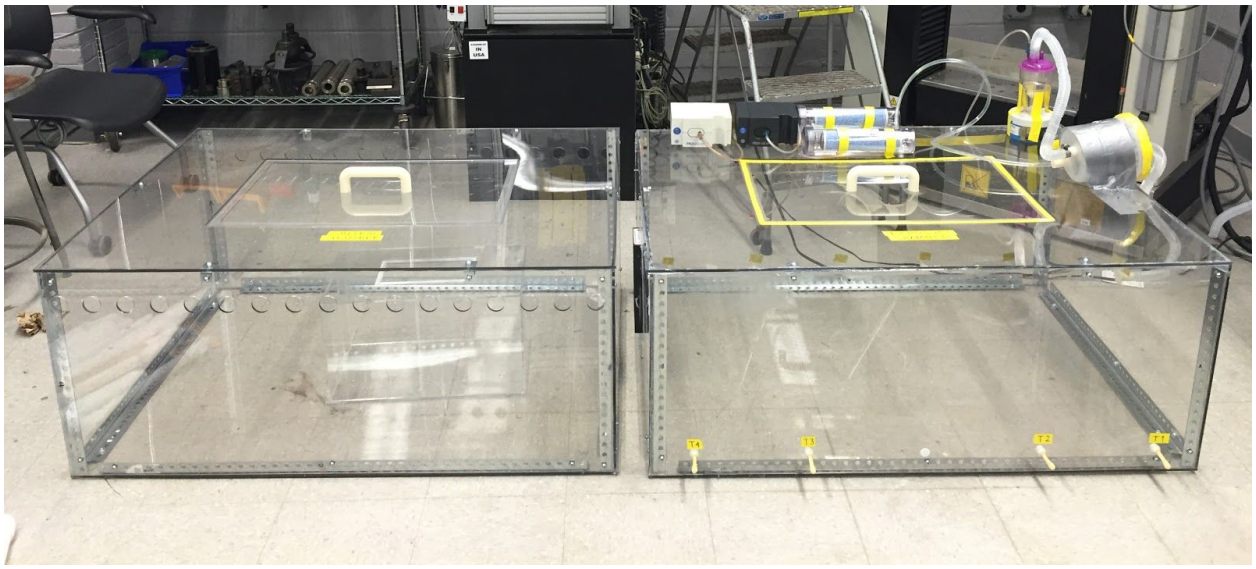
Cummings School of Veterinary Medicine

Final Design Report

Particulate Matter Pipe Distribution System



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EXECUTIVE SUMMARY

A Particulate Matter distribution system was designed and manufactured to be used in an experiment by our client, Ben Nephew, who will research the effects of PM on development of autism using pregnant rats. The system was designed and built so that it would transfer and evenly distribute aerosol PM into a chamber that has 6 rat cages in it. The HEPA filter in the cage would exhaust the excess PM, creating a safe laboratory environment.

After the client needs were identified, important concepts were generated and a final design was obtained. The safety of the rats and scientist, a regulated, constant flow and a constant PM concentration inside the exposure chamber were some of the priorities for us. In addition the repeatability, durability and accuracy of the product were very important. We used various design concepts and materials to meet these needs such as strong polycarbonate sheets, metal brackets and sealant.

We built two boxes, exposure chamber and control chamber, with the dimensions 48 x 36 x 20 in that would both have 6 rat cages inside for the experiment. We designed every aspect to increase usability and meet our client's needs. We also prepared a user manual, explaining how to use the product for our client and other researchers. After manufacturing the boxes and building the setup, we tested our product using NaCl since our current laboratory environment was not appropriate for testings with PM. We conducted a hypothetical flow analysis in order to determine how to achieve the desired concentration level in the chamber. However, after testing it was clear that we would not be able to verify our analysis since the device we used to determine the concentration was recording concentrations of large ambient particles as well as the $PM_{2.5}$ particles which we were targeting thus the data we recorded was distorted.

Our next step would be adding the rat cages inside the chambers to measure the rate of PM absorption in real testing conditions. In addition we would use PM instead of Sodium Chloride and test if the concentration is constant and the ideal conditions are maintained. It is also important to conduct testings with the animals inside, since it will affect the PM concentration inside the chambers. We would also add a particle filter to the exposure chamber to make sure the large particles are filtered out and thus conduct further tests to analyze the flow model we made.

The team has successfully designed and built a product that meets the client's needs and engineering requirements. We got positive feedback from the client and our product will be used in his experiments in The Cummings School of Veterinary Medicine at Tufts University soon. The team will be included in the publications involving the boxes.

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1.0 Problem Background

Ever since the industrial revolution in the 19th century, environmental pollution is becoming increasingly prevalent. Its effects have been a cause for concern among many. The most worrisome forms of pollution are the fine particulate matter as these are particles that are small enough to be inhaled and can penetrate deep into the lungs. The size of the particulate matter can be put in perspective using Figure 1, shown below.

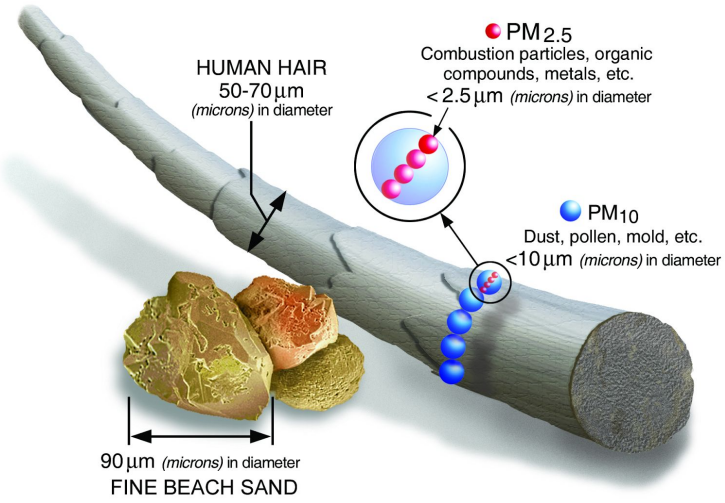


Figure 1: Particulate Matter Size Comparison [1]

In particular there has been increased attention to investigating the effects of particulate matter on developing autism. "Autism spectrum disorders (ASD) are pervasive neurodevelopmental disorders characterized by deficits in communication and social interactions, as well as the presence of stereotypic behaviors. ASD may affect as many as 1 in 45 children in the USA, but the global prevalence is still under-recognized." [2] A recent study conducted by the Harvard School of Public Health (HSPS) has shown that "women exposed to high levels of fine particulate matter specifically during pregnancy - particularly during the third trimester - may face up to twice the risk of having a child with autism than mothers living in areas with low particulate matter." [3]

Our client, Dr. Ben Nephew, an Assistant Professor at the Tufts Cummings School of Veterinary Medicine, is digging deeper into this relationship and is aiming to investigate the effects of a gestational immune challenge and chronic inhalant pollution, two major risk factors for autism, on inflammatory, neuroanatomical, and behavioral markers of autism in rats." [2]

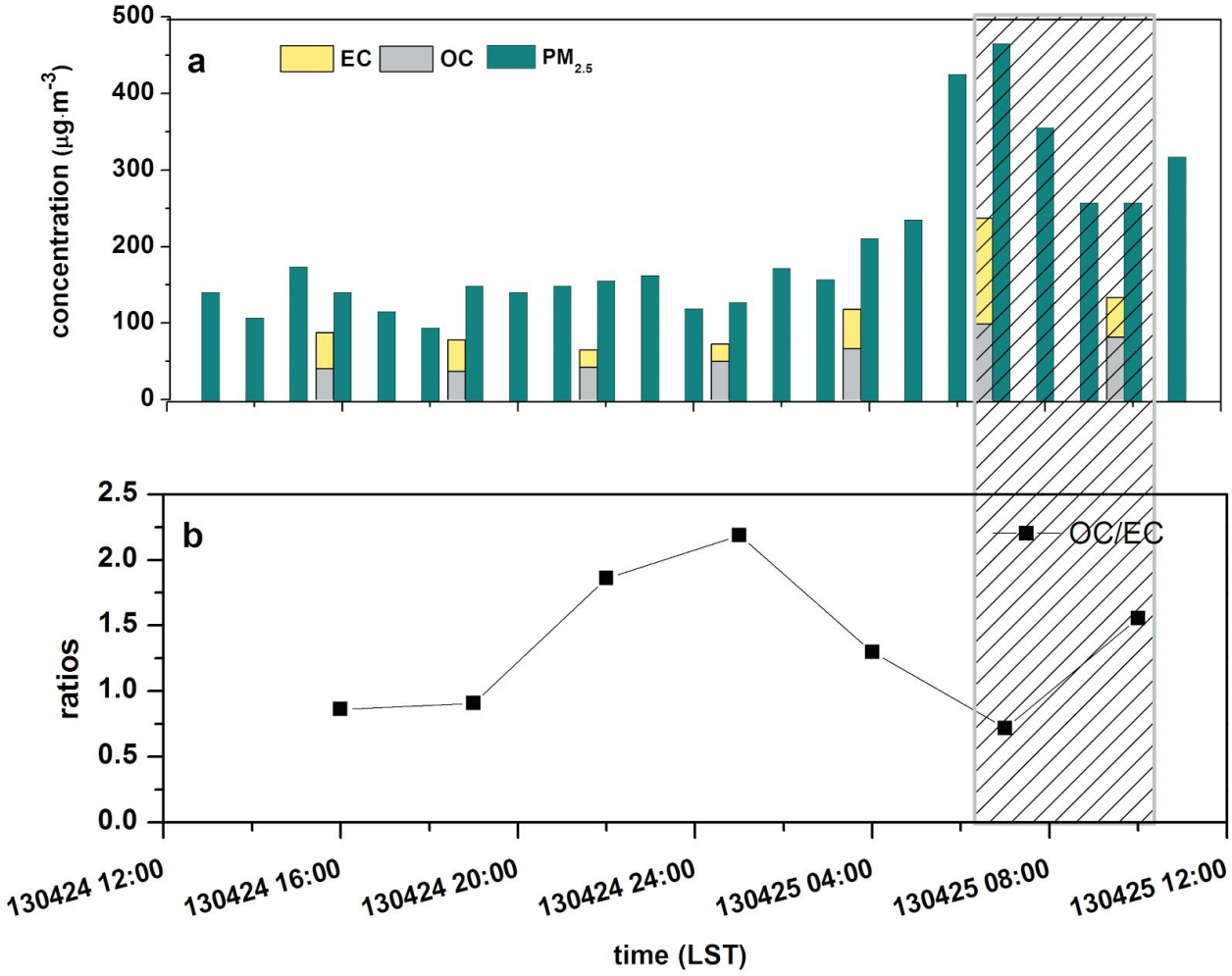


Figure 2:- $PM_{2.5}$ Concentrations in a Road Tunnel in Shanghai, China[4]

The figure above gives us the amount of $PM_{2.5}$ in a tunnel in Shanghai, China. Since studies on effects of pollution on autism are usually based on Chinese populations, we decided to use particulate matter concentrations in a tunnel in Shanghai as a reference . Our client advised us to deliver a concentration of $200\frac{\mu g}{m^3} = 200\frac{mg}{km}$ which is in line with the PM concentrations seen in Shanghai and thus can be used a basis for our model.

2.0 Design Recommendations

2.1 Problem Statement

Our task was to design and construct the setup of an experiment that delivers tunnel Particulate Matter (PM) in aerosol form to a total of 6 cages containing the test animals (rats). Our client would like to investigate autism occurrences as a result to PM exposure. We must ensure the safety of the test animals as well as the surrounding scientists while maintaining ideal conditions during the 5 hour PM exposure period, 3 times a week.

2.2 Requirements and Needs

To begin with our design ideation process we compiled a "Weighted Matrix of Requirements and Needs" by listing all of our needs and our requirements. We then evaluated each of our requirements with all of our needs and came up with the table below.

Table 1:- Weighted Matrix of Requirements and Needs

Need	Description	Weight	Size	Flow Rate	Cost	Pressure	Safety	Concentration
Accuracy	It should evenly distribute the PM to 6 different cages	2	8	7	3	6	3	9
Accuracy	Keep the concentration relatively constant	2	7	7	1	3	7	9
Repeatability	Experiment must be repeated with similar results	4	2	8	2	2	6	8
Durability	Setup must last at least 6 months (duration of experiment)	4	5	1	7	4	4	4
Usability	Easy to gain access to enclosures	3	6	1	4	1	5	1
Usability	Easy to assemble/disassemble experimental equipment	1	9	1	6	1	1	1
Safety	Avoid leakage of pollutants to lab atmosphere	4	1	4	2	7	10	5
Safety	Keep the concentration of PM below a harmful level	5	1	8	3	8	10	4
Total Sum			94	124	85	114	166	128

After constant communication with our client and brainstorming with the group members, we identified the needs and requirements as stated in the matrix above. We determined the flow rate, safety and concentration as the most important requirements for our design using the above schema. In order for the project to be repeatable and the concentration of PM to stay below a harmful level, maintaining the flow rate at a desired level was very essential for us. To create a safe environment for both the scientists and the rats, we must avoid any leakages and keep the concentration at a desired and constant level. In addition, keeping the concentration at a certain level was important for the experiment to be accurate and repeatable.

2.3 Ideation Approach

2.3.1 Research and Overall Idea Generation

Once we determined all the necessary requirements and needs that our client specified we then began brainstorming and coming up with the best course of action to tackle our problem. We began by familiarizing ourselves with the experiment itself as well as exploring similar setups. We did this by having discussions with our client where we were able to identify his needs and were then able to expand on delivering them to him. Giving our own feedback and educated opinion we managed to gain a lot of insight regarding the project specifications.

Furthermore, we visited two different labs which conduct animal research, the labs at the Harvard School of Public Health, in particular Professor John Godleski's lab, as well as labs in the Tufts University School of Environmental Engineering (Professor John Durant) and School of Psychology (Professor Klaus Mizcek). Visiting the labs gave us a chance to see existing setups and obtain expert opinion and advice. We received guidance and propositions on alternatives that we could incorporate in our experiment setup which could prove to be less cumbersome than the ones we were initially considering.

To conclude our research we closely observed an instructional video concerning a similar experiment was carried out in the University of Mexico[5]. The video included detailed steps on constructing a vapor chamber used to expose mice in alcohol. By breaking down every step and isolating the processes used in each step, we managed to familiarize ourselves with the processes and carry out a functional decomposition of our project main components.

Utilizing all the advice and research we accumulated it was evident that the overall idea was to build two chambers: an exposure chamber and a control chamber, each housing 6 rats.

2.3.2 Functional Decomposition

We then broke down the entire problem into separate sub functions as can be seen in the Figure below.

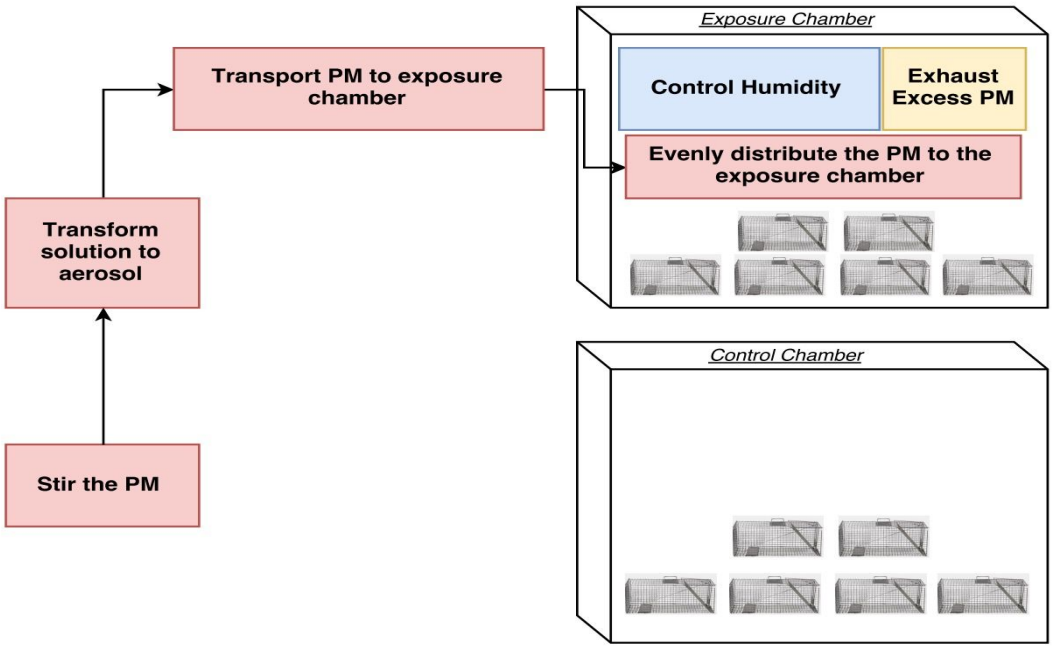


Figure 3: Functional Decomposition

Initially, we need to *dilute and stir the particulate matter* so that we could *transform the homogeneous solution to the aerosol.* After transforming the solution into an aerosol we need to make sure that there was a *safe, leakage-free transportation of the aerosol* containing the particulate matter into our exposure chamber. Once the aerosol was transported into the exposure chamber we need to ensure that it gets *evenly distributed in the exposure chamber* providing the same conditions to all six test rats. Due to the added humidity of our solution that was inserted into the exposure chamber, we need to make sure that we *control the humidity levels* (and temperature). Finally, we need to manage the excess particulate matter and *exhaust it safely*.

According to the "Guidelines for Housing of Rats in Scientific Institutions", humidity levels must be kept at a level higher than 40% in order to avoid risks of the rats developing ringtail disease as well as to avoid enhancing the proliferation of bacteria and ammonia production in the cages. Thus a recommended humidity range is 40-70%. Furthermore, it is recommended that temperatures be kept within regular room temperatures of 20-26 C [6].

2.3.3 Morphological Analysis

To identify the best alternative for each of the sub-functions we decided that the best ideation process was through morphological analysis. This was the best solution to unpacking the different sub functions as each of them are individual of the other meaning that any combination of the concepts can be implemented. Using all the input from previous research everyone came up with alternatives for each sub-function and compiled all the ideas in a table.

Table 2:- Morphological Analysis of Different Concepts for Each Sub-Function

Sub-Functions	**Concept 1**	**Concept 2**	**Concept 3**
Stir the PM	Magnetic Stirrer	Manual	Blender
Transform Solution to Aerosol	Dust feeder	Nebulizer	Rapid Cooling
Exhaust Excess PM	Hepa Filter	Pipe from exit hole to atmosphere	Open Ventilation (in lab)
Transport PM aerosol to E.C.	Manifold System	Common container	Attach device to E.C.
Evenly Distribute PM in E.C.	Flute	Double Input/Output	Single Input/Output
Control Humidity	Dehumidifier	Mix PM with dry air	Refrigerator Coil

2.4 Decision Matrices

In order to further evaluate these concepts, we decided to create decision matrices and deduced the best solution and course of action for each sub-function as presented below.

Table 3: Stirring the Particulate Matter - Decision Matrix

Selection Criteria	Weight	Concepts					
		Magnetic Stirrer		Manual		Blender	
		Rating	Score	Rating	Score	Rating	Score
Safety	0.1	8	0.8	4	0.4	3	0.3
Cost	0.3	8	2.4	2	0.6	5	1.5
Speed	0.2	9	1.8	5	1	8	1.6
Size	0.2	10	2	3	0.6	4	0.8
Usability	0.1	8	0.8	8	0.8	6	0.6
Durability	0.1	2	0.2	7	0.7	6	0.6
Total Score			8		4.1		5.4

We evaluated a magnetic stirrer, manual stirring and a blender as our three concepts for stirring the PM. We observed that the magnetic stirrer was by far the most advantageous solution outscoring both the manual stirring and blender concept in all 6 selection criteria except for durability. We were not very preoccupied with durability since is was of the least importance given that the experiment that we are setting up needs to be running only for 6 months, and in the unlikely situation that the magnetic stirrer malfunctions, replacing it would be effortless and relatively inexpensive.

Table 4: Transforming the Solution into an Aerosol - Decision Matrix

Selection Criteria	Weight	Concepts					
		Dust Feeder		Nebulizer		Rapid Cooling	
		Rating	Score	Rating	Score	Rating	Score
Safety	0.1	8	0.8	9	0.9	6	0.6
Cost	0.3	2	0.6	10	3	4	1.2
Accuracy	0.2	9	1.8	7	1.4	7	1.4
Size	0.1	6	0.6	9	0.9	2	0.2
Usability	0.1	7	0.7	6	0.6	3	0.3
Durability	0.2	7	1.4	5	1	4	0.8
Total Score			5.9		7.8		4.5

To transform the liquid solution to an aerosol, we evaluated a dust feeder, a nebulizer-air compressor combination, and rapid cooling of the solution. After speaking to Joy Lawrence at Harvard School of Public Health, we narrowed our concept selection down to the dust feeder and nebulizer. Taking into consideration that the dust feeder was extremely expensive for our client's and our combined budget, we evaluated the ideas and decided to proceed with a nebulizer attached to an air compressor despite the added accuracy and precision that was provided by the dust feeder.

Table 5: Exhausting the Excess PM - Decision Matrix

Selection Criteria	Weight	Concepts					
		HEPA Filter		Pipe from exit hole to atmosphere		Open ventilation (in lab)	
		Rating	Score	Rating	Score	Rating	Score
Safety	0.5	8	4	7	3.5	3	1.5
Cost	0.3	6	1.8	7	2.1	10	3
Size	0.05	7	0.35	2	0.1	10	0.5
Usability	0.05	9	0.45	3	0.15	8	0.4
Durability	0.1	6	0.6	5	0.5	7	0.7
Total Score			7.2		6.35		6.1

Deciding on the direction that we would take for exhausting the excess particulate matter in the mixing and exposure chamber was harder since all three options that we came up with had their own advantages and disadvantages. The result of our decision matrix eventually proved that HEPA Filters were the best option to continue with. Open ventilation with the lab would have been a good idea but given that the experiment deals with particulate matter transformed into aerosol, that option could potentially harm scientist and researchers during the exposure period. Moreover, since we do not know the specifications of the room in which our setup is going to be housed in, we were uncertain whether we would be able to have a pipe exhausting the air in the atmosphere.

Table 6: Transporting the PM Aerosol into the Exposure Chamber - Decision Matrix

Selection Criteria	Weight	Concepts					
		Manifold system		Common container		Attach device to EC	
		Rating	Score	Rating	Score	Rating	Score
Safety	0.2	8	1.6	2	0.4	5	1
Cost	0.3	7	2.1	9	2.7	8	2.4
Fabrication	0.25	4	1	6	1.5	3	0.75
Size	0.1	5	0.5	2	0.2	8	0.8
Usability	0.05	9	0.45	6	0.3	4	0.2
Durability	0.1	8	0.8	8	0.8	5	0.5
Total Score			6.45		5.9		5.65

Moving on to the options for transporting the particulate matter aerosol to the exposure chamber, we concluded that the best approach was using a manifold system. The most important factors for analysing each concept of this sub-function were safety, cost, and fabrication. The manifold system presents the most viable option for leakage prevention as it allows for increased monitoring and control of the transportation of the aerosol from the nebulizer to the exposure chamber. Furthermore, in terms of safety the common container concept brings about a serious potential for hazard towards the rats, as there can be no control of possible leakages from the mixing process. This in turn, could increase the concentration to undesired levels and harm the

rats. For the overall transportation of the PM aerosol, we used Tygon pipes to create a manifold system since it would be the most accurate and safe solution.

Table 7: PM Distribution in the Exposure Chamber - Decision Matrix

Selection Criteria	Weight	Concepts					
		Flute		Single Input/ Output		Double Input/ Output	
		Rating	Score	Rating	Score	Rating	Score
Safety	0.2	8	1.6	7	1.4	7	1.4
Cost	0.3	4	1.2	10	3	8	2.4
Fabrication	0.2	2	0.4	9	1.8	7	1.4
Size	0.05	5	0.25	9	0.45	6	0.3
Accuracy	0.2	9	1.8	6	1.2	8	1.6
Durability	0.05	7	0.35	8	0.4	8	0.4
Total Score			5.6		8.25		7.5

Mainly due to durability, fabrication and cost factors, we decided to go with a single input/ output distribution system. We were advised by Professor Godleski that implementing a double input/output system or a flute system would not affect our results much compared to a single input/output system, since the 5 hour exposure time would ensure an even distribution of the PM.

Table 8: Controlling Humidity - Decision Matrix

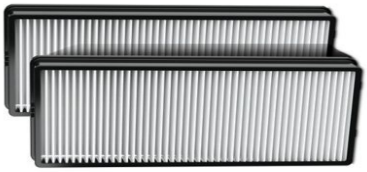
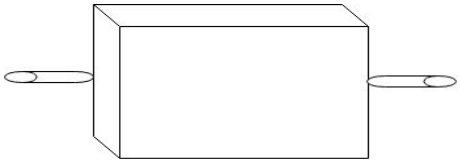
Selection Criteria	Weight	Concepts					
		Dehumidifier		Mix PM aerosol with dry air		Refrigerator Coil	
		Rating	Score	Rating	Score	Rating	Score
Safety	0.1	8	0.8	9	0.9	6	0.6
Cost	0.4	3	1.2	7	2.8	4	1.6
Fabrication	0.2	4	0.8	7	1.4	4	0.8
Size	0.1	5	0.5	9	0.9	6	0.6
Accuracy	0.15	6	0.9	5	0.75	9	1.35
Durability	0.05	9	0.45	8	0.4	6	0.3
Total Score			4.65		7.15		5.25

Since the solution is initially in a liquid form, it increased the humidity in the exposure chambers so we needed to come up with a solution to bring the humidity inside the exposure chamber above 40% to avoid harming the rats. The most important criteria we considered was the cost, due to the fact that humidity wouldn't have a significant effect on our results. Thus we consulted Dr.Ben Nephew and Professor John Godleski about this issue on our visit to Harvard Labs. After our results and their recommendation we decided that mixing PM aerosol with dry air using would be the best solution to control the humidity in the chambers.

2.5 Concepts Pursued

Below is a table highlighting the concepts we decided to pursue according to the results of the decision matrices based on the criteria we set to evaluate each of the concepts for the different sub functions.

Table 9: Final Concepts Pursued

Chosen Concepts	Visual Representation
Magnetic Stirrer Used to stir the solution and keep it homogeneous.	
Nebulizer Used along with an air compressor the nebulizer will be used to transform the solution into an aerosol.	
HEPA Filter Used to exhaust the excess aerosol and diffuse any harmful effect that the PM might have to the exposed scientists.	
Manifold System Used to transport the PM into the exposure chamber without allowing any interaction with the outside environment.	
Single Input Output Distribution System Used to evenly distribute the PM inside the exposure chamber.	
Dry Air Humidity Controller Used to add dry air in the exposure chamber and keep its humidity at the required levels.	

2.6 Fabrication Processes

To summarize the final deliverable will contain the following elements:

- Control chamber - a container for the control group of rats
- Exposure chamber - sealed container with an inlet, a HEPA filter exhaust, and test ports along the front and back.
- PM production system - compressor to nebulizer to mixing chamber.
- Dry Air production system - compressor to silicon gel tubes to mixing chamber, mixing chamber to exposure chamber.

The figure below is a schematic of our exposure system and pollution system:

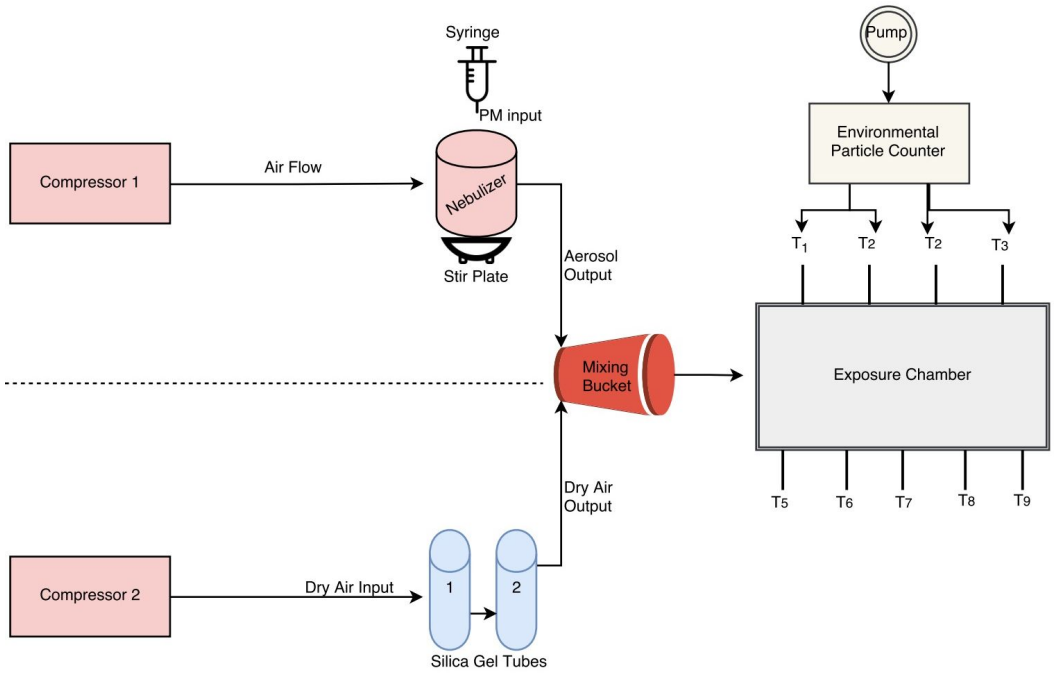


Figure 4: Schematic of Final Setup

2.6.1 Construction of the Chambers

The size of each rat cage is 19.5L x 10.5W x 10.5H inches. Our client would like to fit a total of 6 of these cages in each of the chambers with an arrangement of 2 cages at the front and 4 at the back. In order to minimize the total size of the chambers given the constraints, we decided to have the 2 cages at the front lined up on their length side and the four at the back orientated at a 90 degree rotation from the two cages at the front with their widths lined up. Factoring in extra space in between each cage and between the sides of the chamber and the cages as well as taking into account height space needed for easy access to the chamber we decided that the final dimensions of each chamber to be 48L x 36W x 20H inches.

We decided to use polycarbonate sheets called Makrolon for the construction of the chambers. We used this material due to the size of the chambers which made it important to select the most

appropriate material. Makrolon is a thermoplastic sheet material with good impact resistance, small susceptibility to cracks and is clear material which meets all the requirements for the material we need.[6] We compared it to acrylic/plexiglass and found that it is both better suited in terms of its strength as well as its cost as it is less expensive. It also bonds well using adhesives. The sides were attached by SciGrip/Weld on #16, an epoxy used to bond together acrylics or polycarbonates. However, due to the shear size of our chambers, we decided to reinforce the structure using boltmaster slotted angle beams (BSA). Every side of the BSA was attached to a Makrolon with three quarter-inch bolted screws. We decided to put the door of the chambers on the top as the door must allow for the cages to be inserted and taken out therefore having a door on the front would not adhere to the required size specifications. We thus etched a border for the door to rest upon. A 3D printed handle was glued on the door as shown in Figure A.11 of Appendix A. The size of the Makrolon sheets we needed cutting were too big for any of the laser cutters we had access to and thus the cutting of the sheets and the holes within them was outsourced to the Machine Shop on Colby Street in the Science and Technology Center at Tufts University. A CNC milling machine was used by those at the Machine Shop to perform the precise cuts that we needed.

There were differences in the design of the control and exposure chamber. For the control chamber there were holes cut through the front and back to permit airflow. For the exposure chamber, the only holes cut were one for the aerosol input on the left side and a hole to fit a HEPA filter on the right side, opposite to the inlet. We also added small holes on the front and back for testing concentrations at different locations within the chamber to ensure that the concentration is both at the desired level and that it is relatively evenly distributed. All connections and screw were covered with silicon sealant in order to minimize leakages of the PM to the environment. Figures of the sides of the two chambers can be seen in Figures of Appendix A.

2.6.2 PM Aerosol and Dry Air Generation

The pollutant was generated by two parallel streams of equal flow, of dry air and air from the nebulizer which converged at the mixing chamber. The mixing chamber is made out of a plastic bucket. There are two inlets, one for each stream and one outlet which connects with the exposure chamber through a 15/16 inch pipe.

The dry air stream starts from a 10 L/min compressor, the air at this point is room air, which then passes through two silicon gels tube connected in series. Those gels dry the air and half a lasting life of about 6 months. All connection of this stream are through ¼ inch pipes.

The other stream also begins with a compressor which feeds room air in the nebulizer through a ¼ inch tube. The nebulizer contains the PM solution and sits on a magnetic stirrer. Aerosol comes out along with the air at a rate of 0.5 mL/min. The nebulizer is then connected to the mixing chamber through a 15/18 inch tube. Finally, opposite to the inlet there is a HEPA filter, filtering out all the PM infused air that fills the exposure chamber.

In order to put together all the different components we had to find the correct tubing and find the appropriate nozzles to fit all the piping together. We decided to use cadding and 3D printing to design nozzles that would perfectly to cater our needs (Figure A.10) This allowed us to fit our tubing snugly keeping the flow continuous. By filleting the edges we made sure turbidity was not minimized to achieve as close to a steady flow as possible.

2.7 Providing the Ideal Concentrations

The deliverable has to model the pollution levels of a polluted city. Our client does not have high demand for the accuracy of the concentration level of the pollutant, but it needs to be about twice as much more polluted than in any random urban area or 200 micrograms per cubic meter.

The initial plan was to use a flow regulator provided by our client. Flow would be regulated for dry air and air with PM separately and used to control humidity and PM concentration for the exposure chamber. Testing showed that the flow regulator is used for lower flow rates and would not be able to support sufficient flow for this experiment. We bought two valve based flow regulators, which were not supplying air that desired rate due to leakages of the flow regulators. In similar experiments conducted in labs we visited, the flow is 10-15 L/min, the compressor we use provides air at 10-13 L/min (as they are old it's probably closer to 10/min). If both dry air and nebulizer operate in full capacity the air is within the target humidity range. Thus, we decided to control PM concentration in the exposure chamber by changing the concentration of PM in the liquid solution in the nebulizer. The figure below shows data regarding flow through the nebulizer. In order to keep the output constant the nebulizer will always be operating at full capacity, at 240 mL. At this level the aerosol generation rate is 0.5 mL /min, which is important to the analysis that follows.

Table 10: HEART Nebulizer Specifications [8]

HEART NEBULIZER SPECIFICATIONS			Nominal Run Time Rate		Aerosol Generation Rate	
Product Name	Capacity (mL)	Flowrate (L/min)	Hours	Minutes	mL/hour	mL/min
HEART High-Output Nebulizer	240	10	8.0	480	30	0.50
HEART High-Output Nebulizer	240	15	4.8	288	50	0.83
Uni-HEART Universal Nebulizer	10	2	2.5	150	4	0.07
Uni-HEART Universal Nebulizer	10	3	1.5	92	6.5	0.11
Uni-HEART Universal Nebulizer	10	4	1.1	67	9	0.15
Mini-HEART Hi-Flo Nebulizer	30	8	1.5	90	20	0.33
Mini-HEART Lo-Flo Nebulizer	30	2	3.8	225	8	0.133

Median Particle size = 2-3 µm Run Times ±15%

2.7.1 Theoretical Flow Analysis

The following assumptions were used to conduct the flow analysis:

- Uniform Flow
- Steady State
- Each Compressor Output = 10LPM (According to Product Specifications)
- Rats intake and fur absorption is negligible

➔ Target concentration $d = 200 \frac{\mu g}{m^3}$

➔ Volume of exposure chamber $V = 560\ L$

➔ Flow rate of nebulizer $\overline{V}_{nebulizer} \sim 10\ L/min$

➔ Flow rate at input $v \sim 20\ L/min$

➔ Residence time of the pollutant is $\frac{V}{\overline{V}nebulizer} = 56\ min$

Using the amount suggested by Table 10 of aerosol, at any given time is

$$V_{aerosol} = (Redisdence\ Time) * (Aerosol\ Generation\ Rate) = 56\ min * 0.5\ mL/min = 28mL$$

The amount of pollutant needed is

$$P = 200 \frac{\mu g}{m^3} * 0.560 = 112\ \mu g$$

So the concentration we need is

$$\rho = \frac{P}{V_{aerosol}} = \frac{112}{28} \frac{\mu g}{mL} = 4 \frac{\mu g}{mL}$$

So when operating the nebulizer at full capacity we would need to have the following mass of PM in the solution:

$$m = 4 \frac{\mu g}{mL} * 240\ mL = 960 \mu g = 0.96 g$$

2.7.2 Testing Analysis

We then tested our setup using the theoretical quantities calculated. We used sodium chloride (salt) instead of PM due to safety concerns inside the lab. To measure concentration we used a device called “Environmental Particle Counter” which measures the concentration of particles in the chamber by expanding particles collected using water droplets in order to measure the concentration. Below is the Figure representing the test which we conducted.

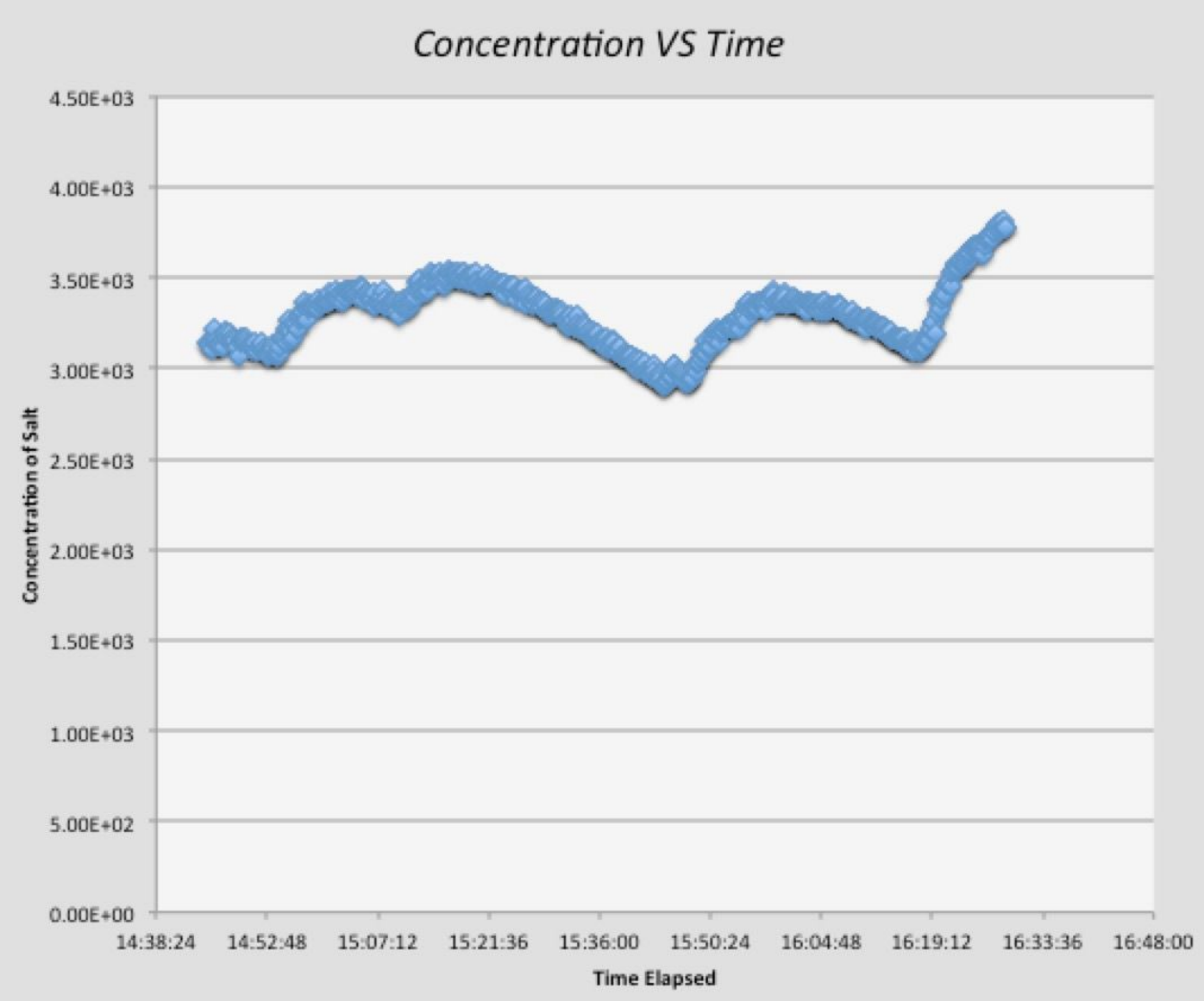


Figure 5: Concentration vs Time: Data points collected every 10 seconds across 2 ½ hours. We first collected a few ambient data points. The plot shows concentration in PPM, 3000 PPM=3g/L.

We expected to receive a graph with inconclusive results as it was brought to our attention by Professor Durant that the device only works if the ambient particles are filtered out otherwise they will interfere with the data collected. Thus the graph does not depict the true concentration of $PM_{2.5}$ in the chamber at the different locations.

3.0 Conclusion

As depicted in the table below, the final product we delivered met the user needs and got positive feedback from the client. Even though we had made some changes to our initial design, we finalized our product with desired functions. The chambers and the distribution system are ready to use by the client in his experiment on investigating effects of PM on development of autism.

Needs	
Evenly distribute the PM to 6 cages	✓ **Achieved : One inlet/outlet**
Repeatability	✓ **Achieved : Constant PM concentration**
Keep concentration constant	✓ **Achieved : Constant nebulizer output, sealing**
Last at least 6 months	✓ **Achieved : Durable materials and metal brackets**
Easy access to cages	✓ **Achieved : Wide lid on top**
Avoid leakage of PM to lab atmosphere	✓ **Achieved : Sealed boxes and clamped pipes**
Keep the concentration of PM below a harmful level	✓ **Achieved : Concentration testings and HEPA filter (for the lab)**

4.0 Future Directions

There are some important tasks that could further be done for this project. First of all, testings with tunnel PM should be done using this setup. It is important to do a dry run in order to see if the concentration is constant throughout the box and the experimental conditions are ideal while using PM. Currently all tests have been carried out using Sodium Chloride in an empty exposure chamber. In order to make the testing to be more realistic and accurate we initially need to place the rat cages with beddings inside the exposure chamber and use PM instead of sodium chloride. After analyzing the results, we would place the rats inside their cages if the test results are favorable. Furthermore, we would add a particle filter to make sure that large particles are filtered out. We would also monitor the concentrations to observe the effect of absorption from both the rats and their fur. Once we are satisfied with the results and the conditions of the chamber, we would contact our client to conduct the experiment.

Furthermore, we have provided a User Manual for our client (Appendix B) and will remain in close contact with him to ensure that everything goes according to plan throughout the experiment.

List of References

[1] "Particulate Matter (PM) Basics." *EPA*. Environmental Protection Agency, n.d. Web. 8 Nov. 2016.

[2] Nephew, Benjamin C., Dr. "Inflammation-Based Collaborative Grant Submission Form." Tufts University, 2016.

[3] Dwyer, M. “Fine Particulate Air Pollution Linked with Increased Autism Risk” (2014): Available at <https://www.hsph.harvard.edu/news/press-releases/fine-particulate-air-pollution-linked-with-increased-autism-risk/ >

[4] http://journals.plos.org/plosone/article?id=10.1371/journal.pone.0112195#pone-0112195-g008

[5] "Construction of Vapor Chambers Used to Expose Mice to Alcohol During the Equivalent of All Three Trimesters of Human Development | Protocol." *Russell A. Morton*. N.p., n.d. Web. 11 Nov. 2016:
Available at https://www.jove.com/video/51839/construction-vapor-chambers-used-to-expose-mice-to-alcohol-during

[6] http://www.animalethics.org.au/__data/assets/pdf_file/0014/222512/housing-rats-scientific-institutions.pdf

[7] http://www.aetnaplastics.com/products/d/makrolon

[8] http://westmedinc.com/heart/

[9] http://www.plastics.covestro.com/en/Products/Makrolon

Appendix A: Technical Drawings

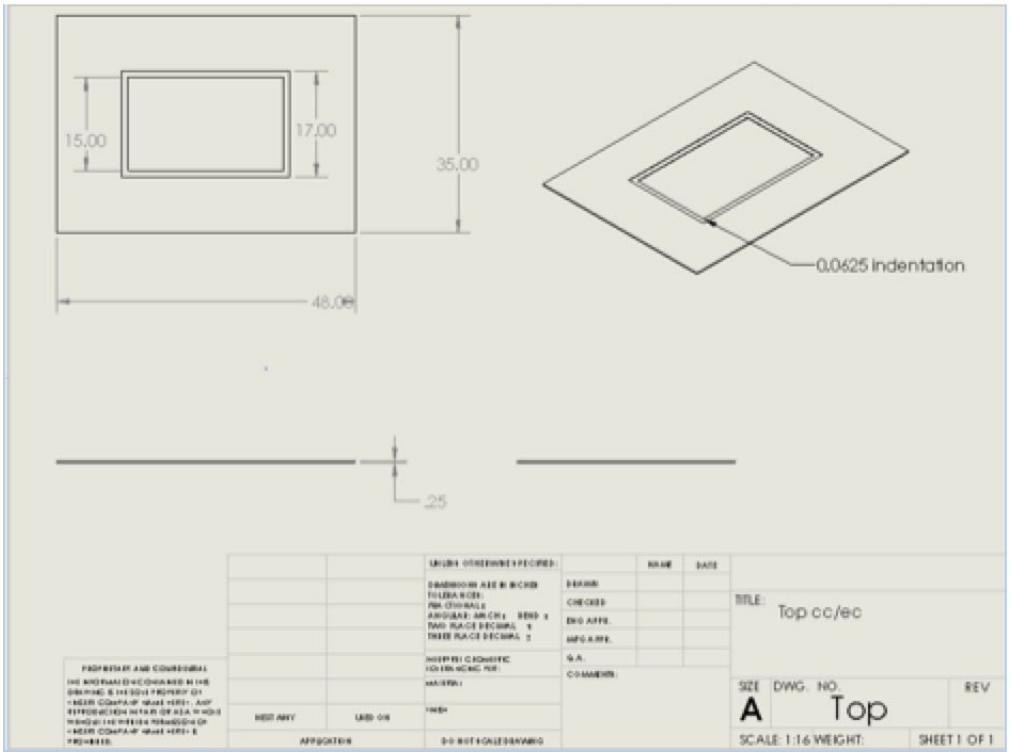


Figure A.1: Top View of Exposure and Control Chamber

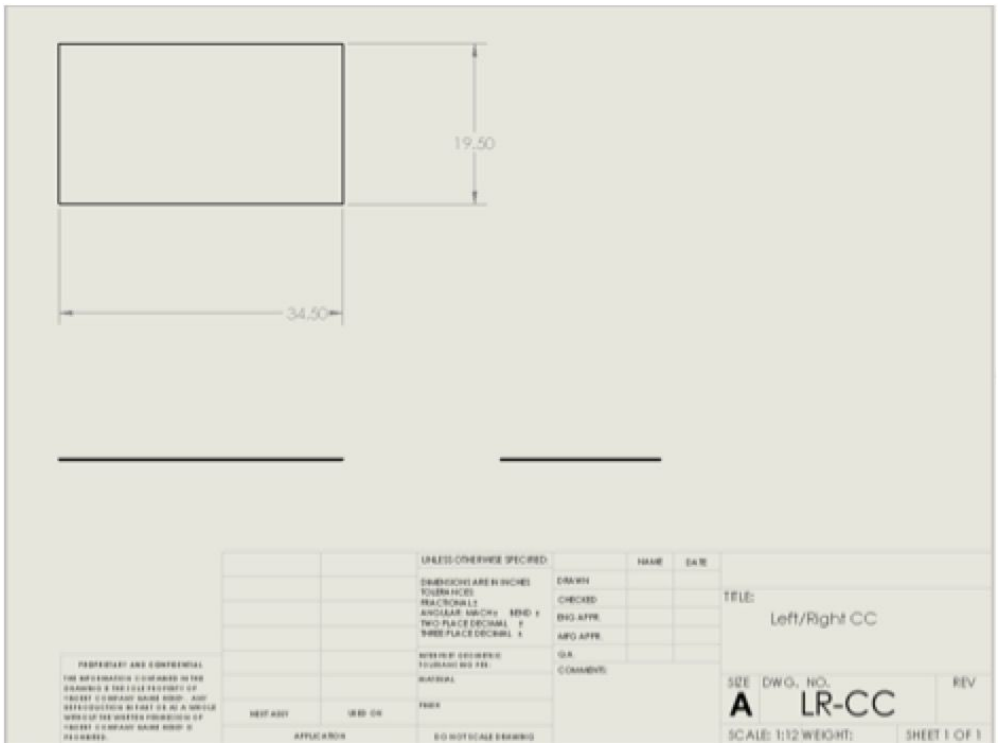


Figure A.2: Left and Right View of Control Chamber

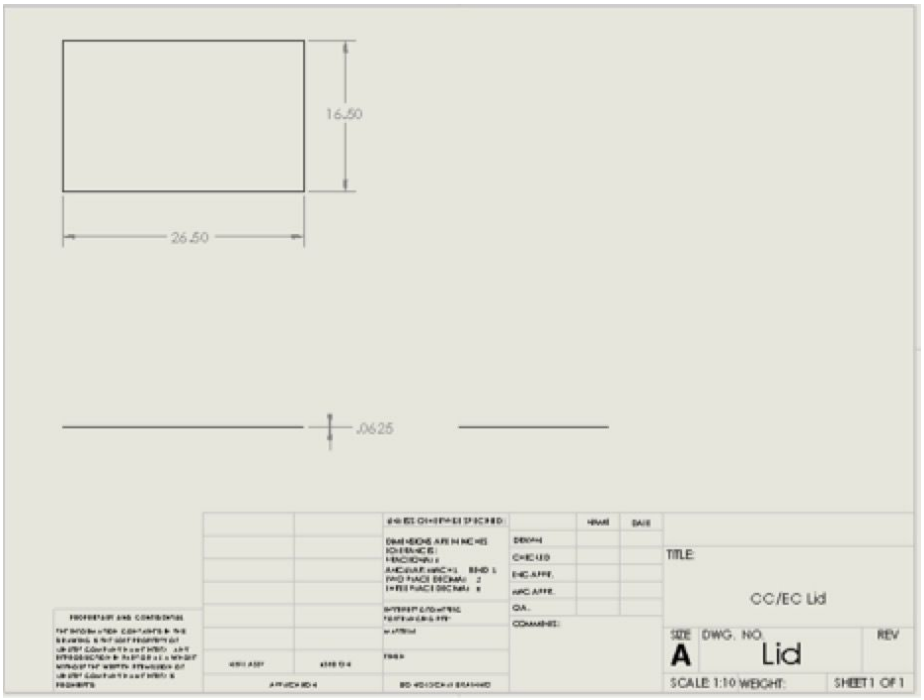


Figure A.3: Door Exposure and Control Chamber

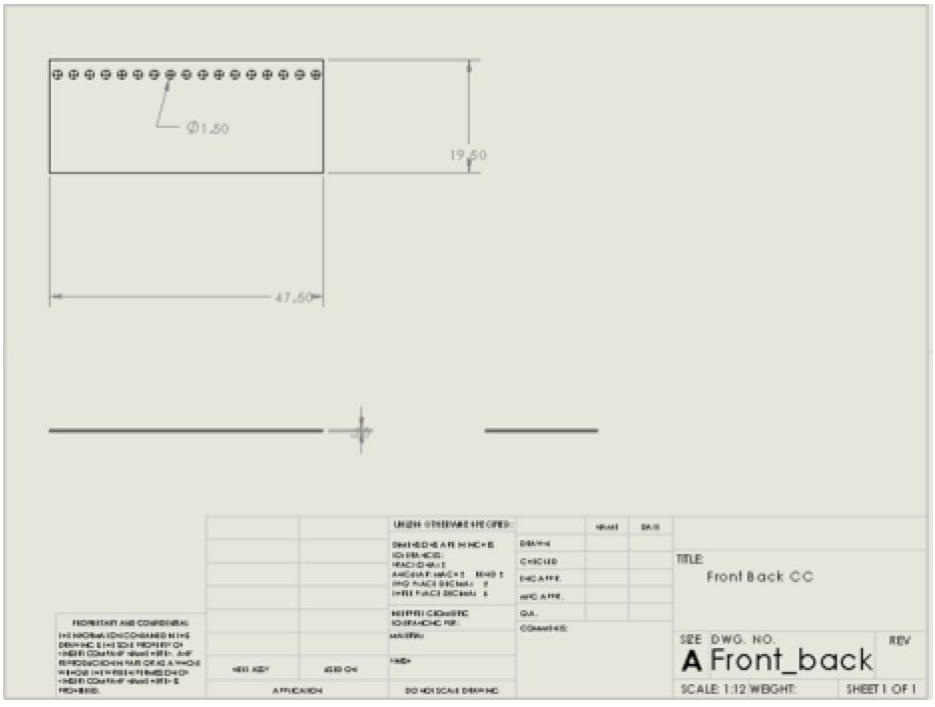


Figure A.4: Front and Back View of Control Chamber

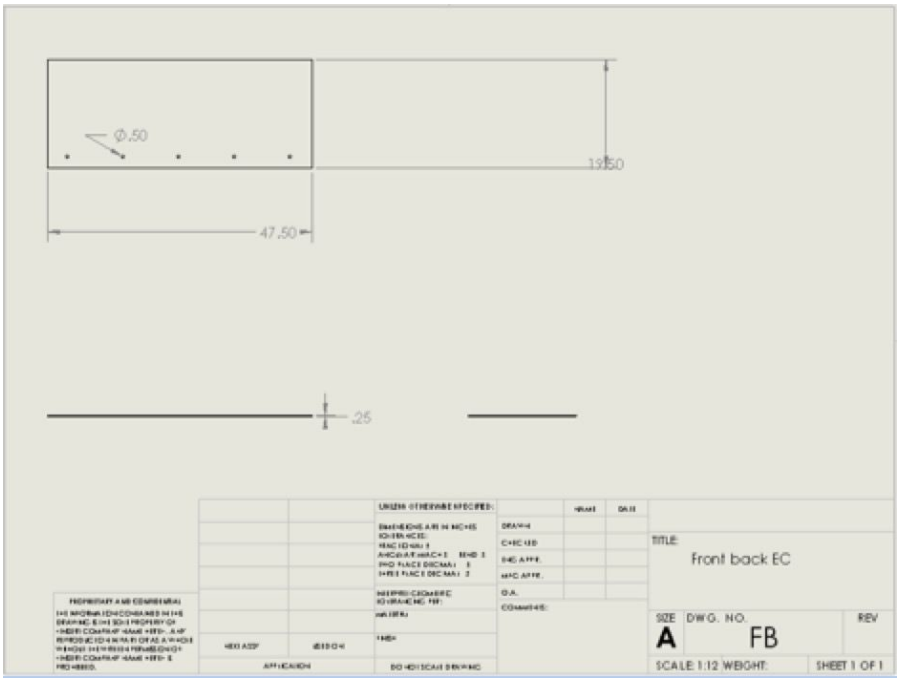


Figure A.5: Front and Back View of Exposure Chamber

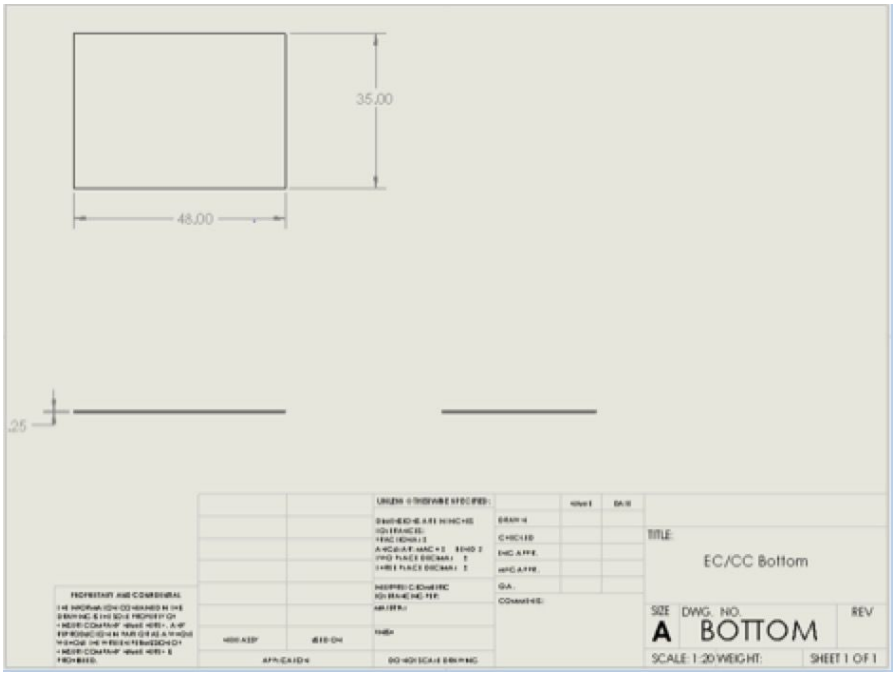


Figure A.6: Bottom View of Control and Exposure Chambers

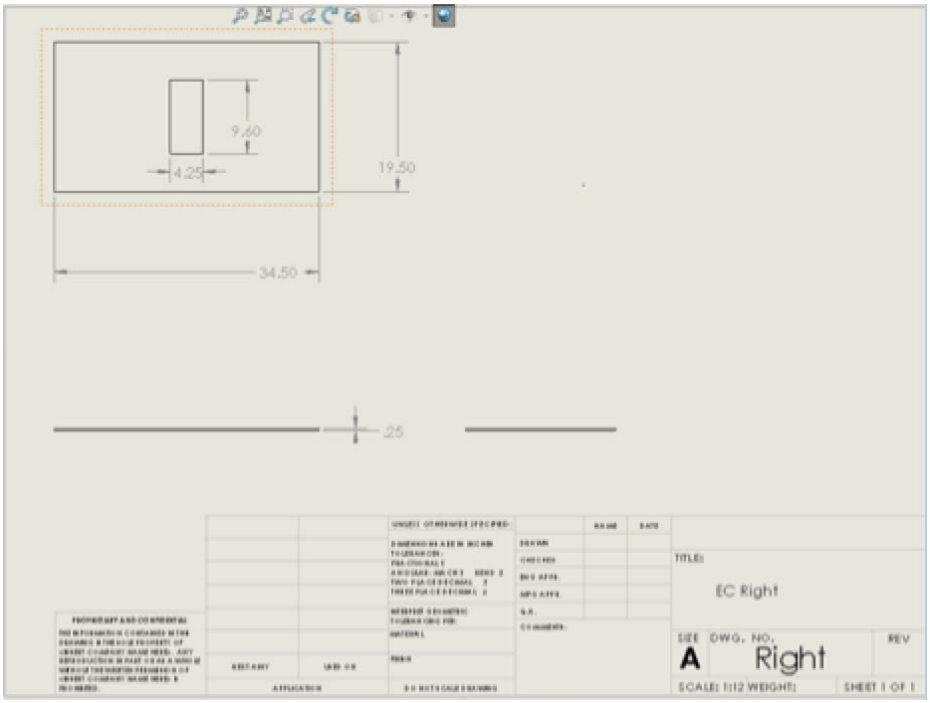


Figure A.7: Right View of Exposure Chamber

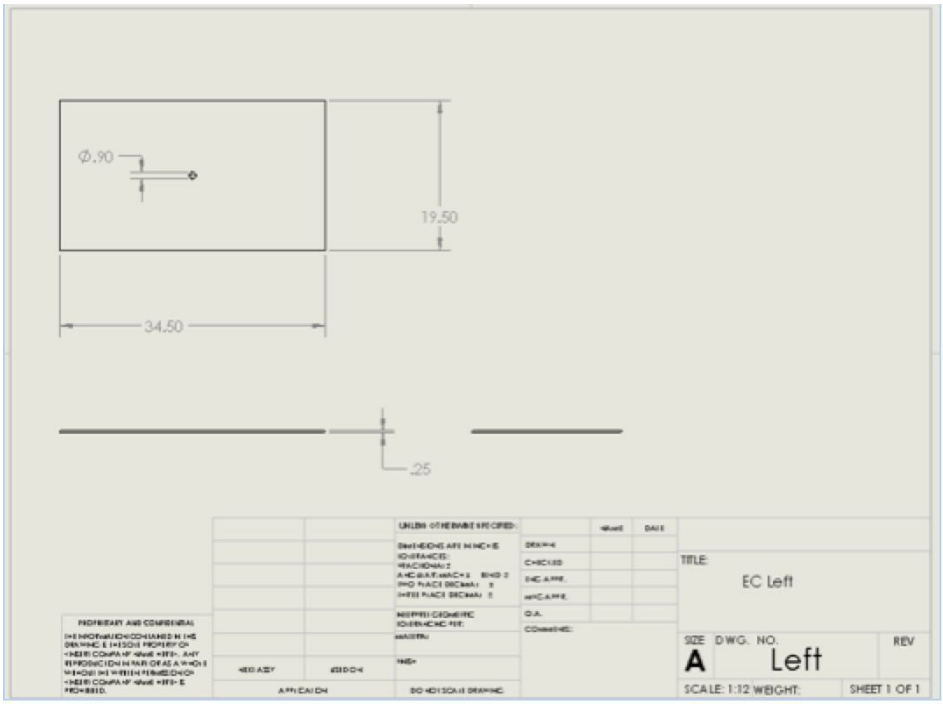


Figure A.8: Left View of Exposure Chamber

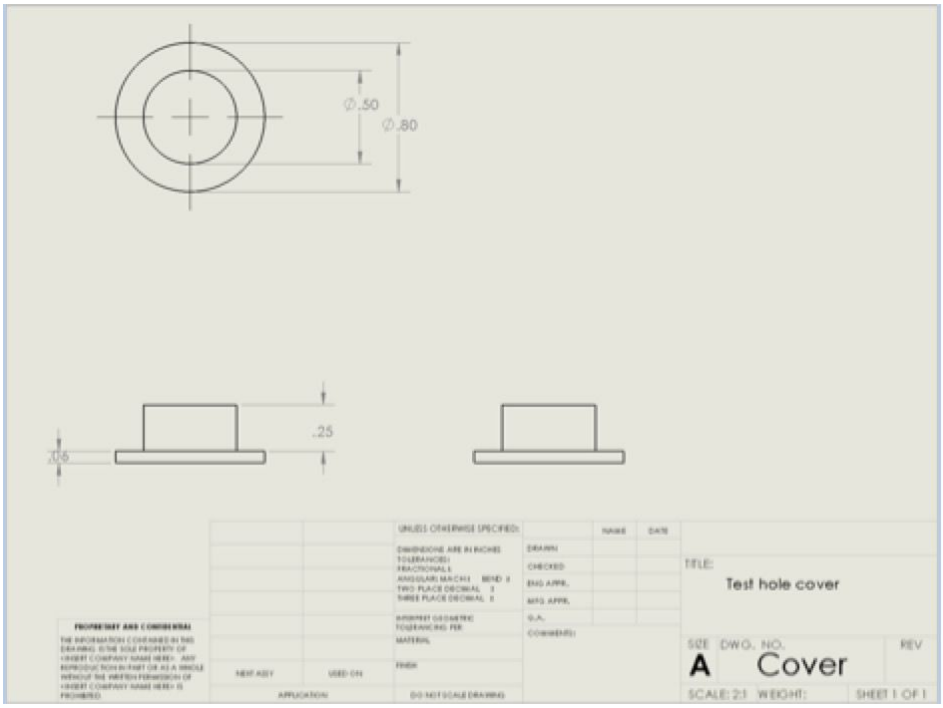


Figure A.9: Plugs for Test Ports that are not in use

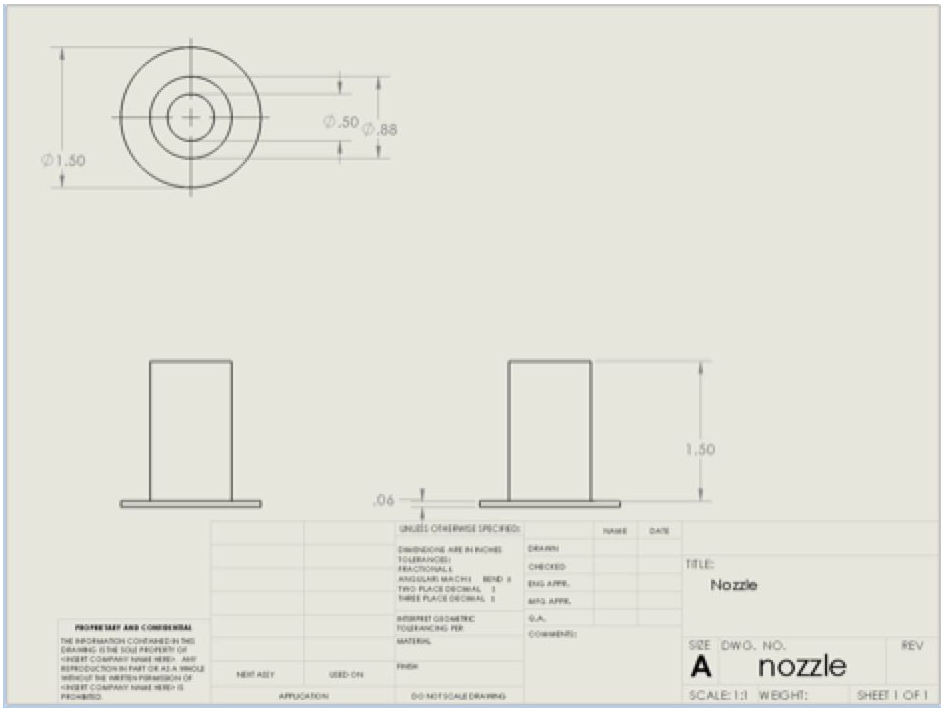


Figure A.10: Design of Custom Nozzles

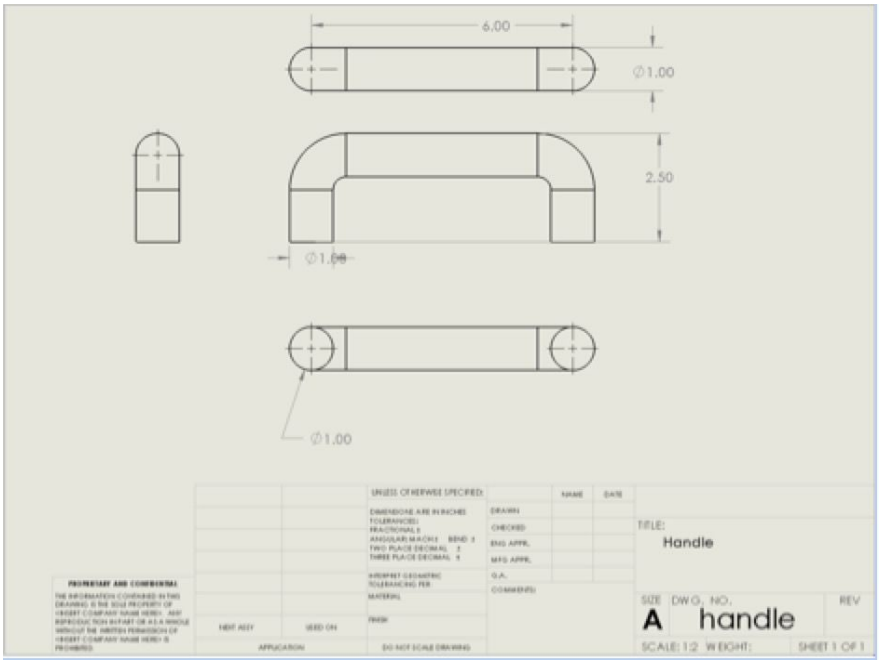


Figure A.11: Design of Door Handle

Appendix B: User Manual

(Refer to Figure 4 for a visual representation)

Part A: Setup of PM generation phase

1. Clean Nebulizer of any sediments and waste from previous exposure (once a week).
2. Connect Compressor 1 to the ¼" air input of the Nebulizer as shown in Figure #
3. Place the nebulizer on the Stir Plate and place the magnetic stirrer inside the nebulizer.
4. Tape the nebulizer to stir plate to ensure it does not fall during exposure period and drop the PM solution on the Exposure Chamber.
5. Connect 7/8" output from the nebulizer to the corresponding inlet in the mixing bucket.
6. Connect 7/8" output from mixing bucket to the inlet labeled to the right side of the Exposure Chamber.
7. Fill nebulizer with 240 ml of warm water (full capacity).
8. Add 1 g of PM in the solution in order to attain 2 g/L in the exposure chamber.
9. Add PM solution with the same ratio of PM to water in the syringe.

Part B: Set up of Dry Air Generation phase

10. Connect Compressor 2 (White) to inlet of Silica gel tube 1.
11. Connect Silica gel tubes 1 and 2 in series.
12. Connect the output of Silica gel tube 2 to the ¼" inlet of the mixing bucket.

Part C: Starting Exposure Period

13. Close Exposure Chamber door.
14. Ensure all test ports (T_1:T_9) are all plugged with caps to avoid leakages.
15. Ensure all tube connections are tightly fitted to avoid leakages.
16. Power on Compressor 1 and 2 and Stir Plate.
17. Throughout the 5-hour exposure, ensure that the nebulizer is running at maximum fluid capacity. In order to do so, please shake the syringe and add fluid every 30 minutes up to the 240ml mark.

Part D: Post Exposure Period

18. After 5 hour exposure period, power off the stir plate and compressor one to put a stop to PM aerosol generation.
19. Leave Compressor 2 running for an additional 10-15 minutes in order to clear out any excess PM through the HEPA filter.
20. Open Exposure Chamber door.

Appendix C: Cradle to Cradle Analysis

Table C.1: List of Materials Used

	Name of Item	Purpose
1	Sodium Chloride	Testing the concentrations
2	Makrolon Polycarbonate	Casing of the exposure and control chamber
3	Bucket	Mixing dry air with PM aerosol
4	Large Capacity Siringe	Re-filling the nebulizer
5	Sillica gel tubes	Drying the air
6	HOBO temp/RH logger	Measuringthe humidity in the exposure chamber
7	Heart Nebulizer	Diluting the PM with water and making it into an aerosol
8	Magnetic Stirrer	Stir the PM in the nebulizer
9	Tygon Piping inner diameter 15/16, 3 feet	Transports the PM to the nebulizer, bucket and inlet
10	Tygon Piping c inner diameter 1/4, 3 feet	Transports the PM to the sillica tubes and bucket
11	Hepa Filters	Cleans the air as it exits the exposure chamber
12	Electric Tape	Used to tape components, and piping on chambers
13	Machine Screws 1/4in - 20 x 1/2in	Fasten both the exposure and control chamber structure
14	Weld on #16/ SciGrip	Holds Malcrom structure of boxes together
15	Compressors	Pumped the air through the pipes
16	1/4 Hex Nut	Fastened the screws in the exposure and control chamber
17	3D Printed Door Handle	Provides the handle for the lids in the two chambers
18	Plexiglass	Material used to lasercut the lids of the two chambers
19	Boltmaster Slotted Angle	Support for the exposure and control chamber structures
20	Environmental Particle Counter	Measures the PM concentration in the cage
21	Stir Plate	Magnetic surface on which the stirer is placed

According to the Cradle to Cradle Banned Substances List, none of the materials we used fall into any of the categories. However, we will take a close look into a few potentially harmful materials used and see whether they are truly harmful to the environment and if so how they can be substituted for materials that are more acceptable.

- Makrolon:- Most post-production waste is mechanically recycled into “recyclate grade” polycarbonate blends.[9] Thus it seems that Makrolon was a good choice in light of C2C principles.
- Silica gel (tubes):- If not disposed of properly, silica gel can harm animal life due to its toxicity. Furthermore, the fact that the tubes have a 6 month lifetime after which they are

disposed of entirely open the possibility of having refillable silica gel tubes as opposed to disposing of the entire enclosure.

- Tygon tubing:- has a long lifetime, longer than most other types of tubing and thus makes it ideal for reducing waste.
- Silicon sealant:- biodegrade easily and poses no harmful effect on living organisms in the environment.

Appendix D: Pictures of Fabrication Process

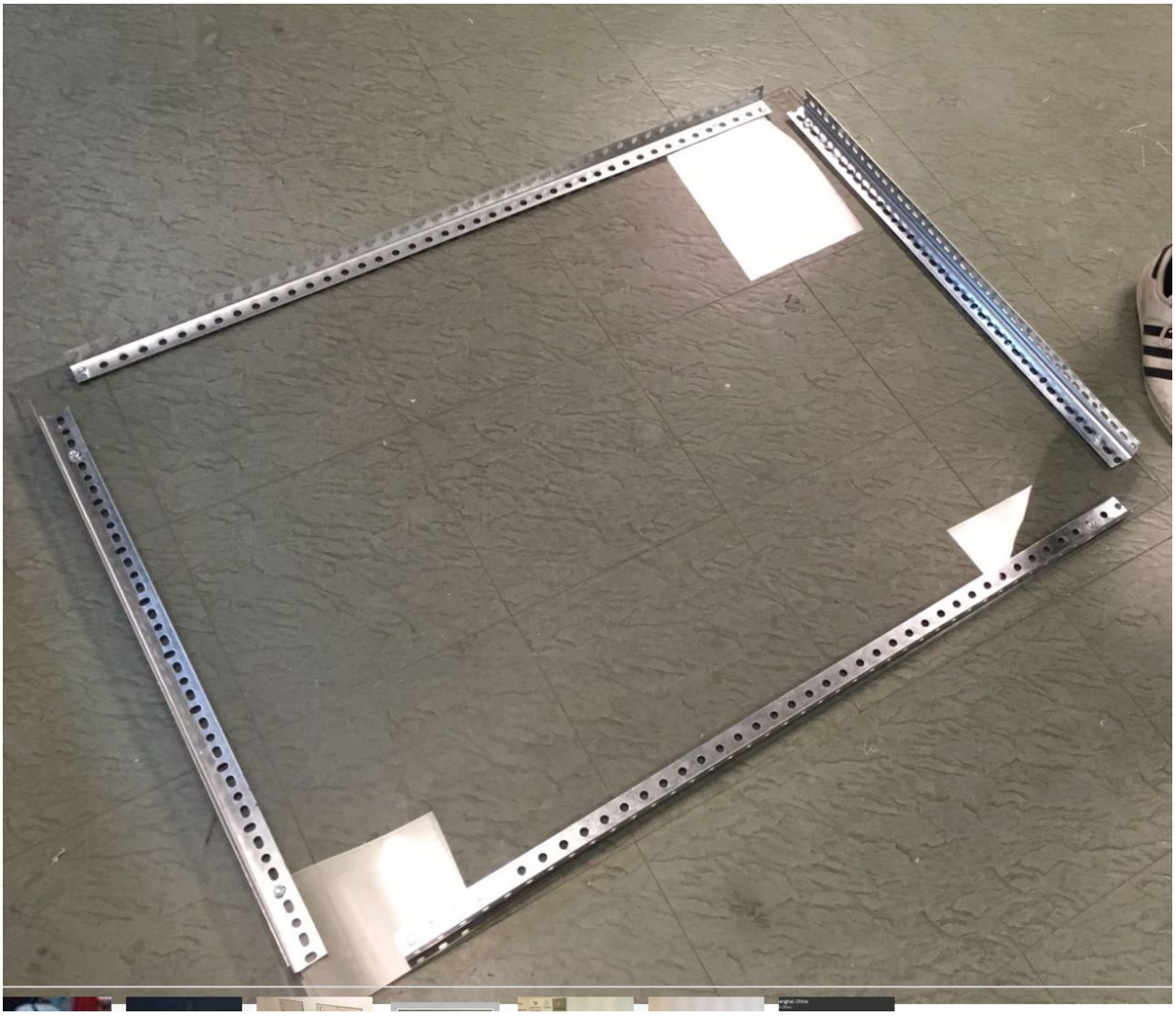


Figure D.1: Building Base

Figure D.2: Using SciGrip and BSA to join sides

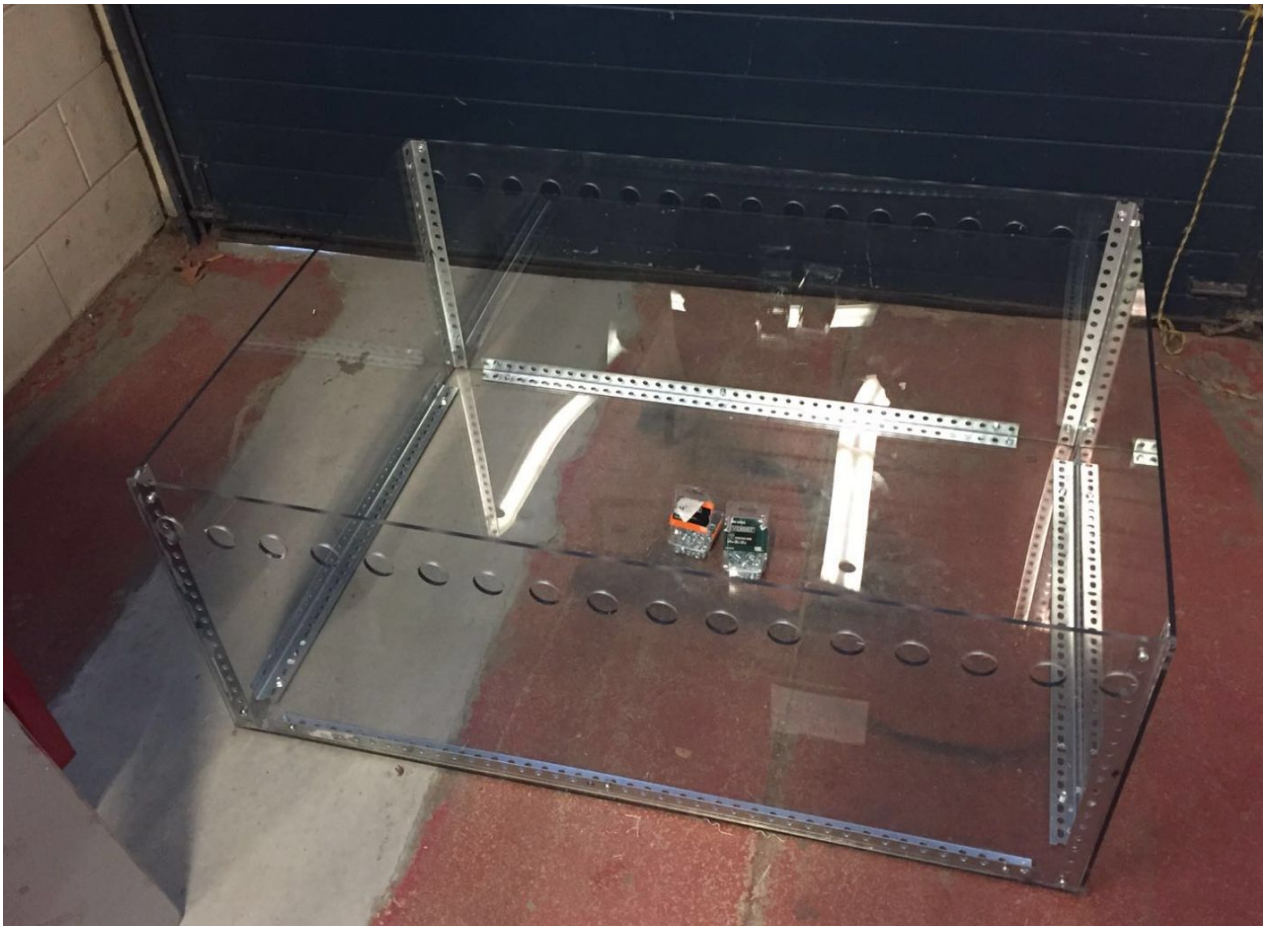


Figure D.3: Assembling all sides of chamber and attaching it to the base

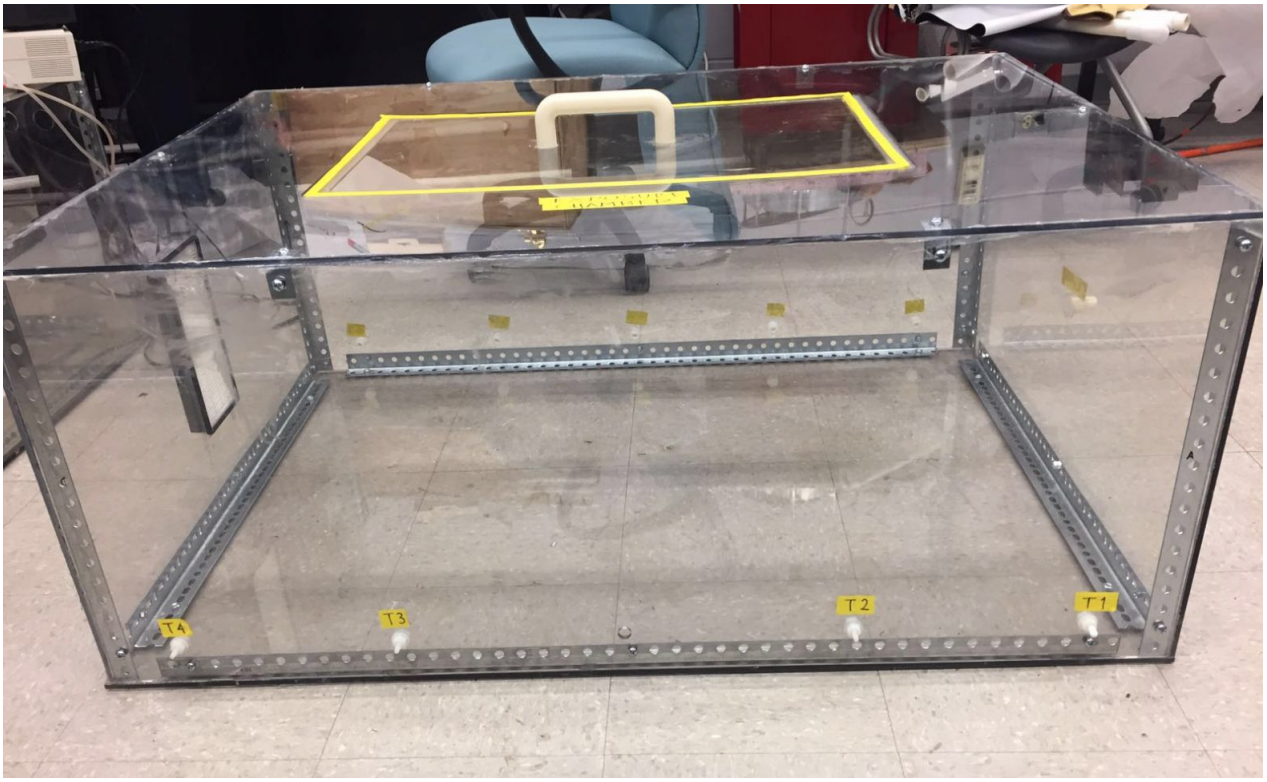


Figure D.4: Final Front View of Exposure Chamber

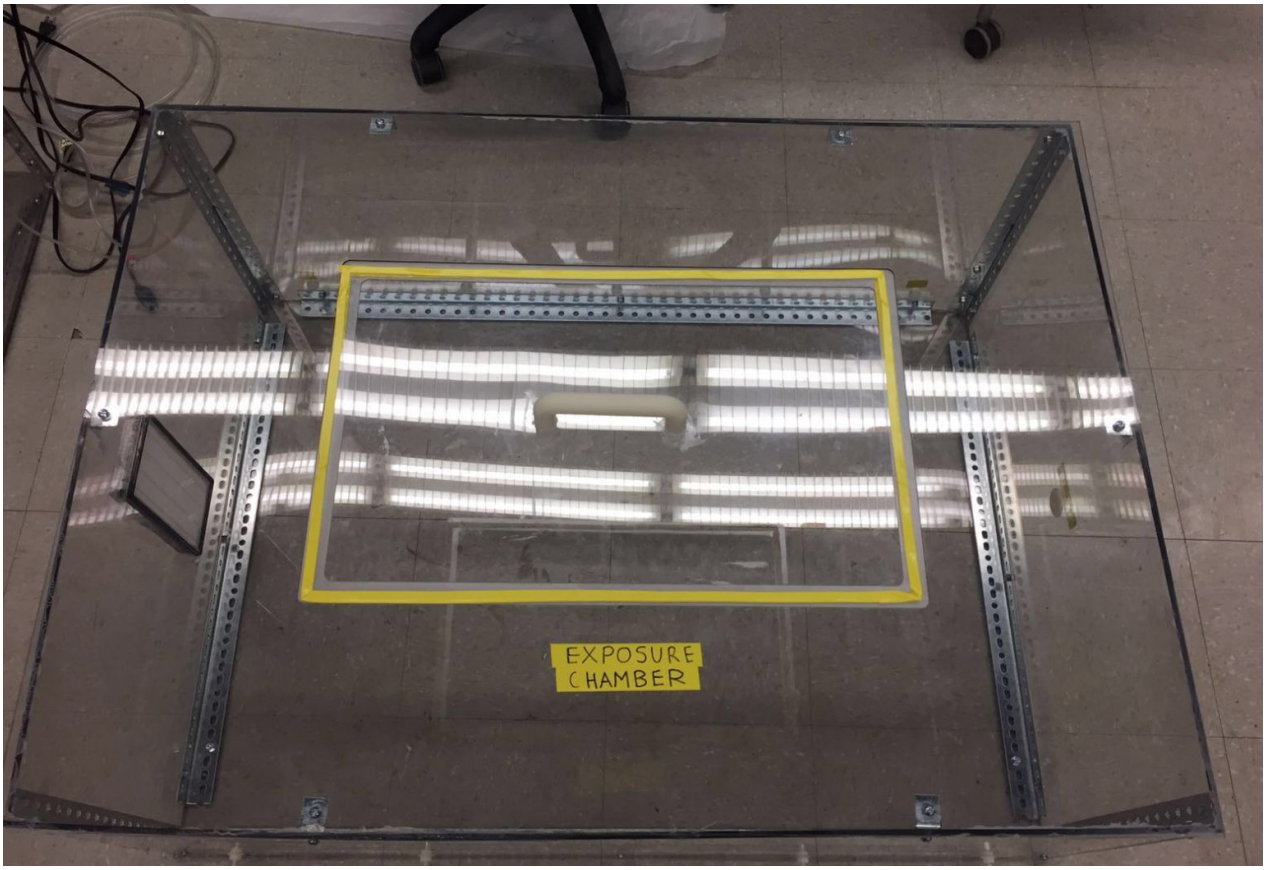


Figure D.5: Final Top View of Exposure Chamber (without setup)

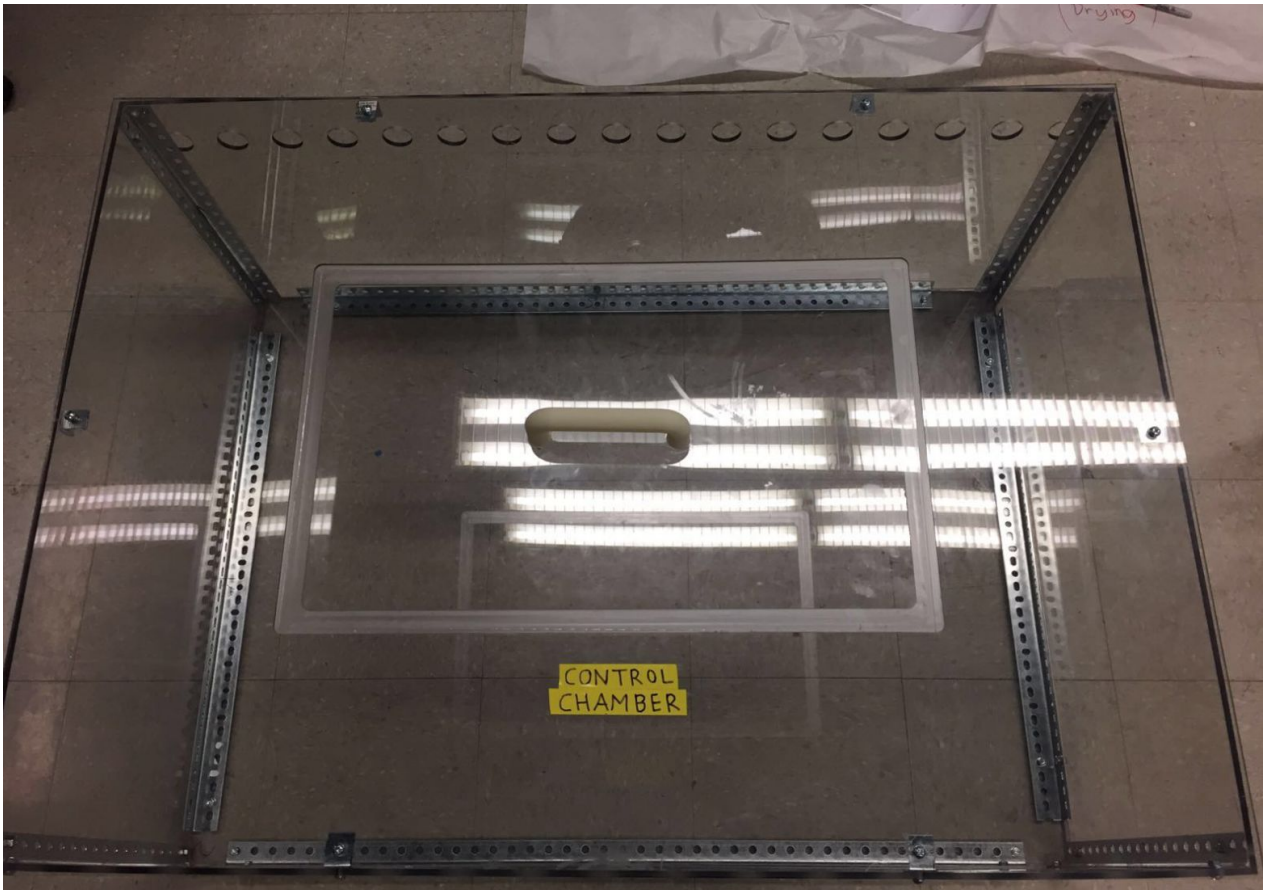


Figure D.6; Final Top View of Control Chamber

Figure D.7: Final Top View of Exposure Chamber with Setup