experience in maternal behavior. There are diff ways that reproductive experience can change your brain... how? Neural substrate produced, what is the difference between virgin female and experienced.
  - ○ Multiple reproductive experiences have impact on behavioral outputs. So, what is happening in brain here?
  - ○ How addiction changes maternal behavior.
  - ○ Outcomes of reproductive experience on perception.

Appendix B: Pairwise Comparisons

Client's Pairwise Chart

Primary Objectives	Delivery	Quantification	Evacuation	Ease of Use	Cost Effectiveness	Total
Delivery	X	1	0.5	1	1	3.5
Quantification	0	X	0	1	1	2
Evacuation	0.5	1	X	1	1	3.5
Ease of Use	0.5	0	0	X	1	1.5
Cost Effectiveness	0	0	0	0	X	0

Team's Pairwise Charts

Primary Objectives	Delivery	Quantification	Evacuation	Ease of Use	Cost Effectiveness	Total
Delivery	X	1	1	1	1	4
Quantification	0	X	1	1	1	3
Evacuation	0	0	X	1	1	2
Ease of Use	0	0	0	X	0	0
Cost Effectiveness	0	0	0	1	X	1

Primary Objectives	Delivery	Quantification	Evacuation	Ease of Use	Cost Effectiveness	Total
Delivery	X	1	1	1	1	4
Quantification	0	X	1	1	1	3
Evacuation	0	0	X	1	1	2
Ease of Use	0	0	0	X	1	1
Cost Effectiveness	0	0	0	0	X	0

Primary Objectives	Delivery	Quantification	Evacuation	Ease of Use	Cost Effectiveness	Total
Delivery	X	1	1	1	1	4
Quantification	0	X	1	1	1	3
Evacuation	0	0	X	1	1	2
Ease of Use	0	0	0	X	0	0
Cost Effectiveness	0	0	0	1	X	1

Primary Objectives	Delivery	Quantification	Evacuation	Ease of Use	Cost Effectiveness	Total
Delivery	X	1	1	1	1	4
Quantification	0	X	1	1	1	3
Evacuation	0	0	X	1	1	2
Ease of Use	0	0	0	X	0	0
Cost Effectiveness	0	0	0	1	X	1

Appendix C: Gantt Charts

A Term Gantt Chart
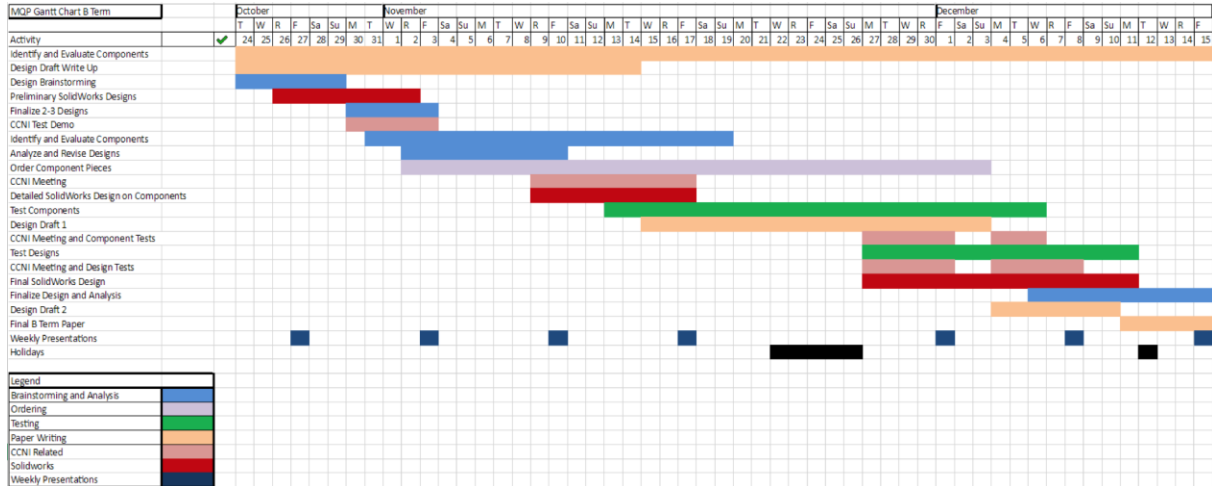
B Term Gantt Chart

C
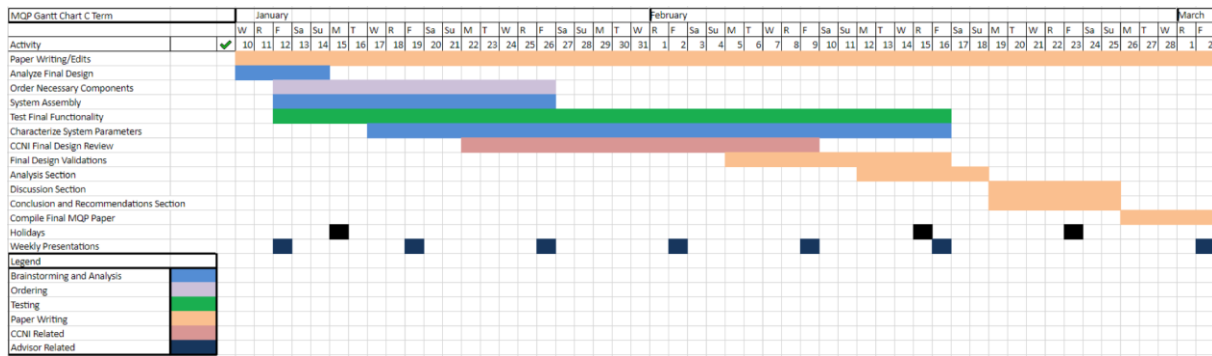
C Term Gantt Chart
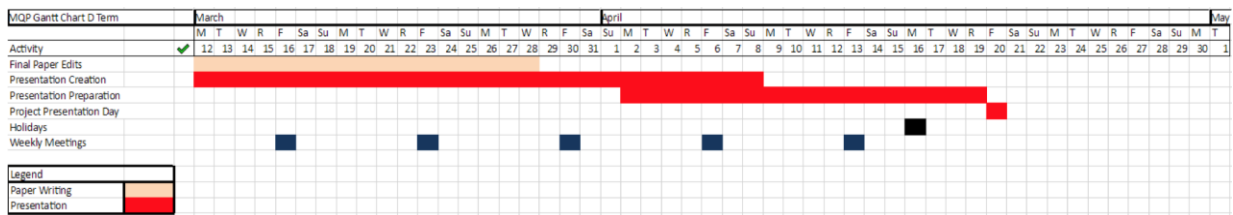
Appendix D: Rating System for Quantitative Means Analysis

<u>Stimuli Variability - Type</u>

4 - All stimulus types (particulate matter, odor volatiles, smoke pup scent, ect.)

3 - Multiple stimuli types (odor volatiles, and particulate matter)

2 - Large amounts of one stimulus (odor volatiles)

1 - Capable of holding limited amounts of liquid or gaseous odor

0 - Incapable of holding stimuli

<u>Stimuli Variability - Number</u>

4 - interchangeable number of stimuli

3 - 5-8 Stimuli

2 - 3-4 Stimuli

1 - 1-2 Stimuli

0 - Incapable of holding stimuli

<u>Simplicity</u>

4 - Automated or less than 5 minute set up

3 - Between 5 and 15 minutes

2 - Operation/set up time <30 and >15 minutes

1 - Long set up/operation time >30 minutes

0 - Complex design requiring assistance for assembly or use

<u>Scalability</u>

4 - Ability to add additional existing components and completely new components after implementation

3 -Able to make sizeable changes to the system after implementation

2 - Able to make some significant changes to the system after implementation

1 - Able to make slight additions to the system after implementation

0 - Unable to be scaled/finite number of components

<u>Adjustability</u>

4 - The device can control the amount of stimulus exposed to the subject and the rate of delivery.

3 - The device can control the amount of stimulus exposed to the subject, both with a variable volume of stimuli and control of volatiles reaching subject.

2 - The device can control the rate of delivery only.

1 - The device can only adjust the rate of delivery or the amount of stimuli delivered slightly.

0 - The device cannot adjust the rate of delivery or the amount of stimuli delivered.

Size
4 - The device sits comfortably on the operator's table and does not interrupt the flow of work, or create difficulties operating the system.

3 - The device sits comfortably on the operator's table and does not interrupt the flow of work.

2 - The device sits comfortably on the operator's table, but does interrupt work flow because of bulk.

1 - The device cannot sit on the operator's table but can be kept in the room near the table.

0 - The size of the device does not allow it to be in the same room are the operating table.

Safety
4 - The device does not expose any party to unnecessary amounts of stimulus, pressure, or dangerous device components and has a successful filtration or evacuation system.

3 - The device does not expose any party to unnecessary amounts of stimulus, pressure.

2 - The device does not expose any party to unnecessary amounts of stimulus.

1 - The device does not expose the test operator to stimuli.

0 - The device puts the animal and test operator at risk.

Value
4 - The usefulness of the device far outweighs the cost of creating or purchasing the device.

3 - The usefulness of the device is not exceeded by the cost of creating the device.

2 - The usefulness of the device is equal to the cost of creating or purchasing the device.

1 - The usefulness of the device is slightly exceeded by the cost of creating or purchasing the device.

0 - The usefulness of the device is extremely exceeded by the cost of creating or purchasing the device.

Lifetime
4 - All components have a warranty of five years.

3 - All components have a warranty of two years.

2 - Most components have a 1 year warranty, including the compressor and filters.

1 - Only the compressor has a warranty of 2 years.

0 - No system is rated to have a life of 1 year.

Flow Rate Variability
4 - The test operators should be able to change the flow rate of the system in a range of 0 to 10 L/min during use.

3 - The test operators should be able to change the flow rate of the system in a range of 0 to 5 L/min during use.

2 - The test operators should be able to change the flow rate of the system in a range of 0 to 2 L/min during use.

1 - The test operators should be able to change the flow rate of the system in a range of 0 to 1 L/min during use.

0 - There is no flow rate variability.

Anesthesia Incorporation

4 - The device can deliver both stimuli and anesthesia, concurrently if the test operators decide that it is necessary for a procedure.

3 - The device can to deliver both stimuli and anesthesia, and can change between the two within 10 seconds.

2 - The device can deliver both stimuli and anesthesia, but not concurrently.

1 - The device can deliver both stimuli and anesthesia, but not concurrently and not with accuracy.

0 - The device can not deliver anesthesia

Response Time

4 - The system delivers stimuli to the test subject within 10 seconds of being activated by a test operator.

3 - The system delivers stimuli to the test subject within 10 seconds of being activated by a test operator.

2 - The system delivers stimuli to the test subject within 1 minute of being activated by a test operator.

1 - The system delivers stimuli to the test subject within 3 minutes of being activated by a test operator.

0 - The system delivers stimuli to the test subject within 30 minutes of being activated by a test operator.

Accuracy

4 - The technique used for quantifying stimuli must meet the client's need for reliable measurements that are an accurate representation of the amounts of stimuli being experienced by the subject within a margin of 5%.

3 - The technique used for quantifying stimuli must meet the client's need for reliable measurements that are an accurate representation of the amounts of stimuli being experienced by the subject within a margin of 10%.

2 - The technique used for quantifying stimuli must meet the client's need for reliable measurements that are an accurate representation of the amounts of stimuli being experienced by the subject within a margin of 25%.

1 - The technique used for quantifying stimuli must meet the client's need for reliable measurements that are an accurate representation of the amounts of stimuli being experienced by the subject within a margin of 50%.

0 - The technique used for quantifying stimuli does not meet the client's need for reliable

measurements that are an accurate representation of the amounts of stimuli being experienced by the subject.

Precision

4 - The technique used for quantification provides reproducible measurements that offer precise readings throughout the lifetime of the device.

3 - The technique used for quantification provides reproducible measurements that offer precise readings for 75% of the tests throughout the lifetime of the device.

2 - The technique used for quantification provides reproducible measurements that offer precise readings for 50% of the tests throughout the lifetime of the device.

1 - The technique used for quantification provides reproducible measurements that offer precise readings for 25% of the tests throughout the lifetime of the device.

0 - The technique used for quantification does not provide reproducible measurements or offer precise readings throughout the lifetime of the device.

Delivery Measurement

4 - The device can measure the concentration of stimuli with an accuracy within 25% that the subject will be exposed to with each round of delivery.

3 - The device can measure the concentration of stimuli with low accuracy within 50% that the subject will be exposed to with each round of delivery.

2 - The device can measure the concentration of stimuli with low accuracy within 75% that the subject will be exposed to with each round of delivery.

1 - The device can measure the concentration of stimuli with low accuracy within 90% that the subject will be exposed to with each round of delivery.

0 - The device cannot measure the concentration of stimuli with that the subject will be exposed to with each round of delivery.

Evacuation Measurement

4 - The system can measure the concentration of stimuli that is removed with in a margin of accuracy of 5% during evacuation to ensure that there is minimal contamination.

3 - The system can measure the concentration of stimuli that is removed with in a margin of accuracy of 15% during evacuation to ensure that there is minimal contamination.

2 - The system can measure the concentration of stimuli that is removed with in a margin of accuracy of 50% during evacuation to ensure that there is minimal contamination.

1 - The system can measure the volume of stimuli evacuated.

0 - The system cannot measure the concentration of stimuli that is removed during evacuation.

Effective Removal

4 - The device must be able to remove a 100% of previous test stimuli from the system before the introduction of other stimuli.

3 - The device is able to remove a 75% of previous test stimuli from the system before the introduction of other stimuli.

2 - The device is able to remove a 50% of previous test stimuli from the system before the introduction of other stimuli.

1 - The device is able to remove a 25% of previous test stimuli from the system before the introduction of other stimuli.

0 - The device is not able to remove test stimuli from the system before the introduction of other stimuli.

Limited Exposure

4 - The device ensures that the test operators are not exposed to an unsafe amount of stimulus or anesthesia throughout the preparation, delivery and evacuation of odors.

3 - The device ensures that the test operators are not exposed to an unsafe amount of stimulus or anesthesia throughout the delivery and evacuation of odors.

2 - The device ensures that the test operators are not exposed to an unsafe amount of stimulus or anesthesia throughout the delivery of odors.

1 - The device ensures that the test operators are not exposed to an 50% of unsafe stimuli or anesthesia throughout the delivery and evacuation of odors.

0 - The device exposes test operators to an unsafe amount of stimulus or anesthesia.

Limited Contamination

4 - The device is resistant to the contamination of stimuli through both unexpected mixing or ineffective removal of a previous stimulus.

3 - The device retains less than 1% of the stimuli contamination.

2 - The device retains less than 5% of the stimuli contamination.

1 - The device retains less than 10% of the stimuli contamination.

0 - The device is contaminated with stimuli after one test and equipment must be replaced.

Appendix E: Quantitative Means Analysis

Stimulus Storage:

Constraints	Weight (%)	Individual Vials			Holding Chamber			Plastic Bag		
		Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum
Magnetic Compatibility			Y			Y			Y	
Restraint Compatibility			Y			Y			Y	
Operational Compatibility			Y			Y			Y	
Cost			Y			Y			Y	
Objectives										
Delivery	36.67		2	73.34		1.5	55.005		2	73.34
Stimuli Variability - Type		4	1		2	0.5		4	1	
Stimuli Variability-Number		4	1		4	1		4	1	
Ease of Use	8.39		4	33.56		3	25.17		4	33.56
Simplicity		4	1		2	0.5		4	1	
Scalability		3	0.75		1	0.25		3	0.75	
Adjustability		3	0.75		4	1		3	0.75	
Size		3	0.75		2	0.5		3	0.75	
Safety		3	0.75		3	0.75		3	0.75	
Cost Effectiveness	3.75		2	7.5		1.5	5.625		0.75	2.8125
Value		4	1		3	0.75		2	0.5	
Lifetime		4	1		3	0.75		1	0.25	
Total				114.4			85.8			109.7125

Flow Carrier - Gas Source:

Constraints	Weight (%)	Aquarium Pump			Vacuum Pump			Compressor			Fan			Passive Air		
		Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum
Magnetic Compatibility			Y			Y			Y			Y			Y	
Restraint Compatibility			Y			Y			Y			Y			Y	
Operational Compatibility			Y			Y			Y			Y			Y	
Cost			Y			Y			Y			Y			Y	
Objectives																
Delivery	36.67		4.5	165.015		2.75	100.8425		5	183.35		3	110.01		2	73.34
Stimuli Variability - Type		4	1		4	1		4	1		4	1		4	1	
Stimuli Variability - Number		4	1		4	1		4	1		4	1		4	1	
Flow Rate Variability		3	0.75		0	0		4	1		2	0.5		0	0	
Anesthesia Incorporation		4	1		0	0		4	1		0	0		0	0	
Response Time		3	0.75		3	0.75		4	1		2	0.5		0	0	
Ease of Use	8.39		4.25	35.6575		2.75	23.0725		4.5	37.755		3.5	29.365		3	25.17
Simplicity		4	1		1	0.25		3	0.75		4	1		4	1	
Scalability		3	0.75		2	0.5		4	1		1	0.25		0	0	
Adjustability		2	0.5		0	0		4	1		2	0.5		0	0	
Size		4	1		4	1		4	1		3	0.75		4	1	
Safety		4	1		4	1		3	0.75		4	1		4	1	
Cost Effectiveness	3.75		1.25	4.6875		1.75	6.5625		2	7.5		1.25	4.6875		2	7.5
Value		4	1		3	0.75		4	1		4	1		4	1	
Lifetime		1	0.25		4	1		4	1		1	0.25		4	1	
Total				205.36			130.4775			228.605			144.0625			106.01

Control Method:

Constraints	Weight (%)	Solenoids			Manual Switches			None		
		Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum
Magnetic Compatibility			Y			Y			Y	
Restraint Compatibility			Y			Y			Y	
Operational Compatibility			Y			Y			Y	
Cost			Y			Y			Y	
Objectives										
Delivery	36.67		5	183.35		4	146.68		2	73.34
Stimuli Variability - Type		4	1		4	1		4	1	
Stimuli Variability - Number		4	1		4	1		4	1	
Flow Rate Variability		4	1		4	1		0	0	
Anesthesia Incorporation		4	1		3	0.75		0	0	
Response Time		4	1		1	0.25		0	0	
Ease of Use	8.39		4.75	39.8525		4.5	37.755		2	16.78
Simplicity		3	0.75		3	0.75		4	1	
Scalability		4	1		3	0.75		0	0	
Adjustability		4	1		4	1		0	0	
Size		4	1		4	1		4	1	
Safety		4	1		4	1		0	0	
Cost Effectiveness	3.75		2	7.5		2	7.5		2	7.5
Value		4	1		4	1		4	1	
Lifetime		4	1		4	1		4	1	
Total				230.7025			191.935			97.62

Component Connections:

Constraints	Weight (%)	Flexible Tubing Score	Weighted Score	Weighted Sum	Rigid Piping Score	Weighted Score	Weighted Sum	Direct Connections Score	Weighted Score	Weighted Sum
Magnetic Compatibility										
Restraint Compatibility										
Operational Compatibility										
Cost										
Objectives										
Evacuation	26.67		2.5	66.675		2.5	66.675		2	53.34
Effective Removal		4	1		4	1		2	0.5	
Effective Exposure		4	1		4	1		2	0.5	
Limited Contamination		2	0.5		2	0.5		4	1	
Ease of Use	8.39		5	41.95		3.5	29.365		2.5	20.975
Simplicity		4	1		2	0.5		1	0.5	
Scalability		4	1		3	0.75		0	0	
Adjustability		4	1		1	0.25		0	0	
Size		4	1		4	1		4	1	
Safety		4	1		4	1		4	1	
Cost Effectiveness	3.75		1.75	6.5625		2	7.5		2	7.5
Value		4	1		4	1		4	1	
Lifetime		3	0.75		4	1		4	1	
Total				115.1875			103.54			81.815

Stimulus Quantification Method:

Constraints	Weight (%)	PIDs Score	Weighted Score	Weighted Sum	Mass Spectrometry Score	Weighted Score	Weighted Sum	FIDs Score	Weighted Score	Weighted Sum	Electronic Nose Score	Weighted Score	Weighted Sum	Optical PM Detector Score	Weighted Score	Weighted Sum	Dilution Factor Estimation Score	Weighted Score	Weighted Sum
Magnetic Compatibility		Y			Y			Y			Y			Y					
Restraint Compatibility		Y			Y			Y			Y			Y					
Operational Compatibility		Y			Y			Y			Y			Y					
Cost		N			N			N			N			N					
Objectives																			
Quantification	24.52																	2.5	61.3
Accuracy																	1	0.25	
Precision																	3	0.75	
Delivery Measurement																	3	0.75	
Evacuation Measurement																	3	0.75	
Ease of Use	8.39																	5	41.95
Simplicity																	4	1	
Scalability																	4	1	
Adjustability																	4	1	
Size																	4	1	
Safety																	4	1	
Cost Effectiveness	3.75																	2	7.5
Value																	4	1	
Lifetime																	4	1	
Total																			110.75

Stimulus Evacuation System:

Constraints	Weight (%)	Forced Air Evacuation Score	Weighted Score	Weighted Sum	Forced Water Evacuation Score	Weighted Score	Weighted Sum	Vacuum Evacuation Score	Weighted Score	Weighted Sum	Passive Air Score	Weighted Score	Weighted Sum
Magnetic Compatibility		Y			Y			Y			Y		
Restraint Compatibility		Y			Y			Y			Y		
Operational Compatibility		Y			Y			Y			Y		
Cost		Y			Y			Y			Y		
Objectives													
Evacuation	26.67		2.75	73.3425		3	80.01		2.75	73.3425		0.75	20.0025
Effective Reoval		3	0.75		4	1		3	0.75		1	0.25	
Limited Exposure		4	1		4	1		4	1		1	0.25	
Limited Contamination		4	1		4	1		4	1		1	0.25	
Ease of Use	8.39		5	41.95		1.75	14.6825		4.75	39.8525		2.25	18.8775
Simplicity		4	1		1	0.25		3	0.75		4	1	
Scalability		4	1		1	0.25		4	1		0	0	
Adjustability		4	1		1	0.25		4	1		0	0	
Size		4	1		1	0.25		4	1		4	1	
Safety		4	1		3	0.75		4	1		1	0.25	
Cost Effectiveness	3.75		2	7.5		0.5	1.875		1.75	6.5625		1.5	5.625
Value		4	1		1	0.25		4	1		2	0.5	
Lifetime		4	1		1	0.25		3	0.75		4	1	
Total				122.7925			96.5675			119.7575			44.505

Test Subject Interface:

Constraints	Weight (%)	Existing Nose Cone			Redesigned Nose Cone			Tubing Alone			Hood Method		
		Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum	Score	Weighted Score	Weighted Sum
Magnetic Compatibility			Y			Y			Y			Y	
Restraint Compatibility			Y			Y			Y			Y	
Operational Compatibility			Y			Y			Y			Y	
Cost			Y			Y			Y			Y	
Objectives													
Delivery	36.67		4.25	155.8475		5	183.35		4.25	155.8475		4.25	155.8475
Stimuli Variability - Type		3	0.75		4	1		4	1		4	1	
Stimuli Variability - Number		3	0.75		4	1		4	1		4	1	
Flow Rate Variability		4	1		4	1		2	0.5		2	0.5	
Anesthesia Incorporation		3	0.75		4	1		3	0.75		3	0.75	
Response Time		4	1		4	1		4	1		4	1	
Evacuation	26.67		3	80.01		3	80.01		1.5	40.005		3	80.01
Effective Reoval		4	1		4	1		2	0.5		4	1	
Limited Exposure		4	1		4	1		2	0.5		4	1	
Limited Contamination		4	1		4	1		2	0.5		4	1	
Ease of Use	8.39		3.5	29.365		4.5	37.755		5	41.95		3.5	29.365
Simplicity		4	1		2	0.5		4	1		0	0	
Scalability		1	0.25		4	1		4	1		4	1	
Adjustability		1	0.25		4	1		4	1		1	0.5	
Size		4	1		4	1		4	1		4	1	
Safety		4	1		4	1		4	1		4	1	
Cost Effectiveness	3.75		1.5	5.625		2	7.5		1.75	6.5625		1.25	4.6875
Value		4	1		4	1		3	0.75		2	0.5	
Lifetime		2	0.5		4	1		4	1		3	0.75	
Total				270.8475			308.615			244.365			269.91

Appendix F: Pressure Calculations

Velocity of Flow

Volumetric Flow Rate: 1.3 L/min

Diameter: 3/16 in

Velocity: ?

$$Vel = \frac{4 * (Volumetric\ Flow\ Rate)}{\pi * Diameter^2} = 1.21627\frac{m}{s}$$

Determining the type of flow

Vel = velocity of air through the tube = 1.21627 m/s

L = characteristic length = 0.0047625 m

v = kinematic viscosity of the air at 23 C = 1.5587 E-5 m^2/s

Reynolds Number: $Re = \frac{Vel*L}{v} = 376$

Re < 2100 therefore the flow is laminar

Darcy Friction Factor (or Flow Coefficient) for Laminar Flow

Re = Reynolds Number = 376

$$f_D = \frac{64}{Re} = 0.1702$$

Pressure Loss from the Pipe

L = length = 8.2296 m

ρ = density of the fluid = 1.1925 kg/m^3

D = diameter of the pipe = 0.0047625 m

Vel = mean flow velocity 1.21627 m/sec

f_D = Darcy friction factor = 0.1702

$$\frac{Change\ in\ Pressure}{L} = f_D * \frac{\rho}{2} * \frac{vel^2}{D} = 31.54423 \left(\frac{Pa}{m}\right)$$

$$Change\ in\ Presssure = 31.544233 \left(\frac{Pa}{m}\right) * L = 259.5964\ Pa = 0.03765127458\ psi$$

$$Change\ in\ Pressure = Pin - Pout$$

$$Pin = Change\ in\ Pressure + Pout$$

$$Pin = 0.03765127458\ psia + 14.07\ psia = 14.1076512746\ psia$$

Appendix G: Arduino Program

```
int solenoidPin1 = 53;    //This is the output pin on the Arduino we are using
int solenoidPin2 = 51;
int solenoidPin3 = 49;
int solenoidPin4 = 47;
int solenoidPin5 = 45;
int coolingFanPin = 43;
int startSwitch = 23;
int STATE = 0;
int index = 0; //variable to index through all the arrays
int timer = 0;
int endEvacTime = 30;
long waitTime = 0;

int vialDeliveryNums[20]; //make an array that can hold information for 20 deliveries
int vialNums[20];
int vialDeliveryTimes[20];
int waitTimes[20];
int bufferArray[5]; //sending a four digit number over serial. It sends them one digit at a time. This will
hole the time as a group of 4 independent characters for later use as a single unit.

char response = 0;

boolean doOnce = true;

void setup() { //sets up all the pins
  Serial.begin(9600);
  // put your setup code here, to run once:
  pinMode(solenoidPin1,  OUTPUT);        //Sets the pin as an output
  pinMode(solenoidPin2,  OUTPUT);        //Sets the pin as an output
  pinMode(solenoidPin3,  OUTPUT);        //Sets the pin as an output
  pinMode(solenoidPin4,  OUTPUT);        //Sets the pin as an output
  pinMode(solenoidPin5,  OUTPUT);        //Sets the pin as an output
  pinMode(coolingFanPin, OUTPUT);         //Sets the pin for the control box fan as an output
  pinMode(startSwitch,   INPUT_PULLUP);    //Sets the pin for the switch that starts a certain test
  //start with all the soleniods off
  digitalWrite(solenoidPin1,  HIGH);
  digitalWrite(solenoidPin2,  HIGH);
  digitalWrite(solenoidPin3,  HIGH);
  digitalWrite(solenoidPin4,  HIGH);
  digitalWrite(solenoidPin5,  LOW);
  //start with the fan turning on
  digitalWrite(coolingFanPin, LOW);
```

```
}

void loop() {
 //initialize local variables
 int i = 0;
 int j = 0;
 int flag = 0;
 int tens = 1;
 int inTime = 0;
 switch (STATE) {
  //Input solenoid valve number
  case 0:
    //Print a prompt for the opperator only once per case run
    if (doOnce) {
     doOnce = false;
     Serial.println("What number vial would you like to use?");
    }
    //check for response
    if (Serial.available() > 0) {     // is a character available? Did the operator enter a value?
     response = Serial.read();       // get the character/ responce
     // check if a number was received
     switch (response) {
      case '1':
        //Serial.print("Vial number received: ");
        //Serial.println(response);
        vialDeliveryNums[index] = solenoidPin1;
        vialNums[index] = response - 48;
        doOnce = true;
        STATE = 1;
        break;

      case '2':
        //Serial.print("Vial number received: ");
        //Serial.println(response);
        vialDeliveryNums[index] = solenoidPin2;
        vialNums[index] = response - 48;
        doOnce = true;
        STATE = 1;
        break;

      case '3':
        //Serial.print("Vial number received: ");
        //Serial.println(response);
        vialDeliveryNums[index] = solenoidPin3;
```

```
        vialNums[index] = response - 48;
        doOnce = true;
        STATE = 1;
        break;

      case '4':
        //Serial.print("Vial number received: ");
        //Serial.println(response);
        vialDeliveryNums[index] = solenoidPin4;
        vialNums[index] = response - 48;
        doOnce = true;
        STATE = 1;
        break;

      default:
        Serial.println("Not a number between 1 and 4, please try again!");
    }
  }
  break;

//Input solenoid valve time
case 1:
  //Print a prompt for the opperator only once per case run
  if (doOnce) {
    doOnce = false;
    Serial.println("How long should this stimulus be delivered in seconds?");
  }
  //check for response
  i = 0;
  flag = 0;

  while (Serial.available() > 0) {     // stores each digit in a bufferArray
    bufferArray[i] = Serial.read() - 48;
    // check if a number was received
    if (bufferArray[i] >= 0 && bufferArray[i] <= 9) {
      //flag high chack that you receiving data
      flag = 1;
    }
    else {
      flag = 0;
      Serial.println("Not a number, please try again.");
      break;
    }
    i++; //increment i
```

```
        delay(5);
      }
      //chack that data was received
      if (flag == 1) {
        tens = 1;
        inTime = 0;
        for (int f = i - 1; f >= 0; f--) {
          inTime = inTime + (bufferArray[f] * tens);
          tens *= 10;
        }
        //Serial.print("Vial run time received: ");
        //Serial.println(inTime + " seconds.");
        vialDeliveryTimes[index] = inTime;
        doOnce = true;
        STATE = 2;
      }
      break;

    //Input wait time between next stimulus
    //increment the index after this case is completed
    case 2:
      //Print a prompt for the opperator only once per case run
      if (doOnce) {
        doOnce = false;
        Serial.println("How long should fresh air be delivered after this stimulus (in seconds)? If you are
done entering data enter 'D'");
      }
      //check for response
      i = 0;
      flag = 0;
      while (Serial.available() > 0) {    // stores each digit in a bufferArray
        bufferArray[i] = Serial.read();
        // check if a number was received
        if (((char)bufferArray[i] == 'D') || ((char)bufferArray[i] == 'd')) {
          flag = 1;
          break;
        }
        else if (bufferArray[i] - 48 >= 0 && bufferArray[i] - 48 <= 9) {
          bufferArray[i] -= 48;
          //flag high check that you receiving data
          flag = 2;
        }
        else {
          flag = 0;
```

```
      Serial.println("Not a number, please try again.");
      break;
    }
   i++; //increment i
   delay(5);
 }
 //chack that data was received
 if (flag == 1) {
   Serial.println("Flag 1");
   Serial.println("Done entering data.");
   //Serial.println("Evactuation time is: " + endEvacTime + " seconds.");
   waitTimes[index] = endEvacTime;
   doOnce = true;
   STATE = 3;
 }
 if (flag == 2) {
   Serial.println("Flag 2");
   tens = 1;
   inTime = 0;
   for (int f = i - 1; f >= 0; f--) {
    inTime = inTime + (bufferArray[f] * tens);
    tens *= 10;
    //        Serial.print("bufferArray[f] = ");
    //        Serial.print(bufferArray[f]);
    //        Serial.print(" inTime = ");
    //        Serial.print(inTime);
    //        Serial.print(" index = ");
    //        Serial.print(index);
    //        Serial.print(" f = ");
    //        Serial.print(f);
    //        Serial.print(" i = ");
    //        Serial.println(i);
   }
   //Serial.print("Vial run time received: ");
   //Serial.println(inTime + " seconds.");
   waitTimes[index] = inTime;
   doOnce = true;
   STATE = 0;
   index++;
 }
 break;

//Confirm test schedule
case 3:
```

```
    //Print a prompt for the opperator only once per case run
    if (doOnce) {
      doOnce = false;
      Serial.println("This is the current schedule for the test:");
      for (int i = 0; i < 20; i++) {
        if (vialDeliveryNums[i] == 0) {
          //exit(0);
        }
        else {
          Serial.print("Run vial ");
          Serial.print(vialNums[i]);
          Serial.print(" for ");
          Serial.print(vialDeliveryTimes[i]);
          Serial.print(" with a wait period of ");
          Serial.println(waitTimes[i]);
        }
      }
      Serial.println("Is this schedule correct (Y/N)?");
    }
    if (Serial.available() > 0) {    // is a character available? Did the operator enter a value?
      response = Serial.read();
      if ((response == 'y') || (response == 'Y')) {
        Serial.println("Please turn on the Power Switch, wait for tank to fill up, and then set the flow rate.
To start this test flip the Start Switch.");
        doOnce = true;
        STATE = 4;
      }
      else if ((response == 'n') || (response == 'N')) {
        doOnce = true;
        STATE = 0;//restart the process of entering in data
      }
      else {
        break;
      }
    }
    break;

  //Wait for switch to turn on
  case 4:
    if (digitalRead(startSwitch) == HIGH) {
      STATE = 5;
    }
    break;
```

```
//Run the test
case 5:
  waitTime = millis() + 30000;
  while (millis() < waitTime) {
   //first delivery fresh air through the system for 30 sec
    digitalWrite(solenoidPin5, LOW);
  }
  digitalWrite(solenoidPin5, HIGH);
  //loop throught the 3 arrays
  for (int i = 0; i < 20; i++) {
   if (vialDeliveryNums[i] == 0) {
     STATE = 6;//end test
   }
   else {
     //set the correct solenoid valve pin LOW
     waitTime = millis() + (vialDeliveryTimes[i] * 1000L);
     while (millis() < waitTime) {
       digitalWrite(vialDeliveryNums[i], LOW);
     }
     //set the sloenoid valve closed again
     digitalWrite(vialDeliveryNums[i], HIGH);
     waitTime = millis() + (waitTimes[i] * 1000L);
     while (millis() < waitTime) {
       //open the fresh aie soleniod valve
       digitalWrite(solenoidPin5, LOW);
     }
     //close the fresh air solenoid valve
     digitalWrite(solenoidPin5, HIGH);
   }

  }
  break;

//Test complete
case 6:
  //Print a prompt for the opperator only once per case run
  if (doOnce) {
   doOnce = false;
   Serial.println("Test is complete! Would you like to run another test?");
  }
  if (Serial.available() > 0) {
   response = Serial.read();
   if ((response == 'y') || (response == 'Y')) {
     doOnce = true;
```

```
        STATE = 0;
      }
     else if ((response == 'n') || (response == 'N')) {
      doOnce = true;
       break;
      }
     else {
       break;
      }
     }
    break;

  default:
    // If something bad happens, reset the state machine
    STATE = 0;
 }
}
```

Appendix H: Purge Test Results

Polypropylene Tubing:

Trial	% Oxygen at Start	% Oxygen at End	Purge Time (min:s)
1	20.87	0.03	1:13.21
2	20.90	0.03	1:11.87
3	20.87	0.03	1:05.54
4	20.88	0.03	1:04.91
5	20.88	0.03	1:06.95
6	20.89	0.03	1:06.88
7	20.89	0.03	1:06.88
8	20.90	0.03	1:05.74
9	20.90	0.03	1:05.77
10	20.90	0.03	1:05.94
Mean ± SD	**20.89 ± 0.01**	**0.03 ± 0**	**1:07.40 ± 0:02.83**

Nylon 6 Tubing:

Trial	% Oxygen at Start	% Oxygen at End	Purge Time (min:s)
1	20.64	0.03	1:02.48
2	20.66	0.03	1:00.35
3	20.74	0.03	1:00.62
4	20.76	0.03	0:57.65
5	20.78	0.03	0:59.25
6	20.80	0.03	1:00.61
7	20.79	0.03	1:02.72
8	20.81	0.03	0:59.52
9	20.81	0.03	0:59.21
10	20.81	0.03	1:00.05
Mean ± SD	**20.76 ± 0.06**	**0.03 ± 0**	**1:00.20 ± 0:01.51**

Appendix I: User Manual

Table of Contents

1.) Introduction

1.1) Purpose

The purpose of this guide is to provide users of the MRI Stimuli System with a comprehensive overview of the system and how to operate its various components.

1.2) Scope

The scope of this guide includes detailed schematics of the system, a bill of materials for ordering new parts, an in-depth overview describing the function of each component of the system, and a step by step guide to system operation. The guide is meant to be read from start to finish initially to provide the user with fundamental knowledge of the system's inner workings. However, it can also be used as a quick reference guide for operating the system, maintaining components, and troubleshooting any issues that may occur.

2.) General Information

2.1) System Layout
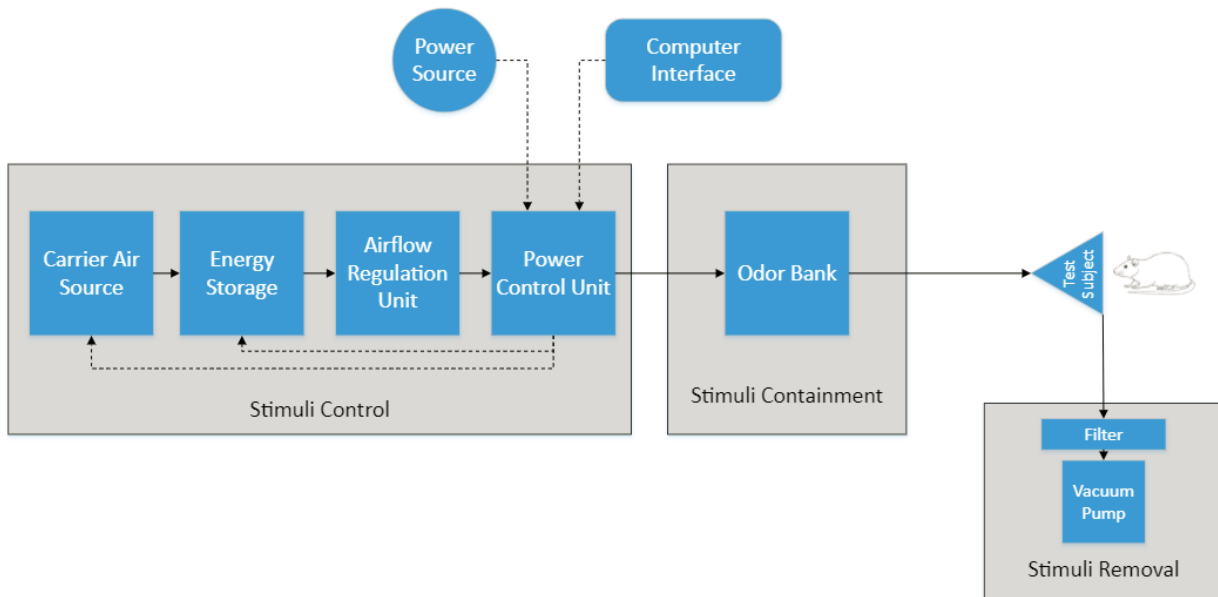
Figure 57: Block diagram of the stimuli delivery system

The MRI Stimuli Delivery System is divided into three phases: stimuli control, stimuli containment, and stimuli removal as shown in Figure 1. The stimuli control portion of the system includes 4 primary components comprised of a carrier air source (compressor), energy storage unit (air tank), air flow regulation unit, and power control box. The stimuli containment phase of the system includes individual odor containment

units (centrifuge tubes) as well as an odor bank to store and organize the tubes. Lastly, the stimuli removal portion of the system is comprised of a dual HEPA and activated carbon filter connected to a vacuum pump at the end of the system. Additionally, a 12V power source must be connected to the power box and a computer interface is used to control operation of the system.

As displayed in Figure 2, airflow begins in the compressor which sends air to the air tank for storage and later usage. Air pressure is maintained at 40-80 psi within the tank by a relay and pressure switch on the tank to provide for an optimal compressor duty cycle. Once the manual flow handle on the tank is opened, air flows to the air regulation unit comprised of a flow regulator and a flow meter. These two pieces of equipment allow the user to fine tune the flow rate of the air before it enters the solenoid valves situated on the control box. Controlled by an Arduino board and graphical user interface
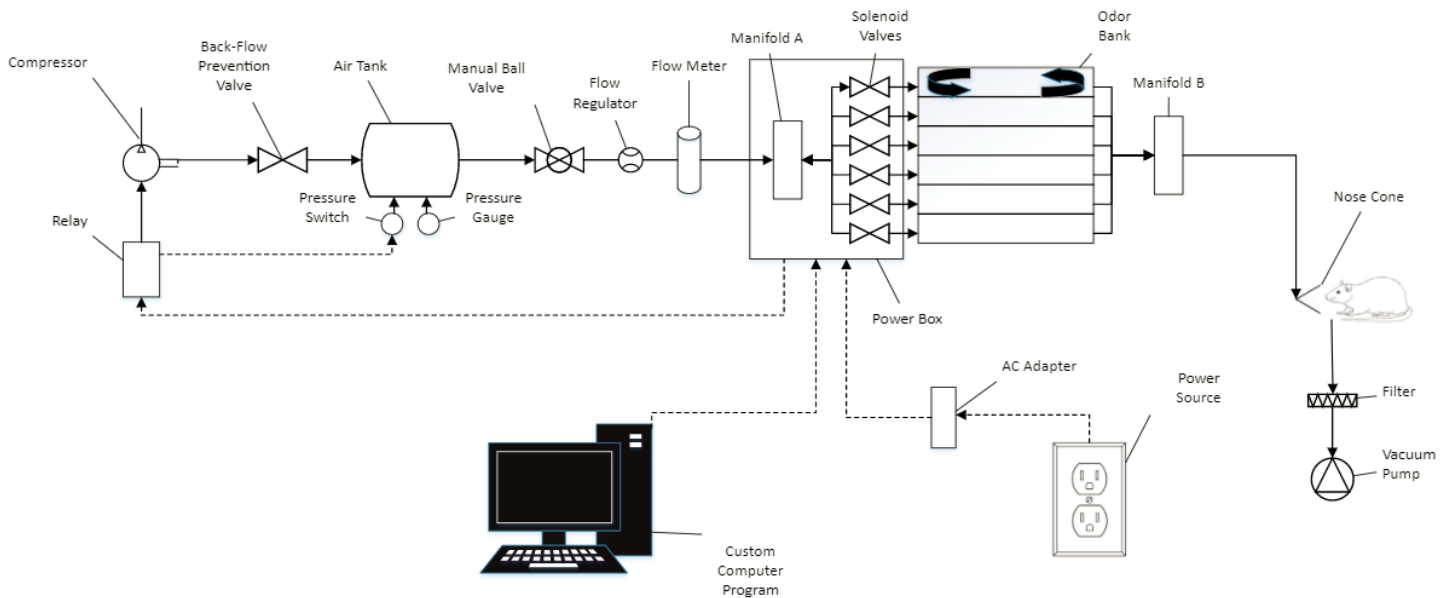
Figure 58: Detailed system layout

(GUI), these solenoid valves can divert the flow of air down any one of five lengths of tubing. The first four lengths of tubing lead to the four stimuli containment units (centrifuge tubes) while the last length of tubing is reserved for fresh air to purge the system.

Once a length of tubing has been selected, the air will flow into the odor containment phase of the system where an odor bank is used to hold four centrifuge tubes filled with liquid stimuli. The air will flow down to the bottom of the tube and bubble up through the liquid impregnating it with the stimuli. From there, the odor laden air will enter a second centrifuge tube that will collect any liquid stimuli that may have escaped the first tube. After this, the air continues on down the tube and is delivered to the test subject via a nose cone inserted into the bore of the MRI magnet.

Once delivery has been executed, the stimuli will be purged from the test subject's environment through the stimuli removal portion of the system. This part of the system begins with of a length of tubing situated at the exit of the nose cone. From the nose cone, air is gently suctioned out by a vacuum pump through a dual HEPA and activated carbon filter that neutralizes deleterious stimuli. After the air passes through the filter and the pump, it is dispelled outside of the MRI room to reduce the risk of stimuli re-entering the test subject's environment.

2.2) Bill of Materials

Tubing:

Part Name	Part Number	Manufacturer/ Supplier	Unit Price	Quantity	Total Price
3/16" ID x 5/16" OD x 1/16" Wall Versilon™ PTFE Tubing	58054	US Plastics	$48.10 for 10 ft	40 ft	$192.4
3/16" ID x 1/4" OD x 1/32" Wall Tygon® Sanitary Silicone Tubing	57293	US Plastics	$18.30 for 10 ft	30 ft	$54.90

Compressor/ Tank System:

Part Name	Part Number	Manufacturer/ Supplier	Unit Price	Quantity	Total Price
Air compressor, 12 volt, 0.88 cfm	Am-2005	AndyMark	$69.00	1	$69.00
E Support™ Car Truck Motor Heavy Duty 12V 40A SPST Relay Socket Plug 4Pin 4 Wire Waterproof Seal		Amazon	$7.19	1	$7.19
Air Hose, 200 PSI with 1/8 x 1/8 NPTF Brass Male Fittings, 200 PSI, red, 2 foot long	1593N45	McMaster Carr	$5.98	1	$5.98
Compact Backflow-Prevention Valve, for Water and Inert Gas, 1/4 NPT Female x 1/4 NPT Male	7768K22	McMaster Carr	$10.42	1	$10.42
Brass On/Off Valve with Lever Handle, 1/4 NPT Female x 1/4 NPT Male	47865K41	McMaster Carr	$9.29	1	$9.29
Vixen Horns VXT1500 6 Ports Train/Air Tank		Amazon	$54.95	1	$54.95

Part Name					
System/Kit 150 Psi with Gauge, Pressure Switch, Drain and Safety Valve, 1.5 gal, 5.6 L					
Vixen Horns 1/4 NPT Male to 1/8 NPT Female Brass Thread Reducer Fitting for Train/Air Horn Tanks - Bundle of two fittings VXA1418-2		Amazon	$7.95 for a pack of two	1 pack	$7.95
Push-to-Connect Tube Fitting for Air, Straight Adapter, for 5/16" Tube OD x 1/4 NPT Male	5779K113	McMaster Carr	$5.35	2	$10.70
Air Compressor Pressure Switch; Range: 25 to 160 psi, Port Type: (1) Port, 1/4" FNPT	3EYP3	Grainger	$13.30	1	$13.30

Air Flow Control:

Part Name	Part Number	Manufacturer/ Supplier	Unit Price	Quantity	Total Price
Scratch-Resistant Acrylic, 12" x 24" x 1/4" White	8505K755	McMaster Carr	$19.93	1	$19.93
Compact Compressed Air Regulator (0-25 psi range), Relieving, Aluminum Housing, 1/8 NPT	6763K81	McMaster Carr	$43.21	1	$43.21
Cole-Parmer Polycarbonate Flowmeter, 0.4-5 LPM, Air Stainless Steel, w/ Valve	EW-32900-46	Cole-Parmer	$70.00	1	$70.00
Mounting Bracket for 1/8 and 1/4 NPT FRL	6763K21	McMaster Carr	$8.44	1	$8.44
Galvanized Steel Corner Bracket, 1-3/8" x 1-3/8" x 2.75"	17715A73	McMaster Carr	$2.55	1	$2.55
Push-to-Connect Tube Fitting for Air, Long 90 Degree Elbow, for 5/16" Tube OD x 1/8 NPT Male	5779K188	McMaster Carr	$10.88	3	$32.64
Push-to-Connect Tube Fitting for Air, 90 Degree	5779K25	McMaster Carr	$4.41	1	$4.41

Part Name	Part Number	Manufacturer/Supplier	Unit Price	Quantity	Total Price
Elbow Connector, for 5/16" Tube OD					
Push-to-Connect Tube Fitting for Air Straight Adapter, for 5/16" Tube OD x 1/8 NPT Male	5779K112	McMaster Carr	$5.35	1	$5.35
6061 Aluminum 3/4" Thick x 3" Wide x 6" Long	8975K231	McMaster Carr	$12.35	1	$12.35

Manifolds:

Part Name	Part Number	Manufacturer/Supplier	Unit Price	Quantity	Total Price
Straight-Flow Rectangular Manifold, 6 Outlets, 1/4 NPT Inlet x 1/8 NPT Outlet	1023N14	McMaster Carr	$30.27	2	$60.54
316 Stainless Steel Threaded Pipe Fitting, Low-Pressure, Plug with External Hex Drive, 1/8 NPT	4452K141	McMaster Carr	$2.50	2	$5.00
Push-to-Connect Tube Fitting for Air, Straight Adapter, for 5/16" Tube OD x 1/4 NPT Male	5779K113	McMaster Carr	$5.35	2	$10.70
Push-to-Connect Tube Fitting for Air Straight Adapter, for 5/16" Tube OD x 1/8 NPT Male	5779K112	McMaster Carr	$5.35	10	$53.50

Control Box:

Part Name	Part Number	Manufacturer/Supplier	Unit Price	Quantity	Total Price
Scratch-Resistant Acrylic, 12" x 24" x 1/4" White	8505K755	McMaster Carr	$19.93	1	$19.93
LED wholesalers 12V 20A 240W AC/DC Power Adapter with 5.5x2.5mm DC Plug and 2.1mm Adapter, Black, 3262-		Amazon	$39.99	1	$39.99

12V, 12 volt, 20 amp, 55" long					
ARDUINO MEGA 2560 REV3	A000067	Arduino	$38.50	1	$38.50
AmazonBasics USB 2.0 Cable - A-Male to B-Male - 6 Feet (1.8 Meters)		Amazon	$4.99	1	$4.99
SainSmart 16-Channel Relay Module		Amazon	$19.29	1	$19.29
HOSL DC 12V 1/4 Inch Electric Solenoid Valve for Air Water / Replacement Brass Valve for Use with Pipelines in Water, Air and Diesel Applications		Amazon	$10.99	5	$54.95
Push-to-Connect Tube Fitting for Air, Straight Adapter, for 5/16" Tube OD x 1/4 NPT Male	5779K113	McMaster Carr	$5.35	10	$53.50
Miniature Toggle Switch, 2 Position, 1 Circuit, Maintained, solder lugs	7347K75	McMaster Carr	$7.86	2	$15.72
LED - Basic Red 5mm	COM-09590 ROHS	Sparkfun	$0.35	6	$2.10
LED - Basic Green 5mm	COM-09592 ROHS	Sparkfun	$0.35	2	$0.70
Resistor 330 Ohm 1/6 Watt PTH	COM-11507 ROHS	Sparkfun	$0.95 for a pack of 20	1	$0.95
Resistor 1K Ohm 1/4th Watt PTH	COM-13760 ROHS	Sparkfun	$0.95 for a pack of 20	1	$0.95
E Support™ Car Truck Motor Heavy Duty 12V 40A SPST Relay Socket Plug 4Pin 4 Wire Waterproof Seal, 12V 40A Relay		Amazon	$7.19	1	$7.19
Gdstime Slient 5 Volt 50mm x 50mm x 10mm 2 Inch 0.14A Mini Brushless Cooling fan		Amazon	$8.99	1	$8.99

Part Name	Part Number	Manufacturer/Supplier	Unit Price	Quantity	Total Price
Mortise-Mount Hinge with Nonstandard Hole Pattern, Removable Pin, Square, Zinc-Plated Steel, 1" x 1/2" Leaves	1597A41	McMaster Carr	$0.82	4	$3.28

Odor Bank:

Part Name	Part Number	Manufacturer/Supplier	Unit Price	Quantity	Total Price
Clear Ultra-Scratch-Resistant Acrylic, 12" x 24" x 1/4" Clear	8536K162	McMaster Carr	$53.53	1	$53.53
Clear Ultra-Scratch-Resistant Acrylic, 12" x 24" x 1/8" Clear	8536K132	McMaster Carr	$38.84	1	$38.84
Scratch-Resistant Acrylic, 12" x 24" x 1/4" White	8505K755	McMaster Carr	$19.93	1	$19.93
7/8 in. White Spring Grip	Internet #202305505	Home Depot	$2.58	8	$20.64
50mL Centrifuge Tubes	TC5000R	Argos	$146.18 for a pack of 25	1 pack	$146.18
Oil-Resistant Buna-N O-Ring, 1/16 Fractional Width, Dash Number 047, Fractional ID: 5/16, fractional OD: 1/2	9464K44	McMaster Carr	$5.04 for a pack of 50	1 pack	$5.04
Oval Grip Pull Handles with Unthreaded Through Holes, Zinc-Plated Steel, 4-1/8" Center-to-Center Width	1646A13	McMaster Carr	$2.07	3	$6.21
LEXAN, 12 in. x 24 in. x .093 in. Clear Polycarbonate Sheet	Internet #202038063	Home Depot	$15.98	2	$31.96

Test Subject Interface:

Part Name	Part Number	Manufacturer/Supplier	Unit Price	Quantity	Total Price
Funnel PTFE 30 x 50 mm	342325-0050	Dynalon	$24.52	1	$24.52

Evacuation System:

Part Name	Part Number	Manufacturer/ Supplier	Unit Price	Quantity	Total Price
Oil-Resistant Buna-N O-Ring, 1/16 Fractional Width, Dash Number 047, Fractional ID: 4 1/2, fractional OD: 4 5/8	9452K312	McMaster Carr	$4.90 for a pack of 10	1 pack	$4.90
DC 12V micro air pump Electric pumps mini vacuum pump pumping Booster For Medical		Amazon	$8.99	1	$8.99
WSTA Desktop Air Purifier, Air Ionizer ,Portable Air Purifier, True HEPA Air Cleaner Replacement Filter for W050, W050D, W050S, W050T		Amazon	$10.99	1	$10.99

Total Cost = $1,407.46.

3.) System Overview

3.1) Compressor & Air Tank

The operation of the device begins with the compressor/tank system shown in Figures 3A and 3B, which are responsible for pressurizing and storing the air to be used in the system. This section will explain how to operate these two components and identify the order in which they should be controlled to properly deliver air to the system.
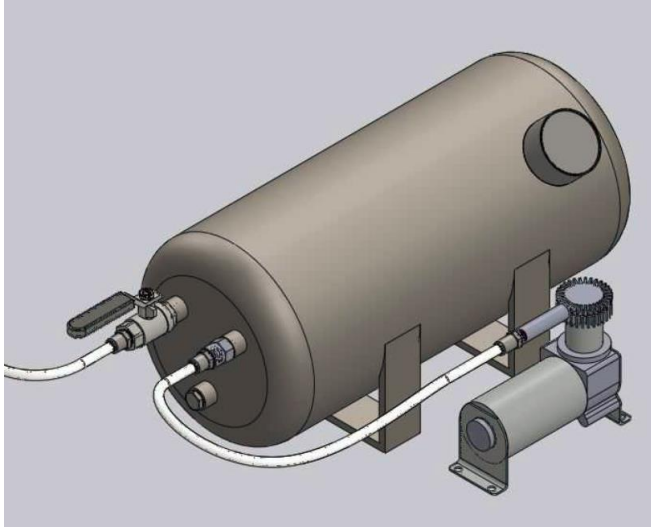
Figure 59A: SolidWorks model of compressor and air tank

Figure 3B: Fully assembled compressor and air tank

3.1.1) Component Description

The tank and compressor, shown in Figure 4, form a system which receives power through the same source as the rest of the device, a 12-V adapter that can be plugged into a wall outlet. The air tank itself has a capacity of 1.5 gallons, which is capable of pressurizing to a maximum of 250 psi, although it is recommended to operate under 125 psi. The tank is required due to its ability to initiate a choked-flow situation, where air flow is delivered to the rest of the system at a continuous flow rate due to the pressure established within the tank and its relationship to the pressure being drawn
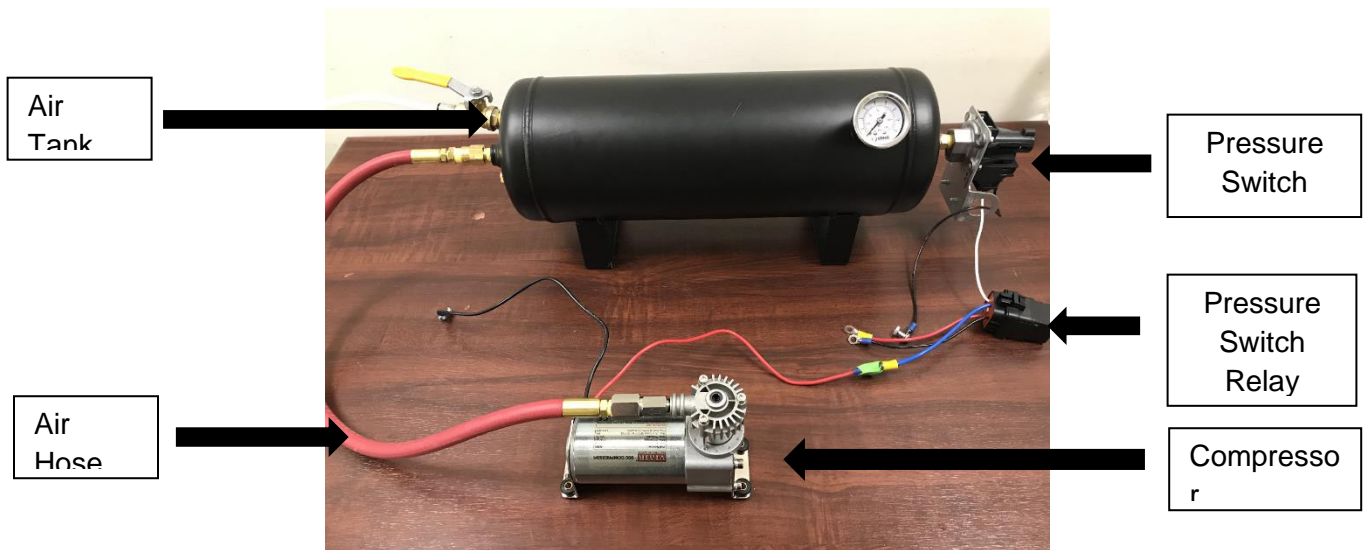

Figure 4: The tank and compressor system complete with pressurized connecting hose and pressure switch with relay

from the flow control unit. Without a tank or similarly pressurized storage unit, a

222

compressor would deliver air at a fluctuating flow rate and would be operating constantly, which produces a large amount of heat and noise.

The compressor is oil-less, which reduces the chance for waste vapors and volatiles entering the delivered air stream, and it is recommended that if the compressor is replaced by an oil lubricated compressor or similar device, that a filter is used to clean the air before it enters the tank. The compressor is connected to the tank through a pressurized hose which attaches with 1/8" to 1/4" female to male fittings. A backflow prevention valve is included in the hose to tank connection to prevent any air from flowing back towards the compressor.

A pressure switch connects the tank and compressor and is responsible for reading the pressures within the tank and adjusting the compressor accordingly. The pressure switch is currently set to activate the compressor when the air tank reaches 40 psi or less and turns the compressor off when the tank is filled to 80 psi. Subsection 3.1.3 details the process of adjusting these pressure settings. This functionality allows the compressor to operate intermittently on its duty cycle, thus mitigating any component damage that might occur from running the compressor continuously.

3.1.2) Component Operation

1. Plug in the components to supply power.

2. If the tank's pressure is below the cutoff pressure, the compressor will automatically turn on at this point.

   A. Turn the yellow valve handle connecting the tank output nozzle to the flow control unit so that it is perpendicular to the tank, as seen in Figure 5A. This closes the nozzle and prevents air from flowing.

   B. Allow the tank to be filled to the cutoff pressure established by the pressure switch.

   C. The compressor will automatically turn off at this point.

1. Next turn the yellow valve handle from step 2a to the parallel position, as seen in Figure 5B, to allow air to flow to the rest of the system.

2. During the test, when the tank reaches the low pressure established by the pressure switch, the compressor will automatically turn on to fill it up without disrupting the test or changing the flow rate.

Figure 5A: Yellow valve handle perpendicular to air tank in the closed position

Figure 5B: Yellow valve handle parallel to air tank in open position

3. The compressor will automatically turn off when the tank pressure reaches the cutoff pressure established by the pressure switch.

4. At the end of the testing sequence, it is recommended to empty the tank by unplugging the system from power and moving the output valve to the parallel position.

3.1.3) Changing the Pressure Switch

For some experiments, or if you decide to use a different tank in the system, the cutoff and cut-on pressures for the device may need to be adjusted. To do this, the pressure switch can be altered. There are two screws located on the underside of the pressure switch, as seen Figure 6 below. The top screw can be turned clockwise to increase the cutoff pressure value. This value corresponds to the maximum pressure needed in the air tank, or the pressure of the air tank that will cause the compressor to turn off. The bottom screw can be turned clockwise to increase the pressure differential. The pressure differential is the value that determines the cut-on pressure, or the pressure at which the compressor will turn on, based on the cutoff pressure. It is simply subtracted from the cutoff pressure to determine the cut-on pressure. For example, if the cutoff pressure is set to 80 psi, and the pressure differential is set to 25 psi, then the compressor will turn on to start filling the tank up at 55 psi.

Unfortunately, the screws do not have units or numbers during this adjustment process, so you will likely have to adjust the screws and then turn on the system to see when the compressor turns on and off. It is recommended that during this process, only one screw is changed at a time.
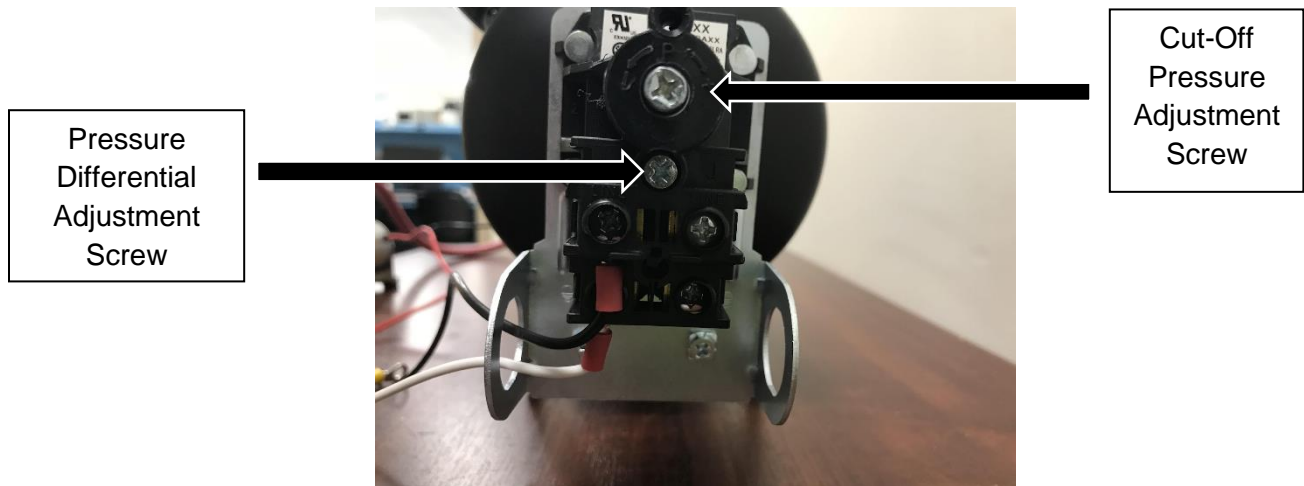

Figure 6: This diagram shows the pressure switch screws. The top screw is used to adjust the cutoff pressure, while the bottom screw is used to adjust the pressure differential

3.2) Air Flow Regulation Unit

The air flow regulation unit is responsible for accurately controlling the flow rate of the air being introduced into the liquid stimuli of the odor bank. As the air flow rate

and concentration of odor delivery is directly correlated, this portion of the system is crucial to accurate stimuli delivery to the test subject.
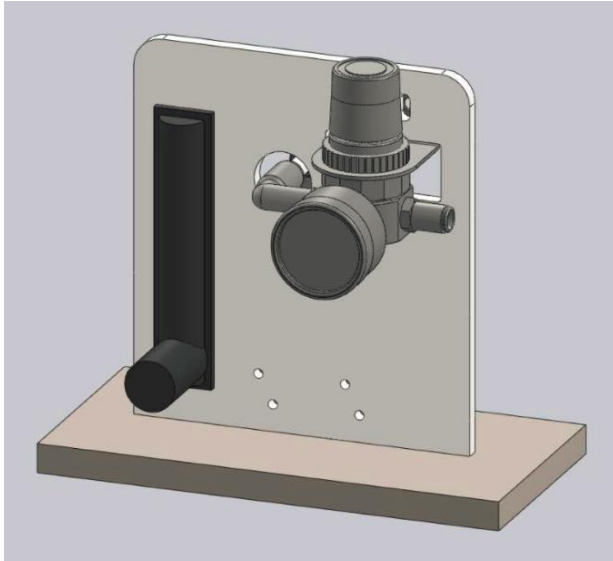

Figure 7A: SolidWorks model of airflow regulation unit

Figure 7B: Fully assembled airflow regulation unit

3.2.1.) Component Descriptions

The air flow regulation unit consists of a McMaster-Carr pressure regulator and a Cole-Farmer polycarbonate flow meter mounted to an acrylic stand and aluminum base as seen in Figure 7B. PTFE tubing from the air tank output is connected to the pressure regulator via a push-to-connect fitting. The pressure regulator is in turn connected to a flow meter which then leads on to manifold A. The pressure regulator allows for pressure adjustment within the range of 0-60 psi and the flow meter allows for flow rate adjustment from 0-5 L/min.

3.2.2) Component Operation

By turning the knob on the top of the pressure regulator, the user can set the output air pressure to a range of 0-60 psi.

1. First pull upwards on the knob until it pops out of the lock position and into the adjustment position
2. The knob can then be turned clockwise to increase air pressure and counter-clockwise to decrease air pressure
3. By adjusting the air pressure passing through the regulator, the user can create an approximate flow rate that leads to the flow meter for additional fine tuning.
4. Push the knob back down when complete to lock it back into place

With an appropriate air pressure leading to the flow meter, the user can then adjust the flow rate. To do this, simply locate the control knob on the bottom of the flow

meter and turn it clockwise to reduce the flow rate and counter-clockwise to increase the flow rate.

3.3) Power Control Box

The control box, which can be seen in Figures 8A and 8B, is the portion of the device responsible for housing the electrical components which allows the system to be automated. The control box itself is made from laser-cut acrylic and assembled using acrylic glue. A waveform pattern and fan are installed to cool internal components through air circulation, and hinges allow for easy access to the interior of the box.
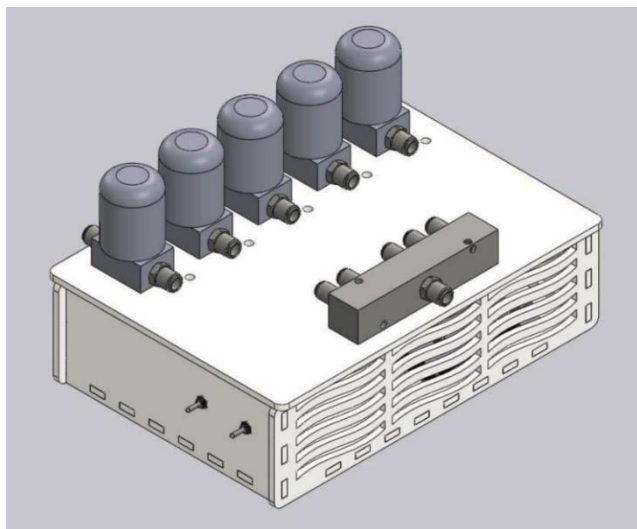

Figure 8A: SolidWorks model of power control box

Figure 8B: Fully assembled power control box

3.3.1) Component Description

Within the control box lie several components that help to control the automation of the device. If you are not confident in circuitry or wiring electronics, it is suggested to ask an expert to make any required changes. As seen in Figure 9, the components included in the interior of the control box are an Arduino Mega, a relay module, a relay, a power switch and run test switch, and a fan.
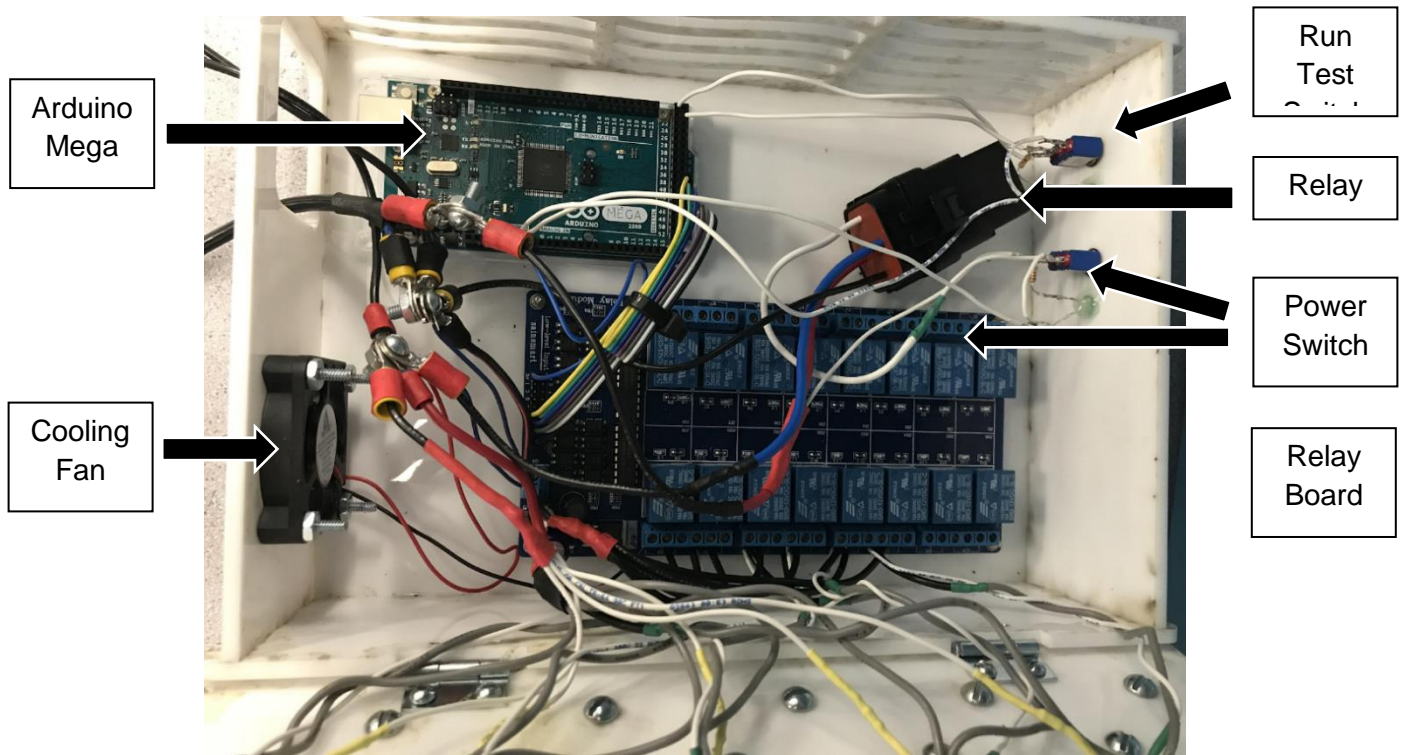
Figure 9: This image shows the interior components of the control box with the most important components labeled

The Arduino Mega is a microprocessor and control board which can run custom-made code to manipulate electronic objects. This device is where you will connect your computer with a USB cable to upload any code for testing alterations. The 16-channel relay module adds additional space to control and interface with more devices than the Arduino Mega can offer alone. They essentially work in tandem to control the rest of the electrical components in the device. The relay acts as an electrical switch which completes certain circuits when power is supplied, and closes circuits when power is not supplied. The run test and power switches mark the interior portions of the labeled switches on the exterior of the control box. They are both accompanied with green LEDs to mark whether or not they have been turned on. The fan is connected to power so that it is turned on as soon as power is delivered to the device so that it can circulate air and cool the internal components.

3.3.2) Circuit Diagrams

In the case of any components getting unplugged or destroyed, these circuit diagrams provide the necessary information for re-wiring the circuitry that we have provided. Additionally, Figure 9 shows the wiring at a more macroscopic view so that both can be followed when wiring the control box. Figures 10, 11A, 11B, and 12 below contain these circuit diagrams with brief captions for more information.
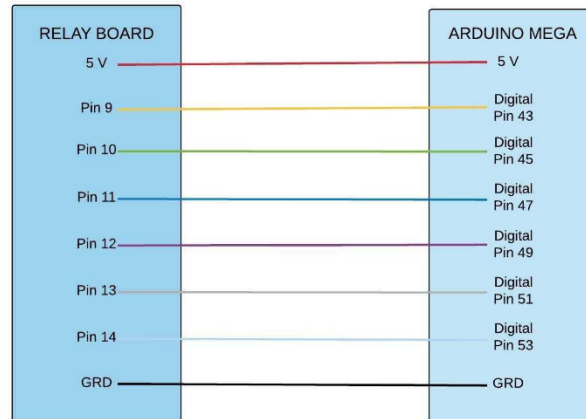
Figure 10: This diagram shows the connections between the Arduino Mega and the relay board. These connections show a straightforward ground to ground and 5V power to 5V connection with the rest of the wires simply connecting pins from the Arduino to those of the relay board
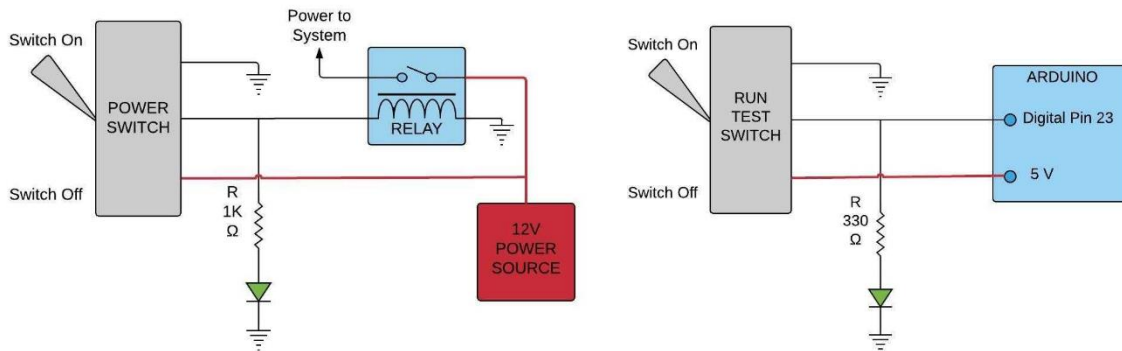

Figure 11A & 11B: The diagram on the left shows how the power switch completes a circuit when on, and how that circuit is then disconnected when the flip is switched off. The diagram on the right shows the same configuration for the run test switch. The dashed lines of descending width forming a triangle represent connections to ground, and jagged lines represent resistors, with labeled resistances. The power switch is connected to the power source and the relay, which allows the switch to power on the rest of the system when it is flipped. The run test switch is connected to the Arduino
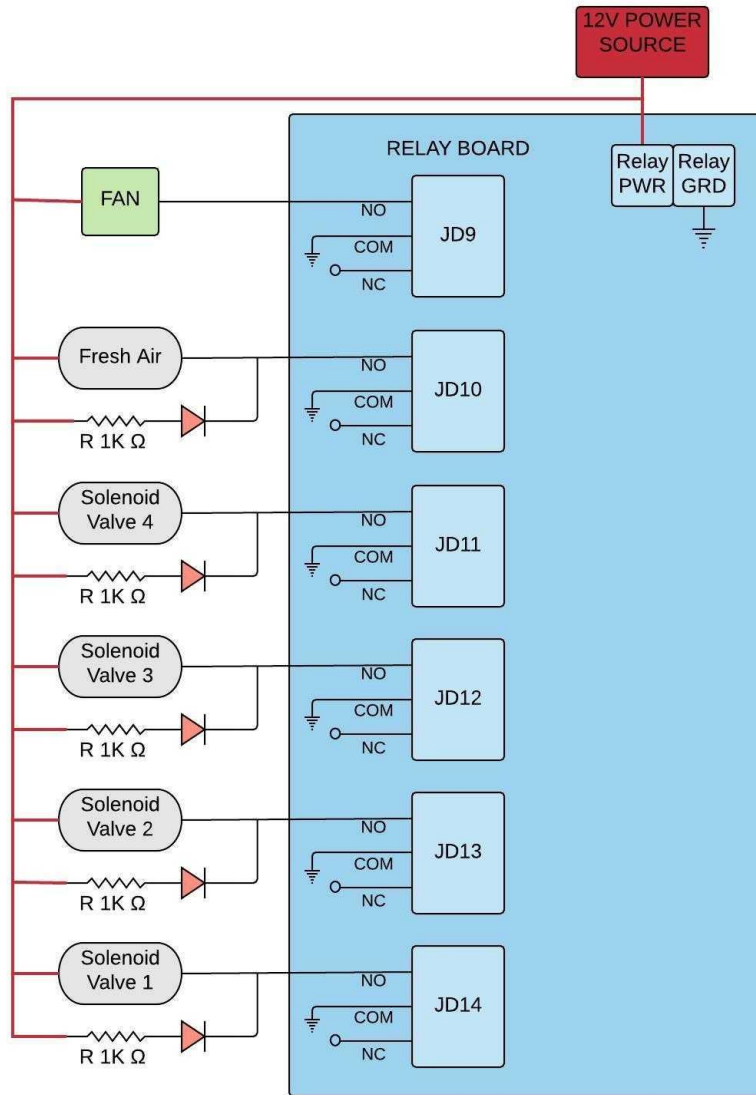
Figure 12: This diagram details the connections made on the relay board itself. Relay power is connected to the 12V power source used by the entire system, and the rest of the connections are to the fan and the solenoid valves. Because the relay board is connected to the Arduino (seen in Figure 10), when the program is loaded into the Arduino, it then communicates with the relay board and instructs it to open and close specific solenoids. Additionally, the fan is connected to the relay, and is instructed by the Arduino to be powered on for the duration of system operation

3.3.3) Component Replacements

If any of the components break or otherwise need replacement, it is suggested that you follow the circuit diagrams to reconnect them. The bill of materials in Section 2.2 details the components used so that you can buy the exact models as used in the original device. If wires are damaged, any conductive wire with a sheath that can fit in the Arduino pins can be used. Otherwise, the component most likely to need replacement in this portion of the device are the LEDs used to mark when the switches and solenoids have been activated. These LEDs are cheap and easy to find, but need to be soldered with the coupling

229

resistor and the ground connection to ensure that they remain in place and powered properly. In order to solder these components, a soldering iron and some solder material (filler metal than can be easily melted) will be needed. Additionally, the LEDs connected to the power switch and run test switch are glued into the control box to ensure that they are visible to the test operator.

3.4) Odor Bank

The odor bank of the stimuli delivery system is responsible for safely holding and containing stimuli used in testing. It has been specifically designed to incorporate the maximum degree of flexibility with user safety.
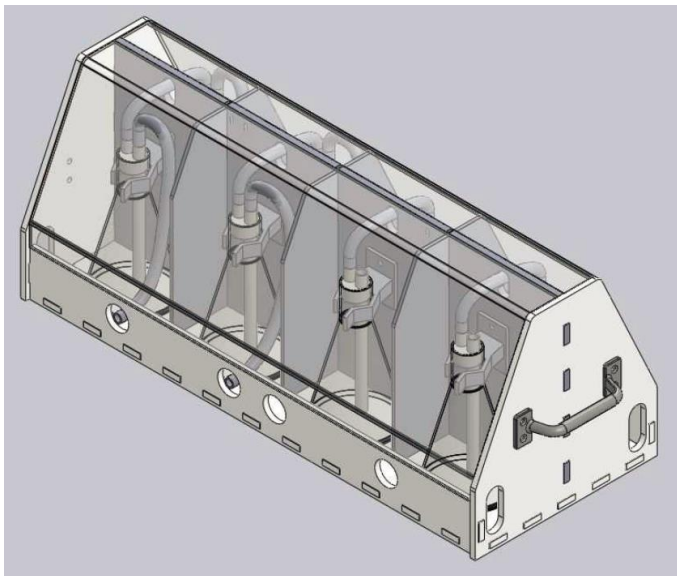

Figure 13A: SolidWorks model of odor bank

Figure 13B: Fully assembled odor bank

3.4.1) Component Description

As seen in Figures 13A and 13B, the odor bank is composed of a 20" by 8" rectangular acrylic base with two 8" tall hexagonal acrylic supports on each end of the base. Surrounding the base there is a 2" high lip to prevent liquid stimuli from spilling out onto the work bench if it escapes the centrifuge tube. Down the middle of the odor bank, there is a transparent acrylic center support that is attached at each end to the hexagonal end pieces. Mounted to the center support are 4 Everbilt brand spring grips screwed in at 5" intervals. This first set of spring grips holds the liquid stimuli and on the other side of the center support, a second set of 4 spring grips holds empty centrifuge tubes to collect any escaped liquid stimuli. To provide additional reinforcement to the center support, hexagonal upright pieces of transparent acrylic are attached between the spring grips. An added benefit of these uprights is that they semi-compartmentalize the stimuli-containing centrifuge tubes to help prevent cross contamination. To complete the

design, handles were added to the side of the odor bank for portability and a Lexan polycarbonate lid was crafted to protect the system users from any potential stimuli splashes or tube ruptures.

3.4.2) Component Operation

1. To set up the odor bank, fill up the first set of centrifuge tubes with the desired amounts of stimuli and place them in the first set of spring grips
2. Next, insert the specially curled PTFE tubing into each of the centrifuge tubes and place the other end into the appropriate solenoid on the power box
3. Then insert a second set of empty centrifuge tubes on the other side of the center support and connect the two sets with the horseshoe shaped tubing pieces
4. After, insert the specially curled tubing into the second set of centrifuge tubes and connect the other ends to manifold B
5. With the centrifuge tubes set up and connected, the user can then place the polycarbonate lid over the entire odor bank for added protection.

3.5) Evacuation System

The evacuation system is responsible for removing contaminants and hazardous particles from the system through the use of a filter. Clean air is then released back into the lab area. This section will explain how to operate the components of the evacuation system and explain how often parts should be replaced.
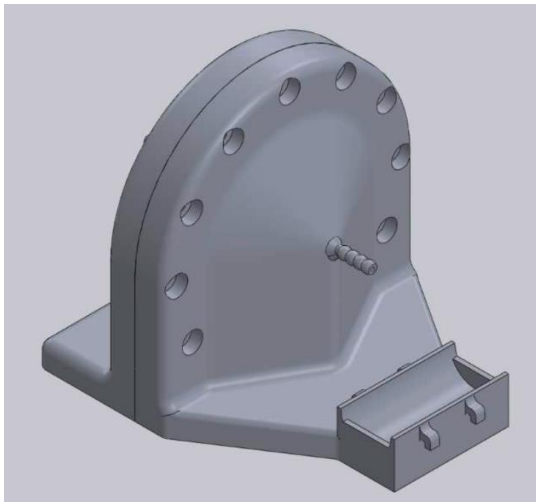

Figure 14A: SolidWorks model of filter adapter

Figure 14B: Fully assembled filter adapter

3.5.1) Component Description

The evacuation system, shown in Figures 14A and 14B, consists of evacuation tubing, an adapter, the filter, and exit tubing. During testing suites, the evacuation system must be kept in the testing room away from the MRI, as it contains metal screws. Evacuation tubing of the device consists of a length of PTFE tubing. The length of the tubing largely depends on the dimensions of the testing and operating rooms, as the tubing begins at the nose cone and travels from the operation room to the testing room

231

where the evacuation system is placed. The adapter is 3D printed out of two pieces of PLA that are secured together using seven 8-32 bolts. The two separate pieces are labeled A and B in order to distinguish between the two. Within the adapter, a replacement filter as seen in Figure 15 manufactured by WSTA for models W050, W050D, W050S, and W050T is used to filter out unwanted contaminants. The filter has a circumference of 3.93 inches and a depth of 0.67 inches and contains a HEPA filter and an activated charcoal filter, enabling it to filter out 99% of particles that have a size greater than or equal to 0.3 micrometers. The filter is secured into place using grooves on the adapter, and an O ring is also included to ensure a snug fit. The exit tubing provided is made out of silicone, but any type of tubing that fits onto the adapter can be used. The length of this tubing also depends on the dimensions of the testing room.
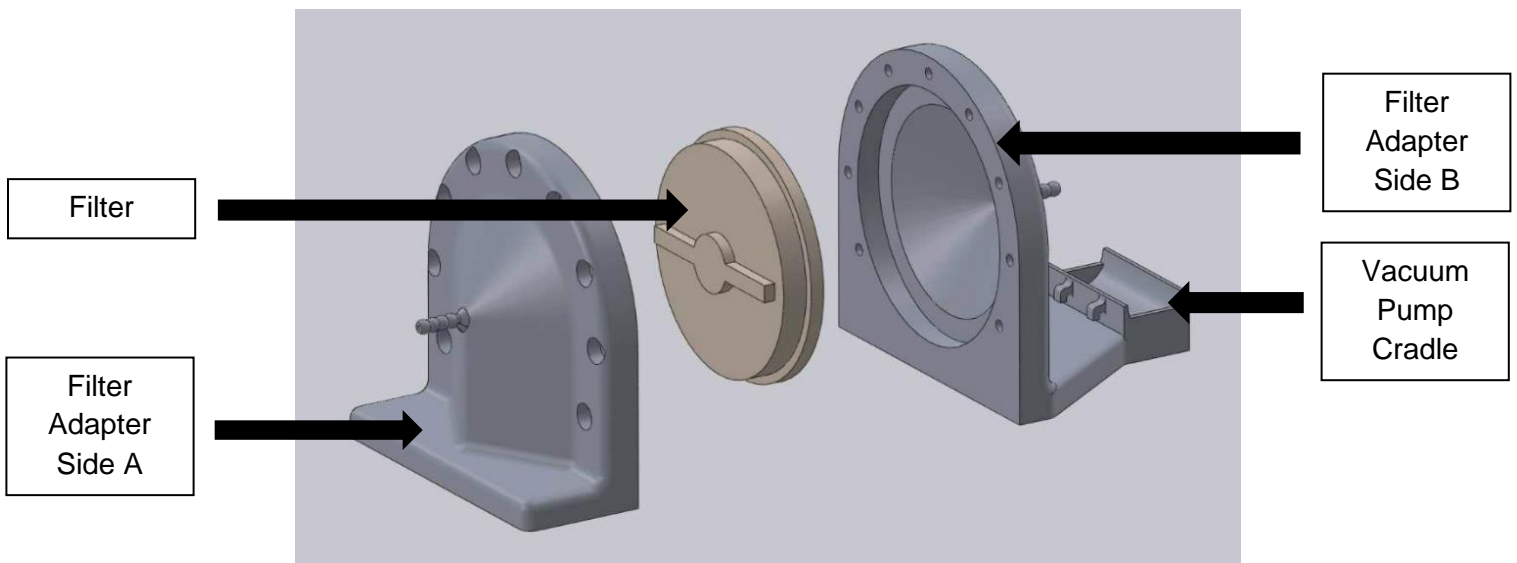

Figure 15: Exploded view of filter adapter and filter

3.5.2) Component Operation
1. Push the O-ring into the small groove on side A of the filter adapter
2. Place the filter into side B of the filter adapter such that it rests in the circular inset as seen in Figure 15
3. Firmly press side A and B of the adapter together and bolt them in place using seven nuts and bolts.
4. Secure the evacuation tubing onto the male fitting of side A
5. Secure the exit tubing onto the male fitting of side B and then connect the other end of the tubing to the vacuum pump as shown in Figure 14B

3.6) Computer Interface

3.6.1) Working with the Arduino Program

The simple graphical user interface (GUI) that you will use to interact with the automated aspects of the device was written with the Arduino programming language, which is based in C++. In the flash drive that we supplied you with, there is a file titled "Solenoid_Control_1" which can be loaded into the Arduino IDE, which can be downloaded on any computer for free by clicking on the following link and selecting your computer's operating system:

https://www.arduino.cc/en/Main/Software

When loading the program into the Arduino IDE, you are able to change any of the parameters to better match your testing requirements. It is suggested that you save a master copy of the program so that you have a backup if any changes render the program inoperable.

Since many of the variables of the program are altered by the test operator during the testing sequence through input, you likely do not have to change anything in the program directly. However, if you require tests that involve more than 20 delivery sequences (more than 20 times the "What number vial would you like to use" prompt is answered), the array used to store that information will need to be expanded. This array is called vialDeliveryNums and is located towards the beginning of the program. Currently, it is an array that can hold 20 pieces of information, but this can be expanded by changing the 20 (in the square brackets) to a larger number that you require.

After working with and changing the Arduino program, hit the check mark button in the top left corner to verify the code. This process will print warning statements if there is anything wrong with the program. If the program does not contain any errors, it can then be uploaded by clicking the horizontal Upload arrow button located next to the Verify button. In order to upload the altered code to the Arduino, the Arduino and computer containing the code must be connected through a USB.

3.6.2) Program Flow Chart

To more easily visualize the operational order of the program, Figure 16 below shows the program flow chart.
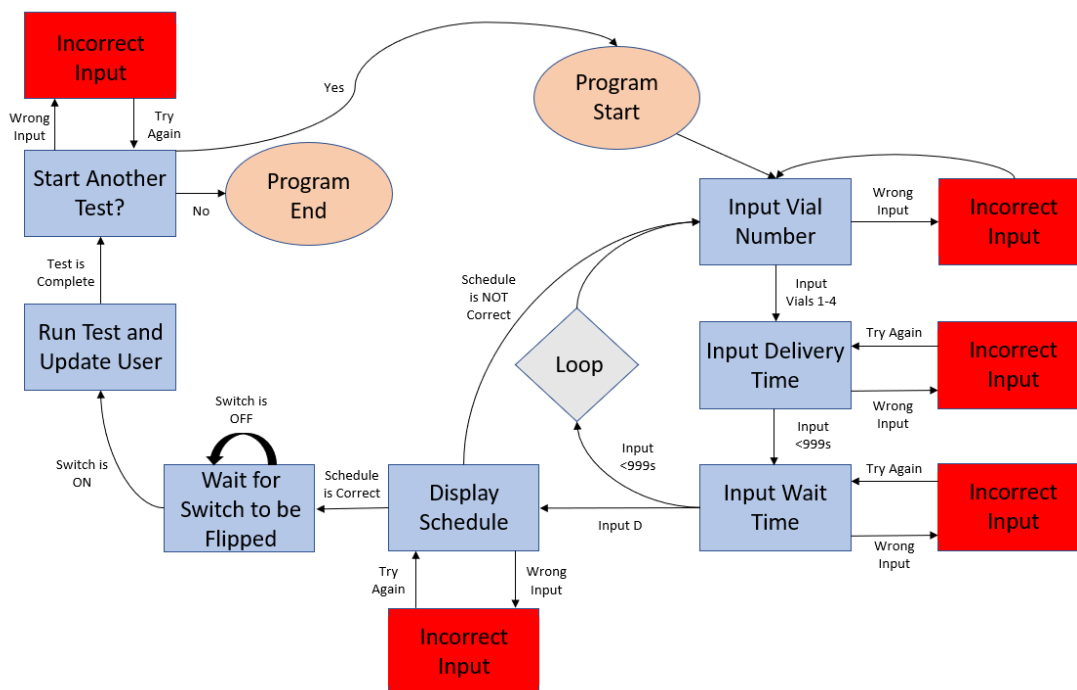
233

Figure 16: A flow chart of the computer program's testing sequence

The flow chart shows that the entire program runs on a loop for a duration that is determined by the number of vials that the user wishes to use. Additionally, the red boxes indicate that whenever a user enters incorrect input for a specified prompt (i.e. a number when a word is requested, or a length of time over 999 seconds), it will be recognized as incorrect and the user will be prompted to enter something else. The blue boxes represent points of interest in the program, which are usually prompts for the user, or printed instruction statements. The two orange circles represent the program beginning and end, and the gray diamond shows the part of the program that is contained in a loop.

The arrows connecting each portion of the flow chart signify the direction of the flow chart and are often accompanied by some keywords that signify what must have occurred in the previous step to lead done the selected path. For example, there are three arrows stemming from the "Input Wait Time" box, and two arrows leading towards it. The first arrow leading towards it stems from "Input Delivery Time" which means that if an acceptable delivery time is entered at that step (a delivery time of less than 999 seconds), the next step prompts the user to enter a wait time. The arrows stemming from this box all signify a different direction the program can take, depending on the input. If the input is incorrect, the program will warn the user and then ask for a proper wait time again (represented by the line accompanied by "Try Again"). If the user enters an acceptable wait time, they are looped back to being asked for the next vial number, and if the user enters "D" or "d" signifying that they are finished entering information, the program will then display the schedule created by the user.

4.) System Operation

4.1) Set-Up

1. Unpack all of the components from storage and place on a hard flat surface within 7-8 feet of a power outlet (the total length of the power cord from power box to plug is 119 inches).
2. Arrange the components linearly in the following order:
    a. Compressor
    b. Air Tank
    c. Air Flow Regulation Unit
    d. Power Control Box
    e. Odor Bank
    f. Nose Cone
    g. Filter Adapter Unit
    h. Vacuum Pump
3. Connect the air tank output to the pressure regulator on the air flow regulation unit with a 1-2 foot piece of PTFE tubing.
4. Connect the flow meter on the air flow regulation unit to manifold A on the power box with a piece of 1-2 foot PTFE tubing.
5. Fill up the first set of centrifuge tubes in the odor bank with the desired amount of liquid stimuli.
6. Connect the solenoid valves on the power box to the first set centrifuge tubes using the specially curled tubing pieces.
    a. Ensure that the PTFE tubing touches the bottom of the centrifuge tube to allow for proper odor impregnation
7. Connect the first set of centrifuge tubes to the second set of centrifuge tubes using the horseshoe shaped pieces of PTFE tubing.
    a. Ensure that the ends of the horseshoe shaped tubing in both centrifuge tubes never touches the liquid stimuli and does not go down into the tube more than an inch. This will prevent stimuli in liquid form from entering the downstream tubing and contaminating the system and disturbing the test subject.
8. Attach the second set of centrifuge tubes to manifold B using the specially curled pieces of PTFE tubing
9. Attach manifold B to the nose cone with a length of PTFE tubing cut to fit the distance from manifold B to the bore of the MRI machine
10. Attach an equal length of flexible tubing from the evacuation port of the nose cone to the dual HEPA/activated carbon filter
11. Attach a 3-4 inch length of flexible tubing from the filter adapter to the vacuum pump
12. With the system fully connected, plug in the 12V power cord to the nearest wall outlet.
13. The system is now ready to be powered on for testing.

4.2) System Usage

      After the system components have been set up and the power source has been connected, open the control box to find a USB link cable attached to the Arduino Mega.

1. Connect the other end of this cable to the computer which contains the program given to you, or your own custom procedure.

2. Open your program with the Arduino IDE.

3. Go to the "Tools" tab of the tool bar at the top left of the program.

4. Select "Board Manager" and set the type of board to an "Arduino/Genuino Mega or Mega 2560."

5. Select "Port" and chose the correct port, which will be the USB port connecting your laptop with the Arduino.

6. Compile the program to ensure there are no errors or warnings, then upload this program to the Arduino.

   a. If the program did not upload, it is possible that the wrong port was chosen, or the Arduino is not properly connected.

1. When the program has been uploaded, follow the command prompts to enter the data concerning the current testing sequence that you would like to run.

2. Keep the Arduino plugged into the computer for the duration of the test to allow test status notifications to be delivered.

3. After the test schedule is confirmed, flip the switch on the control box marked "POWER." This switch will now deliver power to the system, which will be signified by a green LED lighting up, and the compressor turning on if the pressure in the tank is significantly low.

4. While the tank is being filled ensure that the ball valve is closed. Once the tank has been sufficiently filled, the compressor will automatically turn off.

5. Set the flow rate for that specific test. To do this, open the air output valve on the tank as shown in Figure 5B, and adjust the pressure regulator and then the flowmeter.

6. When the desired flow rate is achieved, you are ready to run the test.

7. The automated system will perform all the necessary actions required to run the test and will update you with information along the way.

8. To start a test, flip the switch on the control box labeled "RUN TEST".

9. Once the test has finished, you can run a new test or end the sequence.

10. Once done, turn off the "POWER" and "RUN TEST" switches on the control box and unplug the wall power source.

11. After you have finished testing for the day, it is recommended that you change the centrifuge tubes used to store liquid odorants and clean the tubing exposed to odorants by running water through the disconnected tubing until you can no longer smell anything on them.

4.3) Break-Down & Storage

1. To break down the system after testing has been completed, the user must first disconnect the 12V power cord if not already unplugged.
2. Next simply disconnect the following pieces of equipment by pushing in on the outer ring of the push-to-connect fitting and pulling out on the PTFE tubing:
    a. Air tank output from air flow control unit
    b. Air flow control unit from power control box
    c. Power control box from odor bank
    d. Odor bank from manifold B
    e. Manifold B from nose cone
    f. Filter adapter from nose cone
    g. Vacuum pump from filter adapter
3. With all of the components disconnected, it is recommended to wash all PTFE tubing out with fresh water to remove any stimuli or contaminants.
4. Next, dry all pieces of tubing and tie them into a bundle using rubber bands or wire.
5. Finally, place all equipment into their respective storage boxes as detailed below:
    a. Storage Box 1: Compressor, air tank, power control box, 12V power cord
    b. Storage Box 2: Air flow regulation unit, odor bank, PTFE tubing bundle, centrifuge tubes, filter adapter, vacuum pump
6. Note: Ensure that the system is stored near room temperature in a dry place. Avoid extreme heat or cold to prevent damage to electrical components.

4.4) System Maintenance

In order to maintain the life of this device, all components should be cleaned after each use and stored in a dry, non-humid environment.

1. To clean the tubing and vials, rinse with water and a small amount of dish soap and then let dry. Ensure that all tubing is dry before use in the device. To adjust the length of tubing, use shears or cutters and ensure that the ends of the tubes are cut perpendicularly to the length of tubing
2. Ensure that corrosive stimuli is quickly washed off the 3D printed caps to avoid damaging them
3. During usage, ensure that the pressure switch is working and the duty cycle of the compressor allows ample time for cool down between operating times
4. Calibrate the pressure switch and flow meter before testing to confirm they have accurate read outs
5. To replace wiring, use a sharp edge to score the heat shrink material and heat the wiring connection with a soldering iron to separate the wires. Before soldering new wires together ensure that you first put new heat shrink material on one end of the wired connection. Heat shrink insulates the exposed wires and to reduce it to the correct size you can use either a soldering iron or a heat gun
6. Before and after testing, it is recommended to check the filter and ensure that it is still in proper condition. The filter is rated to run for 6 months on moderate daily usage. However, this number can vary greatly depending on the amount of usage and the type of particles that are filtered. It is recommended to keep a detailed record of how often the filter is used, and what it is used for

If a test does not run successfully or you would simply like to inspect the device before operation, there are several components to check including the electronics, code, and tubing. Before beginning the technical troubleshooting procedure below, it is recommended to eliminate simple causes for error such as the power cord not being plugged in or a loose tubing connection.

1. In the event that a test does not start when expected, first ensure that the Arduino program has been uploaded and that the Arduino is receiving power
2. Whenever the USB cord is plugged into the computer and connected to the Arduino, power will be delivered to the system and a green light will illuminate on the Arduino board
3. Then check that the "POWER" and "RUN TEST" switch are on. This should be confirmed by corresponding green LEDs that will illuminate when these switches are flipped
4. Also check that the 12V wall power adapter is plugged in
5. Next open the control box and check for any damaged, exposed or unplugged wires
6. First check that the connections between the Arduino and the relay board are correct. Refer to Figures 9 and 10 for the correct wiring
7. Then confirm that the "POWER" and "RUN TEST" switches are wired according to Figure 11A and 11B
8. Next, look at the connections between the solenoid valves and the relay board as shown in Figure 12. Power should be connected to one side of the solenoid while the other is connected to the normally closed port on the relay. This ensures that when there is not a signal sent to the relay, all solenoids should be closed. A relay, shown in Figure 12 includes three ports: normally open (NO), communication (COM), and normally closed (NC). The COM switch should always be connected to ground.

5.) Appendices

System Overview: https://www.youtube.com/watch?v=JjYWKVQtMkY

System Operation: https://www.youtube.com/watch?v=vrY7NL2wIms

QR Code for Scanning: