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An Investigation of the Airborne Particulate Matter Related Health Hazards Present in Makerspaces

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By

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Abstract

Airborne particulate matter poses several health hazards ranging from pulmonary inflammation to cardiovascular disease. Particulate matter is produced through many fabrication processes common to makerspaces, such as 3D printing and laser cutting. The danger of these particles is worsened when makerspaces are retrofitted into spaces not designed with good ventilation or safety controls, such as libraries and public schools. This thesis evaluates the relationship between makerspaces and hazardous particle generation with both continuous and motion sensor controlled ventilation, showing that the latter creates unsafe working conditions. Both observational and controlled studies were conducted in Bucknell's Mooney Lab makerspace monitoring particle concentration and size distributions. A model was created based upon this data to help predict particle concentration and removal rates under a wider range of conditions than studied here. Continuous ventilation reduced peak particle concentrations to a third of motion sensor controlled ventilation levels and brought concentrations back near baseline levels 3.5 times faster. Based upon the findings of this study, makerspaces should not be established in any location without a properly sized ventilation system or to run ventilation systems in any configuration other than continuous flow.

1. Introduction

Though sometimes thought of as a mere nuisance, polluted air can actually pose a serious health hazard to individuals breathing it (1). This pollution is commonly caused by airborne particulate matter (PM), comprised of tiny solids ranging from visible dust down to nanometer-size particles (2). Due to their small size, airborne particles can be difficult to detect and are almost impossible to avoid if not removed from an individual's breathing space.

Because of its potential danger and low detectability without monitoring equipment, identifying sources of PM is key when looking at needed safety measures for air quality. This need is most significant in confined or indoor areas, where natural ventilation is not present to remove PM. In such spaces, ventilation or air purification is needed to protect people present from inhaling these particles.

The objective of this study is to evaluate the generation of airborne particulate matter in makerspaces and the efficacy of their removal by the ventilation systems in place. Makerspaces in particular were studied because these labs have been created in a wide variety of spaces. Some of these retrofitted spaces were not originally designed to house equipment that generates large concentrations of particles. Often the ventilation systems are not updated afterwards either, allowing the danger to persist. This study was conducted in the Mooney Lab, a makerspace at Bucknell University's Dana Engineering building, and focuses on comparing the use of motion sensor activated ventilation with traditional, constant ventilation. These two will be evaluated based upon the concentrations of PM generated and the time that it remains airborne at high levels.

2. Background

2.1 The Hazzard of PM

Particulate matter, especially particles nanometer-scale in size, has been shown to have significant harmful effects on the human respiratory system (3) (4). Correlations between exposure to PM and an increased pulmonary mortality have been observed with a wide variety of particle types (5) (6). The nanometer-scale particles, also known as ultrafine particulates (UFPs), can cause significantly more irritation than larger particles when inhaled (7). Through prolonged exposure, human studies also observed that high concentrations of UFPs caused an unhealthy change in lung physiology (1).

In addition to pulmonary illnesses, metallic UFPs have been observed absorbing into the bloodstream through the lungs, presenting a further hazard in areas where they are generated (8). This phenomenon allows the toxic particles to travel throughout the body, with studies finding inhaled material in major organs and throughout the bloodstream. Other studies have found that these UFPs may also travel directly to the brain via the olfactory nerve sheath, bypassing the bloodstream entirely (9). The absorption of nanoparticles into organs like the heart, lungs, and brain is correlated to an increased risk of cardiovascular illness, atherosclerosis, and cancer (10). In general it is true that the smaller the PM particles are the more hazardous they can be to the human body, passing through membranes and tissue with less resistance.

2.2 Identified PM Generators and Makerspaces

Makerspaces, or facilities dedicated to providing public access to tools for making, are growing in popularity throughout the United States (11). As new tools and equipment like 3D printers and laser cutters become more widely used in makerspaces, the hazards associated with these machines are experienced by a growing number of people. While many of the physical hazards in these spaces are well known, the issue of air quality is more easily overlooked by many makerspace users. This danger is exacerbated when makerspaces are created in less regulated settings such as libraries, community centers, and public schools (12). When makerspaces are setup in these kinds of locations, ventilation system modifications are not always made to accommodate the new PM generation sources. The danger in these spaces is made worse when the hazards of airborne PM in unknown to lab users, which is likely the case for school students and hobbyists. It is for this reason that this project aims to quantitatively analyze this risk, hopefully bringing to light areas where makerspaces might fail in protecting their users.

Tools common to makerspaces, such as 3D printers and laser cutters, have been shown to be UFP generators. 3D printers, which must melt and heat plastic to function, produce significant amounts of airborne particulate matter (13). The bulk of the UFPs from 3D printers were 10 nm or less in diameter, furthering the hazard to users (14). Laser cutters, which burn concentrated areas of material, generally produce even more particulate matter than 3D printers. These machines have been observed creating particulate concentrations in the millions per cubic centimeter with sizes from 7 nm to 1000 nm (15). While these devices are usually coupled with their own ventilation system, portions of the produced PM can escape.

An additional source of airborne PM generation in makerspaces is the use of hot or liquid metals. Small metallic PM is usually more toxic to the body compared with other types of materials (9) (16) (17). Many commonly used makerspace tools utilize heated metal components to function, such as 3D printers, soldering irons, welding equipment, and laser cutters. Devices like laser cutters, welders, and soldering irons also cut or melt metal materials when operating, a process shown to emit large concentrations of metal PM into the air (17). Inhalation of these particles can cause ailments like asthma and lung irritation and, in cases of long term exposure, may even affect the body's immune or reproductive systems (18) (19).

3. Methodology

The experimental methodologies used in both the observational and controlled experiments detailed in the following sections was kept the same. That method is detailed in this section along with an explanation of how the equipment used operates. Unique aspects of both studies are detailed within their respective sections.

All testing was conducted in the Mooney Lab in Bucknell University's Dana Engineering building. This makerspace, shown in Figure 1, is 30 feet long by 28 feet wide and has a ten-foot high ceiling, giving a total room volume of 8,400 cubic feet. Two ventilation ducts run along the width of the ceiling, ten feet apart, centered on the room's midpoint. These ducts bring in clean air from outside the building and vent room air outdoors with an air exchange rate of 11, a typical value for lab spaces. During the experiments, air flowrate through the ventilation system was measured with an anemometer at the vent inlets to determine the status of the ventilation system.

The primary particle generating machines in this lab are the 3D printers and the laser cutter. There are five 3D printers in total, each of which can print using polylactic acid (PLA) and acrylonitrile butadiene styrene (ABS) plastics. Two printers are Ultimaker model 2+ Connects and the remaining three are Makergear model M2s. The laser cutter, a 75W Epilog Fusion, is paired with a BOFA fume extractor which is meant to be used when the cutter is running. This fume extractor is a high flowrate ventilation system specifically for the laser cutter.

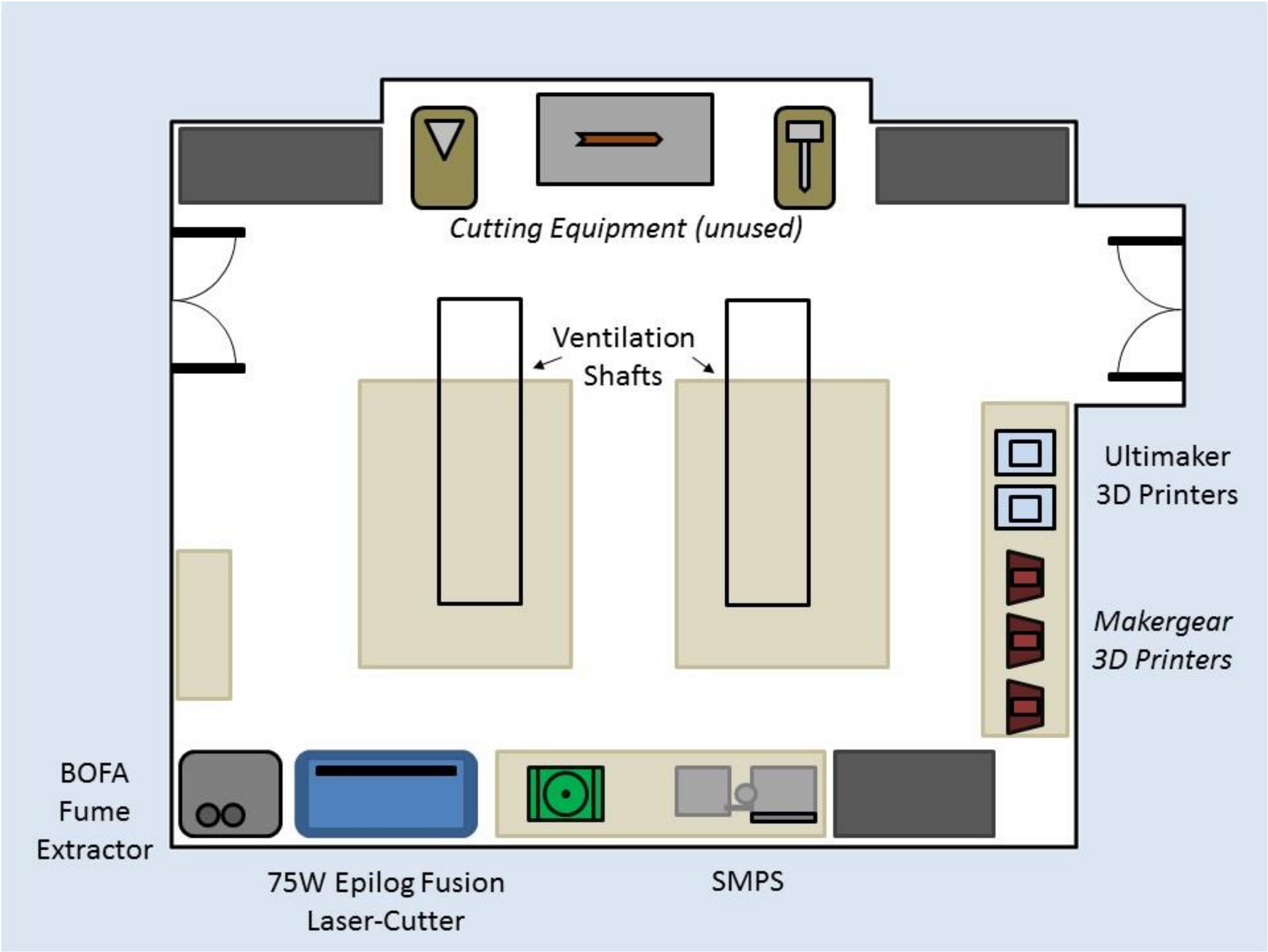

Figure 1: This diagram of the Mooney Lab, as it was during the testing for this thesis, shows the location of the sampling equipment (SMPS & CPC) and the particle generators (Laser-Cutter and 3D Printers). Ventilation ducts run through the room from top to bottom above the beige, central rectangles (tables).

Particle concentration and size measurements were taken using a scanning mobility particle sizer (SMPS), a system comprised of a differential mobility analyzer (DMA) and a condensation particle counter (CPC). These two devices are often used to measure particle concentrations at different sizes between 10 nm and 1 micron. In this study, the largest particles measured were 500 nm – a size range encompassing the particles of primary health concern (20).

The DMA, described in Figure 2, segregates particles based on their electric mobility as they pass through an electromagnetic field (21). To do this, incoming particles are charged to a fixed value through exposure to beta radiation given off by a krypton-85 source. This process, known as neutralization, is accomplished when beta particles emitted from the krypton collide with PM, ionizing it by stripping off electrons up to a specific charges following the Boltzmann distribution (20). Giving the particles a known charge allows the DMA to apply a controlled force upon them, as electromagnetic force depends solely upon particle charge and the strength of the magnetic field. Keeping air conditions constant, a particle's acceleration in response to a given force depends solely upon its size. In this way, the DMA can determine particle size by correlating it to how much the particle is affected by an electromagnetic force, or its electric mobility.

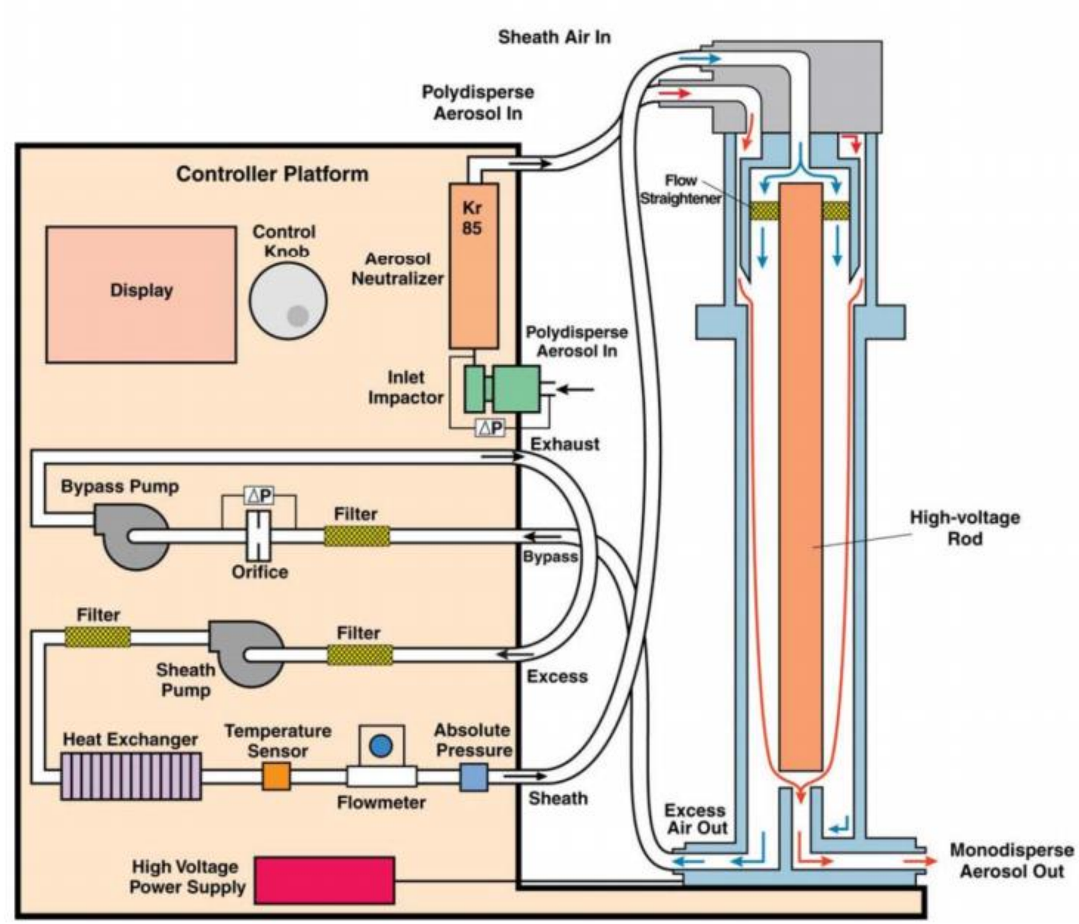

Figure 2: This diagram of a DMA, taken from C Kuang's SMPS Instrument Handbook, shows a typical DMA flow configuration (21). Sample (polydisperse) air is passed through a Kr-85 source to neutralize it. This then mixes with the sheath air and flows through the column's varying electric field, allowing only specific particles to be sent onwards to the CPC (monodisperse outlet).

To measure the particle's electric mobility, or sensitivity to an electromagnetic force, air containing the neutralized particles is passed through a cylinder, or sheath, containing a central rod emitting a variable electromagnetic field. Based upon the strength of the field emitted, the particles are subjected to a known magnetic force pulling them towards the rod. Only a particular size of particles will pass through the length of the sheath and out a slit at the end, as those too large will collide with the outer walls of the sheath and those too small will stick to the rod running down the center. This sorting process can be thought of like a rocket fired at a target. If the rocket is heavier than expected, gravity pulls on it more and it hits the ground; if the rocket is lighter, gravity pulls it less than expected and it overshoots the target. In this way, the electric mobility of a particle allows segregation by the particle's size.

The air fed into the DMA sheath is a combination of filtered air and raw air pulled directly from the room. The additional, HEPA filtered air is used to achieve a constant volumetric flowrate and to dilute the sample air, which contains the particles to be sorted, by a known ratio. This air flowrate is referred to as the sheath flow. Before being combined with the filtered air, the sampled air is passed through an impactor to remove particles much larger than the scanning range such as dust.

The CPC then counts the sorted particles fed to it directly from the DMA. This is done by detecting them as they pass through and scatter the light from a laser. Because UFPs below 50 nm are difficult to detect in this way, all particles are first passed through a chamber saturated with butanol. This air is then passed through a cooler which causes the butanol to condense on the particles to increase their size. This stream of particles is then passed through the laser where they are counted. The CPC has automatic adjustments programmed to account for multiple particles passing through the laser simultaneously when concentrations are high.

The SMPS was run with a sheath flowrate of 4 lpm. The DMA increased and reset its voltage repeatedly such that each cycle scanned for particles from 10 nm up to 500 nm. These scans were divided into a 105 s up time, where particles were measured, and a 15 s down time where voltage was removed and the system was reset, totaling in 2 minutes per scan overall. Many of these individual scans over the range of particle sizes make up an experimental run. The CPC was run in low flow mode, pulling 0.3 lpm of air from the DMA. For each run these instruments were placed in the same location in the Mooney makerspace as shown in Figure 1 to ensure comparability of the data.

4. Observational Makerspace Analysis

4.1 Preliminary Observations

Because of the connections between particle generators and the health risk of PM, an initial study was completed to assess the risk of airborne particulate exposure in makerspaces, starting with the Mooney Lab in Bucknell's engineering building. This study was observational in nature and did not involve constraining either the makerspace itself or any activities within it. The goal for this study was to observe concentrations resulting from natural makerspace usage to determine if creating hazardous conditions was possible and potentially already occurring.

Particulate concentrations and size distributions were recorded for several weeks, as shown in Figure 3. Analyzing the data resulted in several key findings relating both to the generation and removal of airborne PM in this environment. First, the generation of concentrated PM was verified in the makerspace which contains 3D printers, soldering equipment, laser cutters, and similar tools. The second key finding was that concentration of the PM in the makerspace varied to a level that was unexpected. Concentrations were observed spiking to levels much higher than those reasonable for an indoor, ventilated lab space. These variations in concentration created conditions in the space that were hazardous to any individuals who might have been present at that time.

4.2 Hypothesis & Testing

Upon investigating the cause of the unexpected spikes in PM, it was discovered that the ventilation system was being run via motion detectors in the room. These sensors, which also controlled the lighting, were being used in an effort to save electricity by shutting off the ventilation when no one was present in the lab. It was theorized that when the sensors shut off the ventilation machines still running were able to generate the large concentrations observed.

To test this theory, the ventilation was switched to a continuous operating mode. The goal was to observe if large, hazardous concentration spikes were still observed and, if so, to what extent they were decreased. Figure 3 shows the concentration data taken in the Mooney Lab before and after this change was made. Before the change, several high concentration events are visible. For reference, the background concentration in the space is around 3,000 particles per cubic centimeter, meaning that the worse peak was more than 1,000 times higher this level.

A clear decrease in high concentration events was present after the switch. The frequency of events observed before and after the ventilation mode was changed remained roughly constant. Because of this, it was hypothesized that the reduction in PM concentration was attributable to the change in ventilation system and not to a change in the makerspace’s use. The largest concentrations observed with continuous ventilation were all less than 500,000 particles per cubic centimeter, or roughly 150 times more than the background concentration.

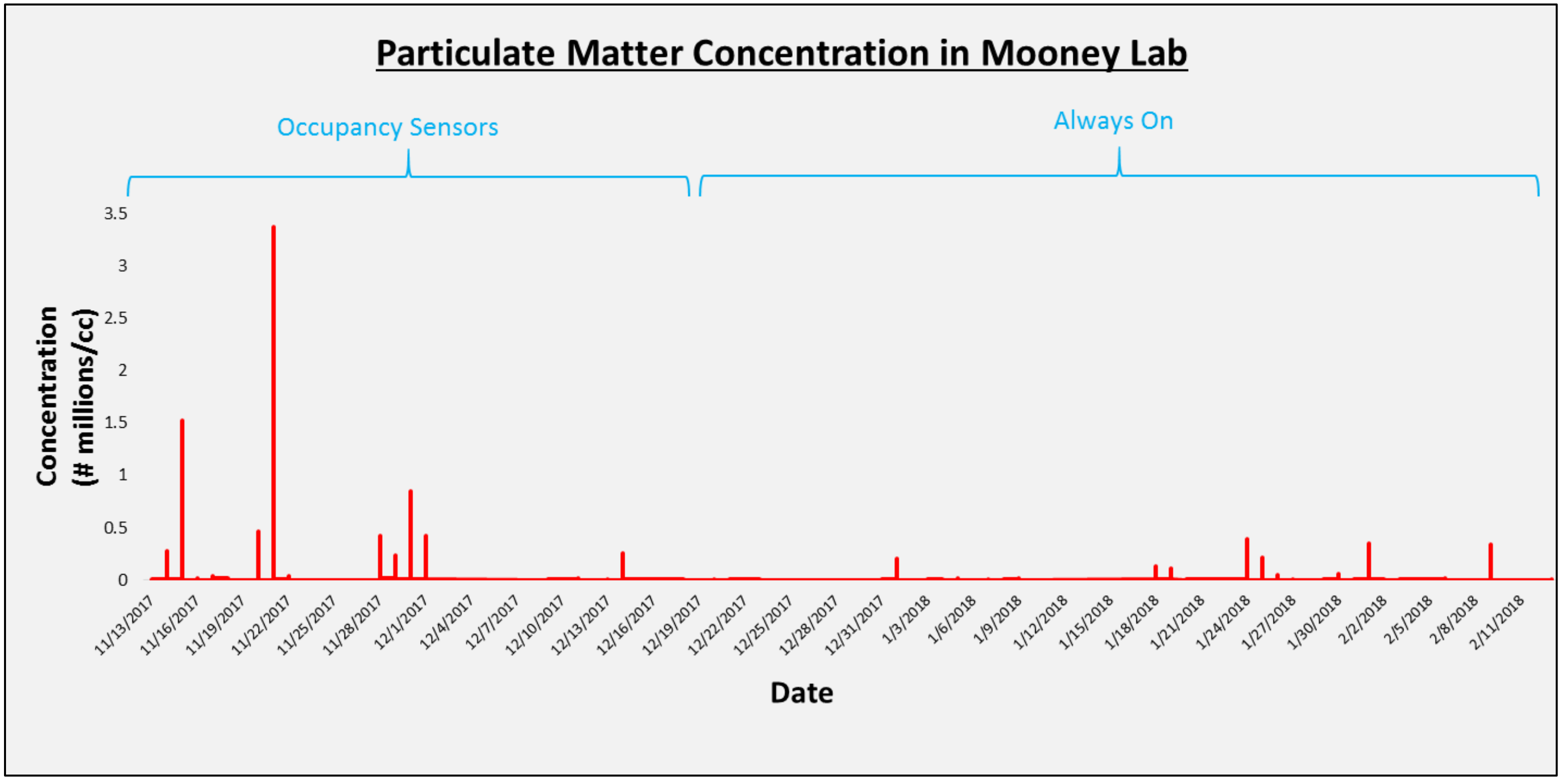

Figure 3: Observational data on PM concentration in Mooney lab shows a clear decrease in large, hazardous spikes after motion sensor ventilation was discontinued. The number of PM generating events is roughly the same in both motion sensor and continuous ventilation observation periods. The "Always On" and "Occupancy Sensors" ranges in blue refer to which ventilation mode was used at that time.

While this study gave credibility to the theory that motion sensor ventilation poses a potential hazard to makerspace users, it could not definitively conclude anything due to being observational in nature. Because the peaks generated could have inconsistent generation events based upon varying student usage of the lab, it is not fair to say that changing the ventilation was the sole reason large spikes in concentration were no longer observed. To further explore this question, a controlled study was needed. This was accomplished in the manner described in the following sections.

5. Controlled Makerspace Analysis

5.1 Controlled Experimental Setup

To determine if a definite relationship could be drawn between the Mooney Lab's ventilation setup and hazardous particle buildup, measurements of predetermined, controlled particle generation in the makerspace were conducted. While a general connection between ventilation and PM concentration could be simply inferred, these tests were meant to determine to what extent this issue might actually occur and what level of danger could exist for given ventilation configurations.

Based upon the results of the observational study in the Mooney Lab, motion sensor controlled ventilation was the primary experimental factor being evaluated. The main goal of the testing was to measure what levels of PM concentrations could be reached while lab machinery was in use and how quickly these levels decay to background levels. Additionally, the particles in the air would be cataloged by size, allowing calculation of a mass concentration in addition to the number concentration. Particles above 500nm were not measured again due to equipment constraints, meaning that number and especially mass concentrations were higher than the values collected in actuality. These larger particles are less harmful when inhaled and settle out of the air much faster compared to those below 500 nm (22) (2).

For comparison, trials were also conducted in the lab with constant ventilation. These runs would serve as the benchmark the motion sensor runs would be measured against. Running with no ventilation whatsoever was deemed unhelpful and was not done as there is no evidence to suggest that doing so would be a safer alternative or that makerspaces without any ventilation are typical.

5.2 Experimental Procedure

Air sampling was done in individual, controlled runs. A run comprised many scans over a long period of time while the makerspace had one of the two ventilation setups. Multiple runs were conducted under the same conditions to verify any relationships in measured data. Each run consisted of two general phases, particle generation and particle dissipation. The goal of this approach was to ensure comparable particle levels were generated in each run. Sampling would cease once a sufficient amount of time had elapsed, such that the particle concentrations after the run were back near the room's baseline levels.

The timeline of a run, consistent for every run, was as follows and can be seen in Figure 4. Sampling, constant through both phases, started prior to the generation phase by 30 minutes. The generation phase was then initiated 30 minutes after the sampling started and would totally conclude after six hours. During the dissipation phase no particles were intentionally generated, but particle concentrations were still monitored for the next 6-8 hours.

During the generation phase of each run, three Makergear and two Ultimaker 3D printers were started. At the same time, a plywood cut job was started on the laser cutter. The 3D printers would all run until the end of the six hour generation phase. The first laser cut job would finish 30 minutes after the start of the generation phase, the laser cutter would be allowed to rest for 5 minutes, and then a second acrylic cut would begin and last for another 10 minutes. All personnel would then leave the lab for the remainder of the run. During motion sensor runs, this would cause the ventilation to stop about 45 minutes into the generation phase, or 75 minutes after sampling started.

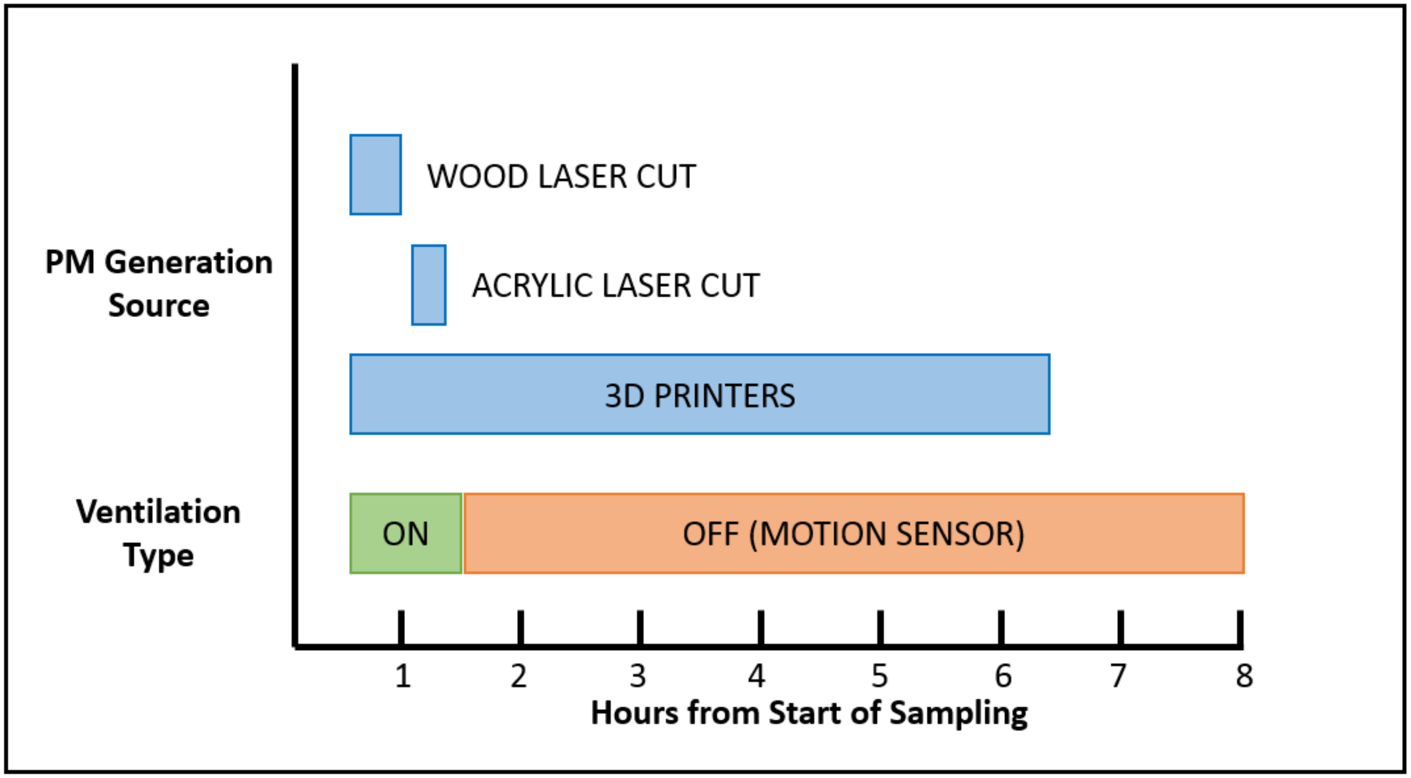

Figure 4: Timeline of the controlled sampling runs. To simulate the exact motion sensor system present in the observational study, ventilation is turned off 1.25 hours after sampling. The generation phase ends after 6.5 hours from sampling when the 3D printers finish their print job.

5.3 Data Processing

The data generated by the SMPS in each run consists of the concentration of each particle size from 10 nm to 500 nm over a number of scans. These concentrations were taken once for each particle size during a given two minute scan. To analyze this data, the concentrations of all particle sizes could be summed to give an overall concentration versus time trend. Another option was to evaluate the data in three dimensions, letting particle size be the third axis. Due to the complexity and sheer amount of numbers generated in these runs, Matlab programs were used in analyzing and plotting the data.

6. Discussion

6.1 Experimental Results

Throughout the course of the controlled runs, anemometer data from the ventilation system showed that there was little to no variation in air flowrate from one run to the next. Additionally, the ventilation system behaved as planned, shutting off around 75 minutes into the motion sensor ventilation runs. The average ambient temperature was also held constant between runs, fluctuating between 20 and 22 C. Relative humidity data from the ventilation exits indicated that the humidity of the lab never reached above 26% or below 12%. All of this suggests that the runs were well controlled and should be comparable based on consistent ambient conditions.

Three controlled runs were conducted for both continuous and motion sensor ventilation configurations. Representative runs were selected for data analysis and comparison. These runs were selected because they contained the least issues with data collection resulting from disturbance variables such as machine malfunctions, weather events, or people entering the lab during sampling. It should be noted that all datasets show a similar trend in particle concentration and size distribution.

Figure 5 shows the average concentration of particles by mass generated in both type of runs. Raw data for each run was smoothed using a running average over 5 samples to create a clearer trend. For this analysis, unit particle density, or 1 g/cm^3, was assumed for all particles. As typical particle densities are higher than 1 g/cm^3, this is a conservative estimate of actual mass concentrations present during the sampling.

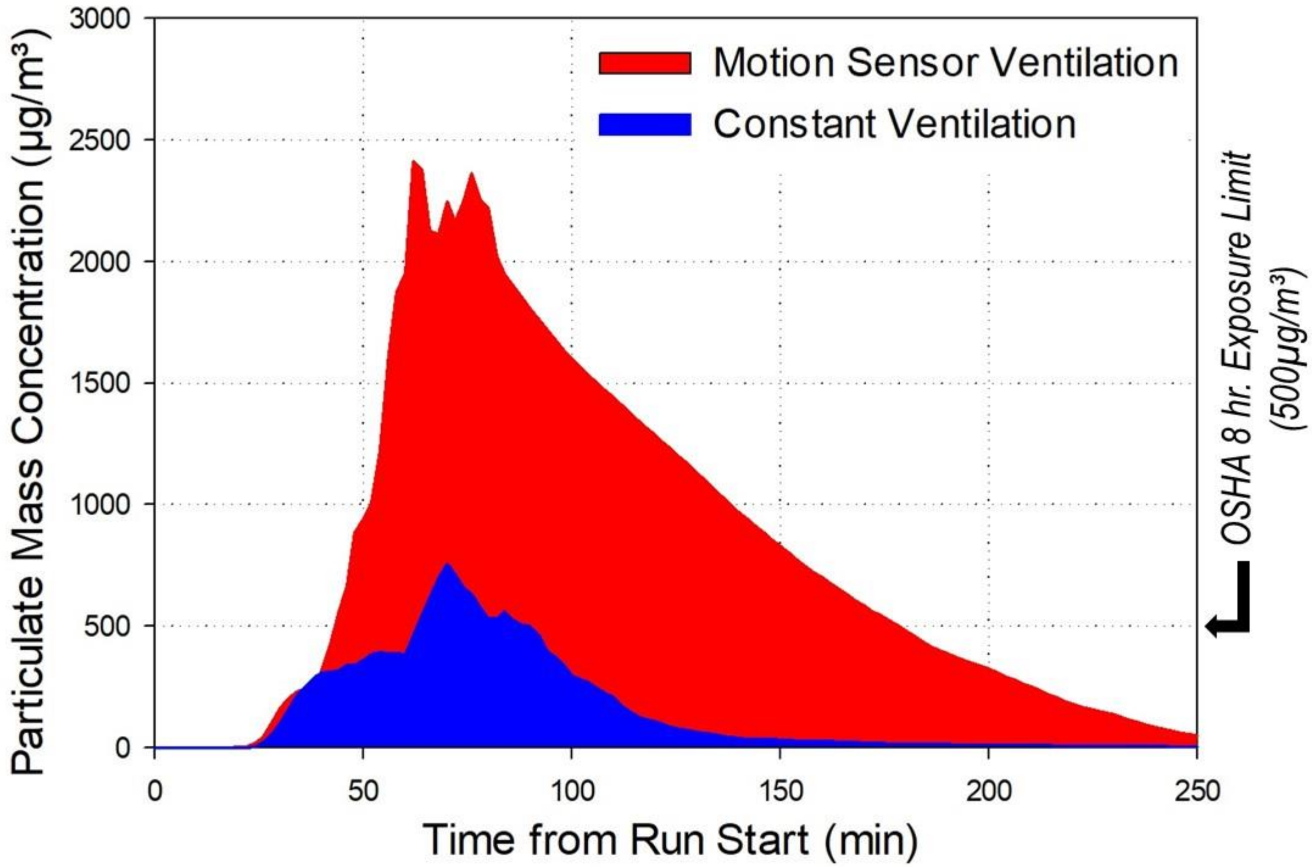

Figure 5: Graph of total mass of particles from 10nm to 500nm generated in makerspace for runs with constant ventilation and runs with motion sensor activated ventilation. Motion sensor runs have both a slower concentration percentage reduction and a higher overall concentration. The peak concentration for motion sensor runs is roughly 3 times larger and decay takes 3.5 times longer. Note that actual mass concentration, taking into account particles larger than 500nm, would be notably higher.

A clear conclusion from the data shown above in Figure 5 is that once personnel leave the laboratory space, motion sensor activated ventilation no longer removes particles effectively. This results in a much higher overall concentration, roughly 3 times more in this study, and requires a significantly longer period of time to return to normal UFP levels. This is not observed with the motion sensor runs, meaning that the concentration reduction by percentage of total concentration is worse than that of the constant ventilation run.

These findings also verify that hazardous particle levels can be intentionally generated in a makerspace using common equipment, like 3D printers and laser cutters, even with continuous ventilation. The highest concentrations reached in this experiment in both the constant and motion sensor ventilation runs would be hazardous to humans for prolonged periods of exposure. Each rises above the OSHA 8 hour exposure limit during the run. The constant ventilation runs had PM concentrations at or above the 8 hour exposure limit for less than an hour. The motion sensor ventilation runs performed much worse, with observed particle concentrations up to four times larger than the OSHA 8 hour limit present for much longer, staying above the OSHA 8 hour limit for over two hours. The average time required to bring PM levels below the OSHA 8 hour limit was roughly 4 times longer using motion sensor systems due both to the higher concentrations and lack of air ventilation.

It should be noted that the OSHA standard is included for comparison and educational reasons, not because official OSHA testing was done. Hazardous conditions were definitively observed, but cannot be truly compared to any OSHA standard. As mentioned above, total PM mass concentration was likely underestimated by assuming unit particle density. Additionally, the use of high efficiency filters and gravimetric analysis is required to conduct actual OSHA air quality studies, while only SMPS sampling was used in this study.

Figure 6 shows average PM concentrations and size distribution over the course of the runs. The redder areas of each graph indicate higher particle concentrations, corresponding to the color concentration axis on the right. The concentration axis was capped at 100,000 $\#/cm^3$ so that both plots could be compared with the same axis. The motion sensor run had much higher concentrations than this limit, most notably directly after the laser cutting portion of the generation phase when the ventilation turned off. The constant ventilation run had peak concentrations only slightly above 100,000 $\#/cm^3$.

Capping the concentration axis allows for more visible comparisons of the size distribution of particles over time, something not attainable from Figure 3. The motion sensor controlled runs had exposures at or above the 100,000 $\#/cm^3$ concentration cap for twice as long as the constant ventilation runs. It should also be noted that the dark blue regions in each graph also contain significant particle concentrations, far above the typical background concentrations indoors of 3000 $\#/cm^3$.

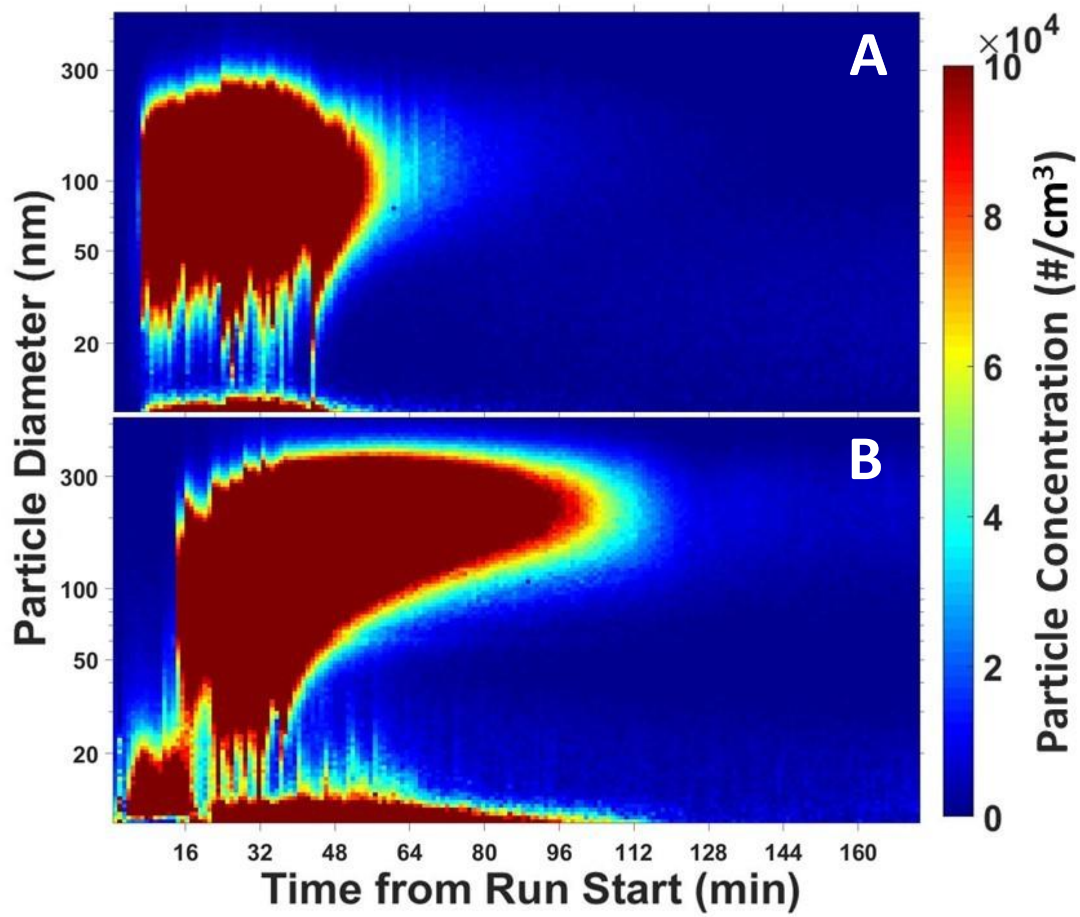

Figure 6: These plots shows particle concentration and size distribution over the course of the runs. Plot A is the constant ventilation run. Plot B is the motion sensor ventilation run. The concentration axis is capped at 100,000 #/cm^3 so that the constant ventilation run is more readily compared to the motion sensor run.

From this data it is evident that two particle size modes are present – larger particles with diameters from 100nm to 300nm and smaller particles with diameters from 10nm to 20nm. Particle size trends upward over the course of the runs due to particle coagulation, where smaller UFPs stick together to form larger particles. The larger diameter particles have a higher settling velocity and are thus more likely to be removed from the air through non-ventilation means such as gravitational settling. The smaller, UFPs settle out of the air at much slower rates, making them hard to remove without ventilation. These principles are observed in Figure 5, particularly when comparing the concentration over time of the smallest particles on the bottom edge of each graph.

The PM data was evaluated at the peak concentrations to further understand the distribution of particles present. This analysis, shown in Figure 7, looks at the particle concentrations at 50 minutes into the run when mass concentration was highest. These plots are generated from a single two minute DMA scan. From the number concentration plot the two size modes of particles mentioned above are again present. This plot also shows that the larger diameter mode is itself somewhat multimodal, with local maximums at 60 nm, 110 nm, and 180 nm. The mass concentration plot demonstrates how PM mass increases rapidly as particle diameter increases, meaning that despite having many small particles the bulk of the PM mass observed was from larger particles.

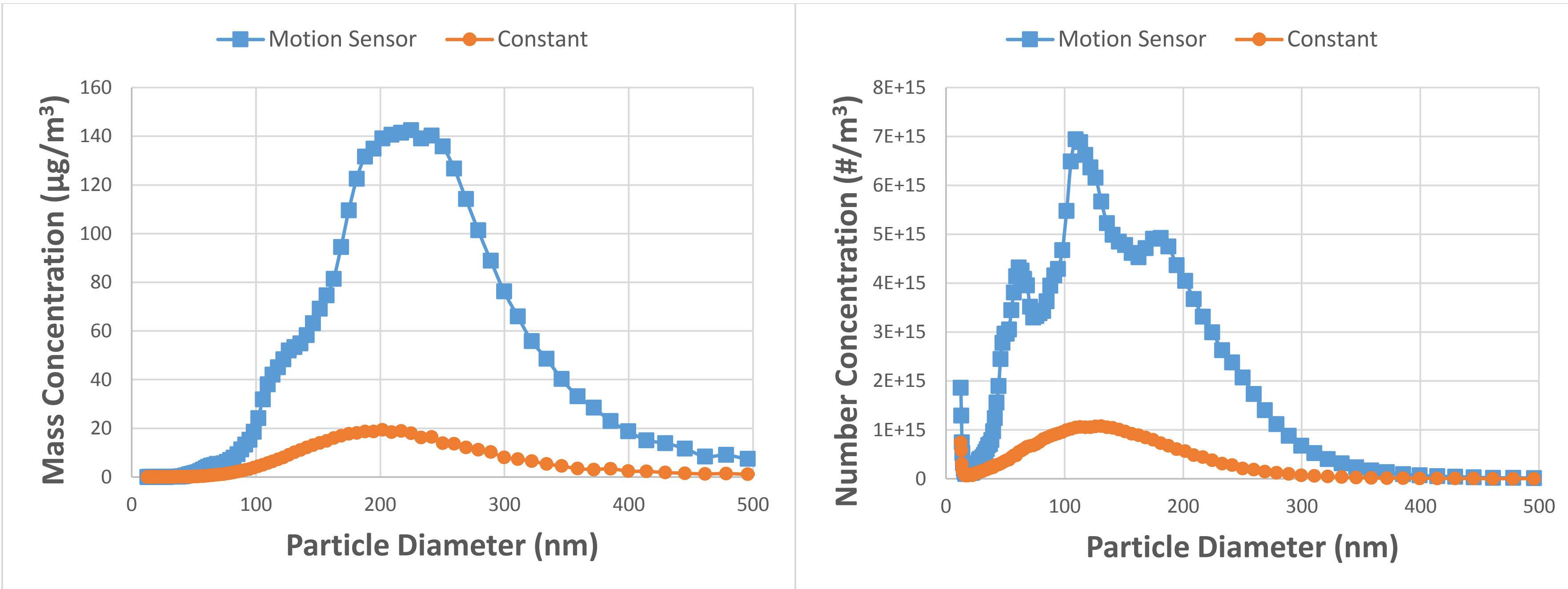

Figure 7: These two plots were generated from the DMA scan starting 50 minutes into the representative motion and continuous ventilation run. The left plot shows mass concentration verses particle diameter, revealing that the majority of the PM mass concentration is from particles 150-300 nm in diameter. The right plot shows number concentration verses diameter, revealing that there were a greater number of smaller particles generated than larger, with several distinct modes.

6.2 Mathematical Model

To assist in describing what was observed in these experiments, a simple model was created to describe the generation and removal of PM in a ventilated space. This model follows the general form of a mass concentration balance, as shown in the equation below:

$$\text{Gen.} - \text{Vent.} - \text{Set.} = \text{Acc}$$

The generation term (Gen) describes how much PM mass per minute is emitted into the air. The ventilation term (Vent) describes what amount of mass is removed from the air each minute as determined by the air exchange rate of the makerspace. The settling term (Set) is a fraction of the room's PM concentration that is removed from the air by non-ventilation means. The settling percentage in this model is kept constant over the course of the run. This model considers PM mass as a whole and not individual particles, though in real systems particle settling behavior is size dependent. The accumulation term (Acc) is the rate of change in the PM concentration.

This mass balance was turned into a Matlab program, detailed in appendix A, so that the experimental results could be modeled. The goal was to recreate the shape of the motion sensor run concentration curve, shown in Figure 5, with the simulated mass balance. To do this, specific times were programmed when generation or ventilation would stop. Generation and settling term values were changed incrementally to best fit the empirical results. Ultimately, it was determined that two generation terms, one for the 3D printers and one for the laser cutter, most accurately modeled the data. The laser cutter term generation was 20 mg/min and the 3D printers was 5 mg/min. Ventilation term values were kept consistent with those observed in the actual Mooney Lab, having a ventilation rate of 1500 ft^3/min.

Figure 8 is the resulting graph of PM mass concentration generated by this Matlab program for motion controlled ventilation. When compared to Figure 5, it can be seen that this mass balance approximates the empirical values fairly well. This model is intended to be useful in predicting PM concentrations in other makerspaces with their own ventilation and generation conditions. This model may also be used to estimate concentrations with continuous ventilation, however, a plot of this was not included because the empirical data did not strictly follow the model.

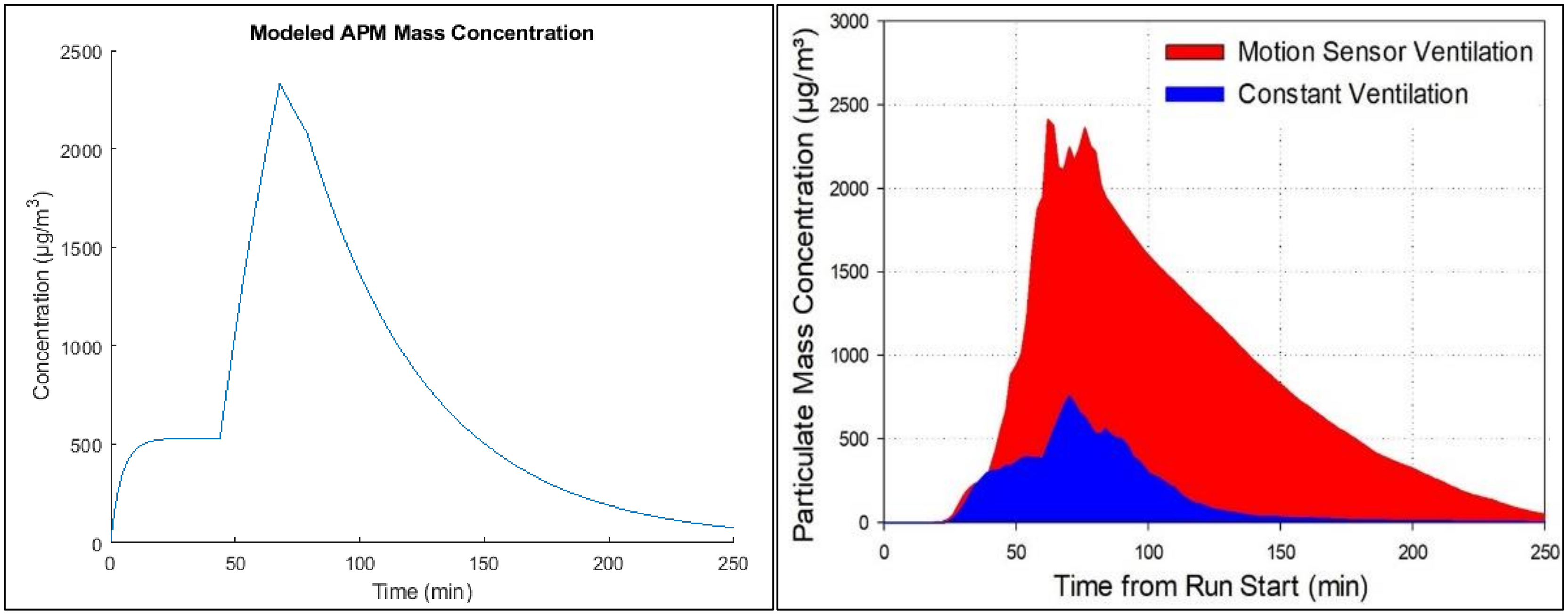

Figure 8: Mass concentration verses time data generated using the mass balance model is shown at left. For this plot, terms were modified to best approximate the empirical data shown in Figure 5, shown again at right. There are distinct times when ventilation stops, generation stops, and particle settling dominates in both the model and the empirical data.

7. Conclusions & Implications

Evaluation of the PM generation and removal in the Mooney Lab makerspace led to several definitive conclusions. First and foremost, the generation of airborne PM in makerspaces was verified and characterized, with hazardous concentrations observed in the observational study originally and then again in both constant and motion sensor controlled ventilation trials. Secondly, the use of motion sensor regulated ventilation systems was deemed to significantly lessen the particle removal rate of a makerspace when occupants left during or soon after using the space, which potentially allows users to be exposed to unacceptably high PM concentrations upon their return. The ventilation provided while users were present was not enough to prevent the creation of hazardous conditions afterwards, when new users could enter and be exposed without warning. The UFPs observed were primarily generated from laser cutting, 3D printing, grinding, and soldering equipment, all of which is typical to many makerspaces. While such a result was expected due to the observational run conducted earlier, this controlled study clearly links the increase in PM concentrations to the change in ventilation.

Continuous ventilation was able to reduce the maximum UFP mass concentration in the makerspace to one third of the motion sensor controlled ventilation's levels. Reduction rates were also compared, showing that constant ventilation reduced mass concentration to normal levels 3.5 times faster than the motion sensor controlled ventilation. Additionally, continuous ventilation was shown to be more effective in removing very fine particles, in the range of 10 to 30 nm, which pose the largest hazard to human health due to their higher ability to pass through membranes and into the body.

Concentrations in motion sensor runs were observed in the millions of particles per cubic centimeter, corresponding to several milligrams of particulate matter in that volume. This is a serious health hazard because any person who would occupy the lab when these concentrations are present would be exposed to unhealthy quantities of particles, most notably UFPs (2). To put this in perspective, studies have shown that typical UFP background concentrations in offices in the US are typically around 50 μg/m3, about 45 times less than the peak levels observed when motion sensor controlled ventilation was used in the Mooney Lab (22). If makerspace users were to return to the lab after the ventilation was shut off for some time, they could be exposed to these high concentrations of UPFs until the ventilation, then reactivated, could catch up and removed them. Likewise, the particles generated when motion sensor controlled ventilation is off do not leave the lab when the air concentration decreases, but rather accumulate on surfaces in the lab. Though it is difficult to re-entrain particles into the air, particle removal via settling takes longer and leaves a undesirable particle film on surfaces.

While the ability to use less electricity running ventilation systems with motion detectors is attractive from a cost standpoint, the risks posed to the makerspace's users must be considered. Ultrafine particulates are a proven hazard to human health and have been shown in this study to be generated in makerspaces by many common machines. Motion sensor systems allow high concentrations of these particles to build up while machines run unattended, creating an environment unsafe for people to enter. The risk is even more severe for makerspaces with worse ventilation systems than those tested in this experiment, such as retrofitted rooms in schools and libraries, especially since the likely users are children who breathe more air per percent bodyweight compared to adults. Because of this, it is not recommended that any makerspace operate without continuous ventilation. Furthermore, careful attention should be given to making sure that the ventilation system can deliver a large enough air exchange rate to handle all the equipment in its space.

8. References

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Appendix A: Motion Sensor Matlab Model

```
close all
clc

%USER INPUT VARIABLES

%Generation (µg/min)
G = 5000 ;
%Additional Generation (µg/min)
AG = 20000 ;
%Ventilation (m^3/min), Mooney = 1500 ft^3/min
E = 42.5 ;
%Room Volume (m^3), Mooney = 8500 ft^3
V = 240 ;
%Total Run Time (min)
T = 250 ;
%Ventilation Off Time (min)
TVOff = 60 ;
%Generation End Time - 3D Printers
TGOff = 80 ;
%Additional Generation End Time - Lazer Cutter
TAGOff = 60 ;
%Base Concentration (µg/m^3)
B = 10 ;
%Particle Settling Factor (% of C/min)
S = 0.02 ;
%Air Exchange Rate (min)
A = V/E ;

%INITIALIZATION OF MODEL

X = [0:1:T];
C = zeros(1,T+1);
C(1) = B;

if TAGOff > TGOff
   disp("ERROR: TAG is greater than TG")
   return
end

%CONCENTRATION MODEL LOOP
```

```
for i = 2:length(X)
   if i-1 < TVOff && i < TAGOff
      C(i) = (C(i-1) + (G/V) + (AG/V) - (C(i-1)*(1/A)) - (C(i-1)-B)*S);
      %Conc. = Initial + Generation - Ventelation - Settled Out
      %Units of each term should be µg/m^3 (time step = 1 min)
   elseif i-1 < TVOff && i < TGOff
      C(i) = (C(i-1) + (G/V) - (C(i-1)*(1/A)) - (C(i-1)-B)*S);
      %Conc. = Initial + Generation - Ventelation - Settled Out
   elseif i-1 < TGOff && i < TAGOff
      C(i) = (C(i-1) + (G/V) + (AG/V) - (C(i-1)-B)*S);
      %Conc. = Initial + Generation - Settled Out
   elseif i-1 < TGOff
      C(i) = (C(i-1) + (G/V) - (C(i-1)-B)*S);
      %Conc. = Initial + Generation - Settled Out
   else
      C(i) = (C(i-1) - (C(i-1)-B)*S);
      %Conc. = Initial - Settled Out
   end
end

%GENERATE PLOT
figure
hold on
plot(X,C)
title('Modeled APM Mass Concentration')
ylabel('Concentration (µg/m^3)')
xlabel('Time (min)')
hold off
```