

3D PRINTING IN THE WILD: A PRELIMINARY INVESTIGATION OF AIR QUALITY IN COLLEGE MAKER SPACES

Bill McDonnell, Xavier Jimenez Guzman, Matthew Dolack,
Timothy W. Simpson, and John M. Cimbala
Mechanical & Nuclear Engineering, Penn State University, University Park, PA 16802

Abstract

Additive manufacturing is a popular method for prototyping and manufacturing custom parts, especially on college campuses. While there is widespread use of 3D printers as part of many engineering classwork, there is little regulation or knowledge regarding emissions. Many plastics, including polycarbonates, ABS, and PLA are known to emit high counts of volatile organic compounds (VOCs) and particulate matters (PMs). This study focuses on VOC and PM counts in several natural environments and dedicated “maker spaces” on a large college campus to gauge the exposure that students and operators experience. Emissions were measured using a photoionization detector and two particle sizers. The photoionization detector measured total VOCs, and the particle size counters measured both total nanoparticles and individual micro-particles based on relative particle diameter. Measurements were taken in hourly increments and then analyzed to determine the degree with which desktop printers emitted VOCs and PM. Our data can be used to determine whether additional ventilation or filtration is needed when 3D printing “in the wild” to enhance operator and bystander safety.

Introduction

As the additive manufacturing industry has developed over the past several decades, the use of consumer-grade (desktop) 3D printers has increased as well. It is now very common for universities to augment their engineering and design programs to include instruction and use of 3D printers given their ability to help visualize ideas and solve complex design problems. Large universities like Penn State University offer a wide array of 3D printing capabilities for in class projects as well as research (e.g., materials development and characterization, multi-extruder systems). These can range from low-cost, open source, do-it-yourself (DIY) 3D printers that are built as part of a class and used in other classes to higher-end polymer systems that are used for senior capstone design projects and fabricating prototypes for research. Many students even have desktop printers in their dorms. With the ever increasing use and popularity of desktop 3D printers, the issue of operator and bystander safety has come into question.

Material extrusion technology, particularly fused deposition modeling (FDM) is rapidly evolving, and as a result the technology is largely unregulated. This is concerning because studies conducted by universities and regulatory agencies have shown that FDM printing emits particulate matter (PM) and volatile organic compounds (VOCs) [1]. Additionally, studies have linked PM and VOC emissions, especially when in high concentrations, to numerous health problems [2]. The emissions of greatest concern are VOCs, ultrafine particulates (UFP), and fine particles. Ultrafine particles and fine particles differ from each other in that ultrafine particles

have a diameter less than 100 nanometers and fine particles have a diameter less than 2.5 micrometers [3]. Ultrafine particles are a subgroup within fine particles. Inhalation of fine particles, UFPs, and certain VOCs are scientifically proven to be carcinogenic [4].

In total, approximately ten studies have been conducted by regulatory agencies, academic institutions and FDM printer manufacturers that have looked into FDM printer emissions. The studies mostly focus on VOC and UFP particle emission, and they typically use a flux chamber to precisely measure emissions. One experiment used a flux chamber to measure emission rates with a TSI 3007 condensation particle counter and TSI 3910 Nano Scan scanning mobility particle sizer (SMPS) [5]. Another study measured particle concentrations in a modified office environment again using a TSI 3910 Nano Scan SMPS [6]. Finally, one study used a sealed, cubic testing chamber with a HEPA filter to measure TVOC concentrations [2].

With this in mind, we set out to study particle emissions and VOC concentrations in naturally environment at seven locations around Penn State's University Park campus. The selected locations all contained FDM printers that are used on a regular basis. Additionally, the environments at all test locations were not modified in any way from their typical daily use and operations in order to best simulate the emission characteristics a printer operator or bystander might experience "in the wild" when in the same room as an operating FDM printer. Samples were taken to compare changes and trends during print time for total particle counts, fine particle concentrations, and VOC concentrations in the seven test environments. Fine particle size distributions were also analyzed and used to calculate fine particle mass concentrations to compare against National Ambient Air Quality Standards (NAAQS) exposure limits and VOC concentrations against National Institute for Occupational Safety and Health (NIOSH) exposure limits.

Test Environments and Experimental Set Up

To test the impact of emissions of 3D printing "in the wild", air sampling instruments were set up in seven different locations at the Penn State University – University Park campus where desktop 3D printers were in frequent use for class projects or research. The testing environments were not altered in order to best replicate the conditions of everyday use. Table 1 summarizes the testing environment and material printed in each sampled location.

Location 1 is a secluded room outside of a staff office designated for 3D printing for Mechanical & Nuclear Engineering students. Students can schedule prints for class and project use. Locations 2 and 6 are printers in classrooms in the Engineering Design program where the University's 3D Printing Club meets and prints various objects for club use and course projects. Location 3 is a secure room located in the University's Pattee/Paterno Library, with a separate, sealed enclosure for all of the printers inside the room. Students upload 3D prints through the University's library website and pick up their prints at the front desk in the library. Location 4 is a student dorm located on campus, where a student uses the printer for class and recreational use. Location 5 is a small room located next to a workshop that is primarily used for wood and metal fabrication. Location 7 is a small graduate research office located nearby off-campus.

Table 1. Test Environment with Respective Room and Printer Characteristics

Test Environment	3D Printers	Thermoplastic Filament	Room Dimensions	Ventilation
1 (Staff Office)	2 Maker Bot Replicators	PLA	10'x11'x9'	4" x 96" air vent & 12" x 24" air return
2 (3D Printing Club Space)	1 Creator Pro Flashforge	PLA	40'x40'x12'	Closed windows w/ standard ceiling duct HVAC system
3 (Library)	18 Maker Bot Replicators	PLA	18'x6'x9'	Fully enclosed w/ multiple air returns above printers
4 (Dorm Room)	Prusa i3	ABS	10'x12'x8'	Closed windows
5 ()	MakerBot Thing-O-Matic (1)	ABS	10'x20'x13'	Closed windows w/ standard ceiling duct HVAC system
6 (3D Printing Club Space)	1 Markforged Mark and 1 Lulzbot Taz5	Nylon	4'x42'x12'	Closed windows w/ standard ceiling duct HVAC system
7 (Grad Student Lab Space)	1 MendelMax	Polycarbonate	15'x8'x10'	10" x 18" air vent & 10" x 18" air return

Experimental Setup

To measure the fine and ultrafine particle counts in each environment during typical use and 3D printer operation, two instruments were used. The first is the TSI 8525 P-Trak Ultrafine Particle Counter which is capable of measuring fine particle counts ranging in size from 0.02 micrometer to 1 micrometer using a sample flow rate of 100 cm³/min and a total flow rate of 700 cm³/min. The P-Trak was lightweight and easy to position within the room. The P-Trak also had a flexible probe attachment that allowed for measurements to be taken in close proximity to the 3D printer and in confined regions larger than the P-Trak unit. The second instrument used to measure the coarser particle emissions was the TSI 9110 Aerotrak Portable Particle Counter with a size range of 0.1 to 10 micrometers and a flow rate of 28,000 cm³/min. The Aerotrak separates particles into 8 different bins based on particle diameters. To measure VOCs, the RAE Systems PPBRAE Plus Photoionization Detector (PID) was used to count concentrations of gases with a range of 0-9999 parts per billion at a flow rate of 400 cm³/min.

The P-Trak 8525 and the Aerotrak 9110 were first shipped to the manufacturer, TSI Inc, for calibration and qualification to ensure their specific ranges and sensitivities could be met. Both meters passed calibration by their manufacturer, TSI Inc., without issue. Following the manufacturer's recommendations, isobutylene gas was used to calibrate the PPBRae PID, according to the manual's specifications. Before any measurement was taken, the PID was zeroed using a VOC filter. A VOC filter ensures that the meter is reading zero VOCs when in a VOC free environment. Likewise, the P-Trak meter was zeroed before every measurement using a high-efficiency particulate arrestance (HEPA) filter to verify the meter read zero particles in a particle free environment. In some test locations, printers were operating before our arrival, which complicated establishing control level VOC and PM measurements.

During printing, the P-Trak Ultrafine Particle Counter was set next to the 3D printers with the probe positioned close to the print bed. The instrument sampled air for the duration of the

prints at five minute intervals, providing data on particle counts/cm³ at that instant. Meanwhile, the Aerotrak Particle Counter was placed within a foot of the 3D printer, and it sampled air continuously throughout the print. The Aerotrak provided data on total particle count throughout the print and the total flow through the instrument. The PPBRae Photoionization Detector was handheld close to the printer for five minutes during every print to sample the VOC concentration. The PID took 5 readings, each with a 60 second sample, and calculated the minimum, maximum, and average concentrations of total volatile organic compounds in ppb.

Calculating Fine Particle Concentrations

Particle concentration data from the P-Trak Ultrafine Particle Counter was used to calculate the number of fine particles (less than 2.5 micrometers in diameter) emitted in each environment. While the P-Trak only provided particle count data for particles less than 1.0 micrometer in diameter, the Aerotrak particle counter indicated that the concentration of particles between 1 and 2.5 micrometers was insignificant in all test environments. With this in mind, the total concentration of particles measured using the P-Trak was used as the total fine particle count. Particle distribution data from the Aerotrak showed that more than half of the total particles counted during each sample fell between 0.1 and 0.15 micrometers in diameter. Table 2 contains particle distribution data from the Aerotrak for PLA-2 and Nylon-6. A plot of the data contained in Table 2 can be seen in Figure 1. Particle concentrations tend to be skewed towards a smaller diameter, moreso than a normal distribution would suggest because particle concentrations typically display a log-normal distribution behavior. Because approximately half of the counted particles were greater than 0.15 micrometers and the remaining half were less than 0.15 micrometers, a Dp-50, or median value of 0.15 micrometers was used as the median diameter for fine particles.

Table 2. Particle Collection Rate (# per minute) for PLA-2 and Nylon Filament

Particle Size (µm)	Particles Emitted per Minute	
	PLA-2	Nylon-6
Bin		
0.10	599482	575460
0.15	249381	344696
0.20	99058	119739
0.25	105333	123969
0.30	62504	68762
0.50	6578	5783
1.00	2883	2227
5.00	368	729

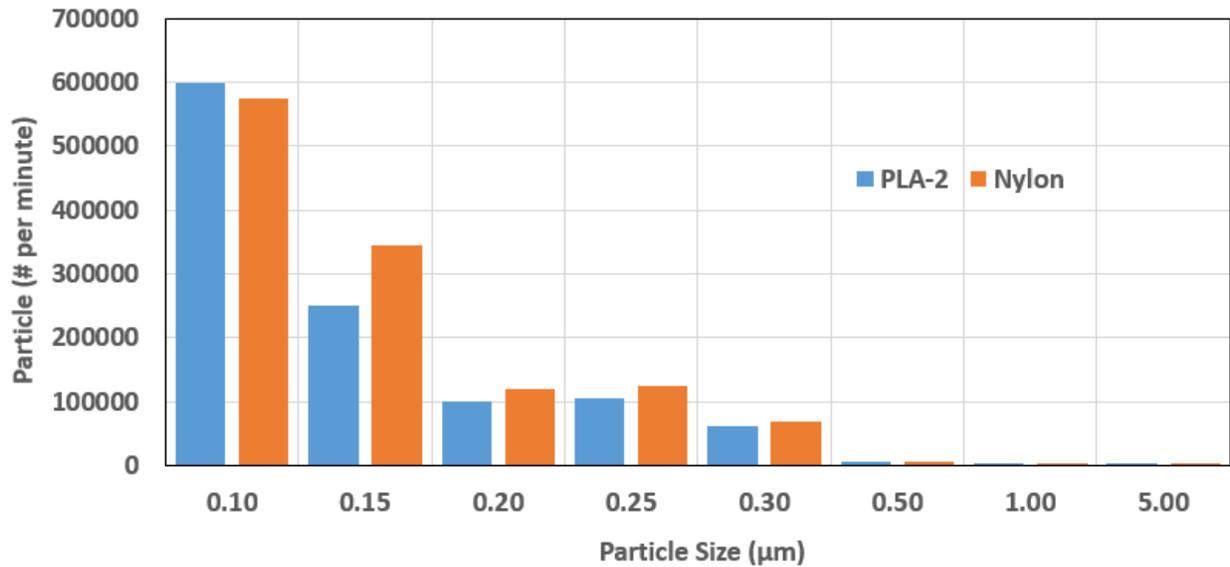


Figure 1. Particle Emission Rate (# per minute) for PLA-2 and Nylon Filament

Calculating Particle Mass Concentration

In order to calculate the mass concentrations of the fine particles, the median particle diameter based on particle count was converted to a median particle diameter based on mass using Equation 1, which was derived from empirical evidence [3]:

$$\ln(D_{p,50}(mass)) = \ln(D_{p,50}(number)) + 3(\ln(\sigma))^2 \quad (1)$$

The standard deviation, σ , of the Aerotrak particle count was calculated to be 0.7 micrometers. Assuming that the particle distribution of the Aerotrak was similar to the particle distribution of the P-Trak count, the same standard deviation was used for Equation 1.

Using these values, a median particle diameter based on mass of 0.22 micrometers was calculated for fine particles. To calculate mass concentrations from fine and ultrafine particle concentrations, Equation 2 was used where c is equal to mass concentration and y is equal to particle concentrations.

$$c = y \times \frac{1}{6} \rho \times \pi \times D_{p,50}(mass)^3 \quad (2)$$

Calculating Total Particle Counts and Concentrations

The Aerotrak particle counter counted the total number of particles per bin. To calculate the total number of particles, the sum was taken from these bin counts. To calculate the particle concentrations in particles/cm³, the total particle counts for each bin were divided by the total centimeters of air that flowed through the meter during the sampling time. The concentration for each bin was also summed for a total. To compare particle counts across the seven different 3D

printing environments, the total counts were divided by the sampling time (in minutes) to determine the total particle counts sampled per minute in each environment.

Classifying Volatile Organic Chemical Concentrations

As mentioned in the previous section, isobutylene was used as the calibration gas for the PID for each sample taken. The PID has different sensitivities for different chemicals; thus, it gives different concentration readings for a certain chemical depending on which gas was used to calibrate it. To account for this, a correction factor was used for each chemical being detected to account for the PID's sensitivity to that chemical relative to the PID's sensitivity to isobutylene. The true concentrations of the VOCs emitted were derived using Equation 3.

$$Concentration_{True} = Concentration_{PID\ Reading} \times CF_{Chemical} \times \%Composition \quad (3)$$

Each correction factor (CF) was tested and calculated by the manufacturer and provided in the product's user manual [7]. Each PID reading comprised of a minimum, median, and maximum VOC concentration in ppb. The average of the median and maximum values from the multiple PID readings was calculated for each environment sampled.

The PID was only used to test total VOC count, not specific VOC composition. With that in mind, a composition of 60% lactide was assumed PLA-1, PLA-2, and PLA-3 (i.e., test environments 1, 2, and 3, which all used PLA). For ABS-4 and ABS-5, referencing VOC emissions data by MakerBot, a composition of 60% styrene and 40% unknown was assumed. For Nylon-6, referencing emissions data from Lulzbot manufactured nylon, a 90% caprolactam composition was assumed. For Polycarbonate-7, 80% of the emissions were assumed to be caprolactam [5].

Experimental Results of 3D Printing “In the Wild”

Fine Particle Concentration

The fine particle count and mass concentrations from the P-Trak ultrafine particle counter are summarized in Table 3. Each testing environment shows an increase in average particle concentration during print time. The environments printing with PLA plastics had the lowest increase in average particle concentrations, with concentrations during printing increasing by 917, 157, and 465 particles/cm³ for Environments 1, 2, and 3, respectively. Environments printing with ABS and nylon plastic increased by 96,573, 13,850, and 35,931 particles/cm³ for Environments 4, 5, and 6, respectively. Environment 7, printing a polycarbonate blend, showed the highest increase in average particle concentrations with an overall increase of 170,597 particles/cm³. Maximum particle concentrations showed significantly higher increases over control concentrations. Environment 1 (PLA) showed a 2,094 particles/cm³ increase, Environment 4 (ABS) showed a 102,588 particles/cm³ increase, and Environment 7 (polycarbonate) showed a 299,927 particles/cm³ increase.

Table 3. Fine Particle Count and Mass Concentration

Environment	Plastic	Fine Particle Concentrations (particles/cm ³)			Fine Particle Mass Concentration (µg/m ³)		
		Control	Average	Maximum	Control	Average	Maximum
1	PLA - 1	1033	1950	3127	0.0072	0.0136	0.0218
2	PLA - 2	1982	2139	2232	0.0138	0.0149	0.0155
3	PLA - 3	3069	3534	4425	0.0214	0.0246	0.0308
4	ABS - 4	6780	103353	109368	0.0404	0.6162	0.6521
5	ABS - 5	7050	20900	48600	0.0420	0.1246	0.2898
6	Nylon - 6	1990	37921	70400	0.0128	0.2430	0.4511
7	Polycarbonate - 7	391	170988	300318	0.0026	1.1434	2.0082

Size range: 0.01-1.0 micrometers

Particle concentration increases during printing with nylon filament were an order of magnitude higher than concentration increases for PLA filament, by a factor of 39.2. The particle concentration increase for Polycarbonate-7 was two orders of magnitudes higher than the concentration increase for PLA-1, as shown in Figure 2. Maximum particle concentration showed a significant increase over average particle concentration during printing for ABS, nylon, and polycarbonate filaments. For Environment 5 (ABS-5), maximum concentration was greater than average concentration by a factor of 2.33, Environment 6 (Nylon-6) showed a 1.86 factor increase, and Environment 7 (Polycarbonate-7) showed a 1.76 factor increase. PLA usage increased concentrations by a factor of 1.60, 1.04, and 1.06 for Environments 1, 2, and 3, respectively.

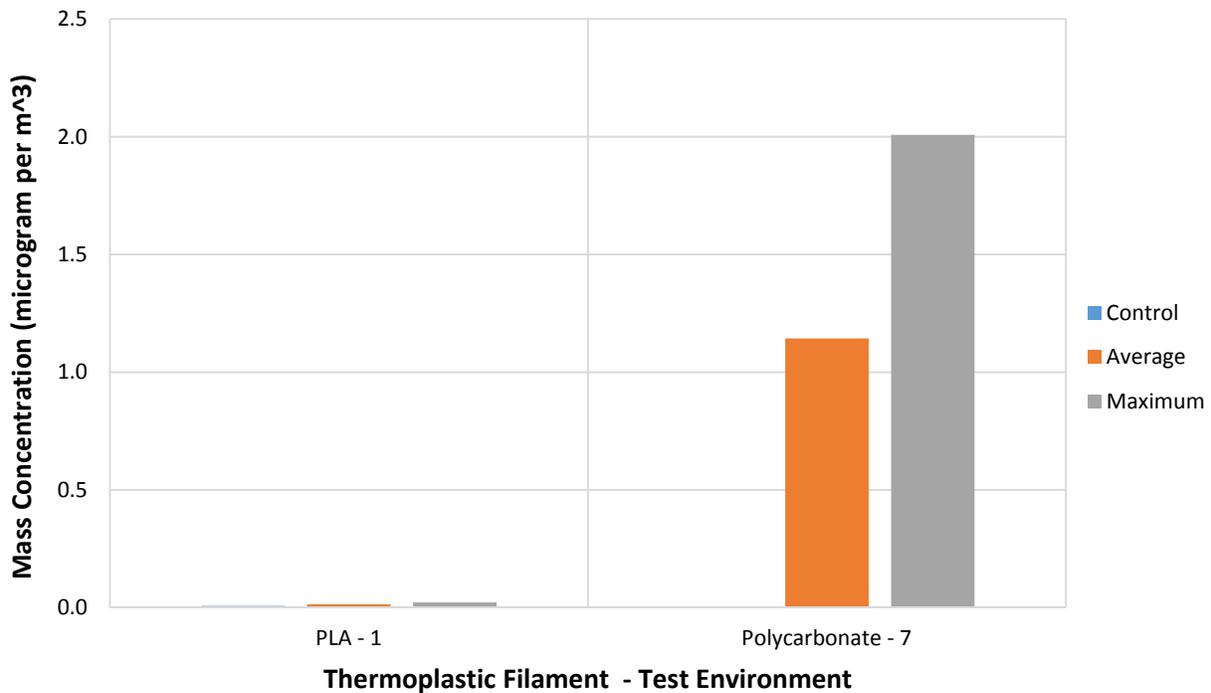


Figure 2. Fine Particle Mass Concentrations for PLA-1 and Polycarbonate-7 Test Environments

For each test environment, fine particle concentration increased with time. Figures 3 and 4 show fine particle concentration trends that appear to increase with time for Environment 1, which used PLA, and Environment 7, which used polycarbonate. PLA-1 shows a steady upward trend. Polycarbonate shows fluctuations (mostly due to interruptions during printing), while still trending upwards. Given the trends, if the prints were to have run longer, particle mass concentrations could be expected to increase at a steady rate.

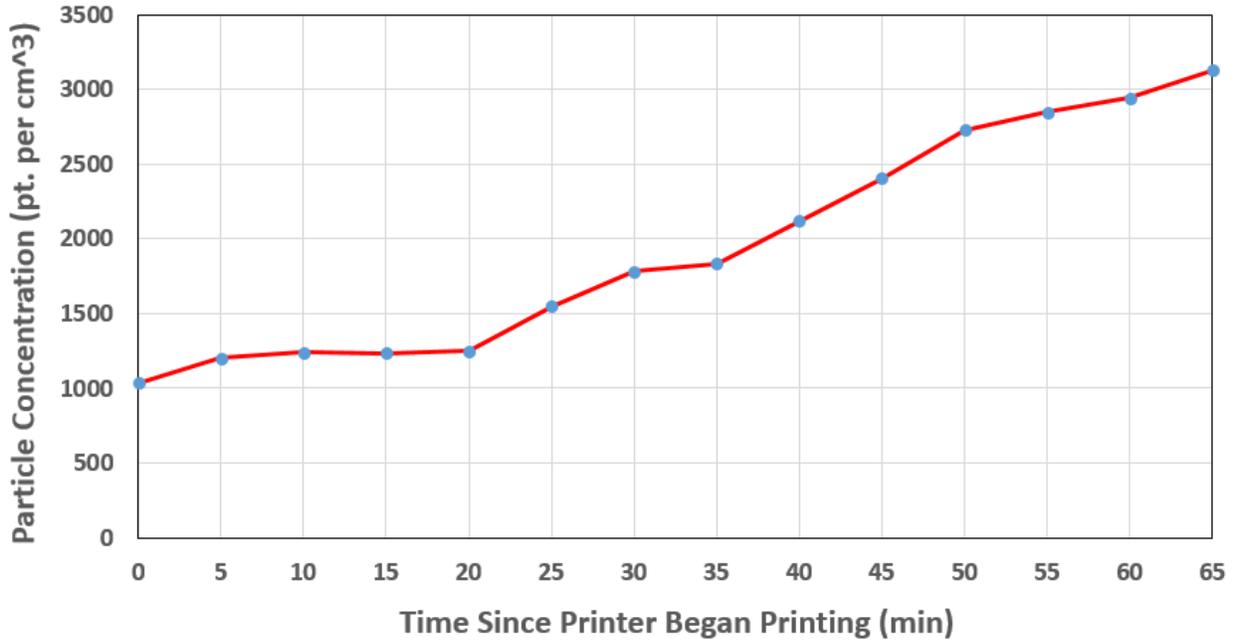


Figure 3. Fine Particle Concentration versus Print Time for PLA-1 Filament.

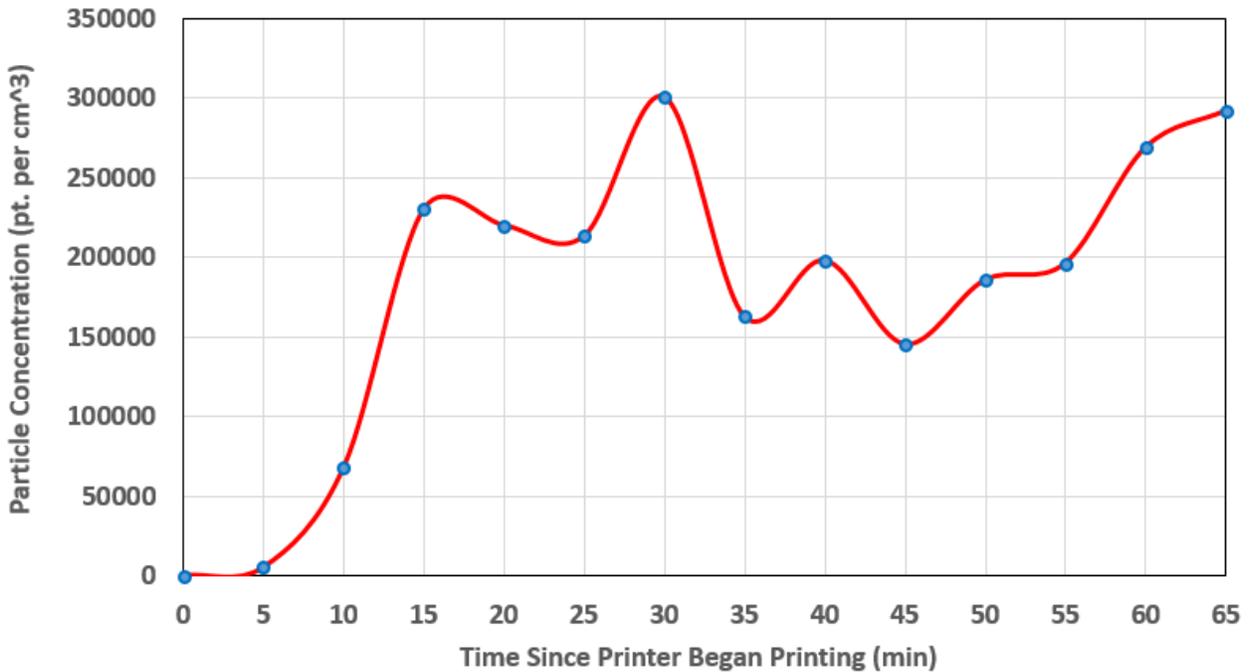


Figure 4. Fine Particle Concentration versus Print Time for Polycarbonate-7 Filament.

Fine Particle Mass Concentration and Size Distribution

Mass concentration is calculated directly from particle concentration; therefore, an increase in mass concentration during printing is directly proportional to an increase in particle concentration during printing. A plot of fine particle mass concentration for all seven test environments can be found in Figure 5. Particle size distribution, which is correlated to mass distribution, was previously shown in Figure 1. Particle size distribution is skewed towards smaller average diameters. Approximately half of all particles measured in each test environment are less than 0.15 micrometers in diameter. Table 2 showed that 53.3% of particles for Environment 2 (PLA-2) have diameters ranging from 0.10 to 0.15 micrometers. Moreover, 46.3% of particles in Environment 6 (Nylon-6) fall into the aforementioned diameter range. Particle diameter and particle count are inversely proportional to each other; when particle diameter decreases, particle count increases. Few particles in each test environment are greater than 0.5 micrometers in diameter. The percentage of total counted particles ranging from 0.5 to 5 micrometers for PLA-2 and Nylon-6 was 0.84% and 0.65%, respectively.

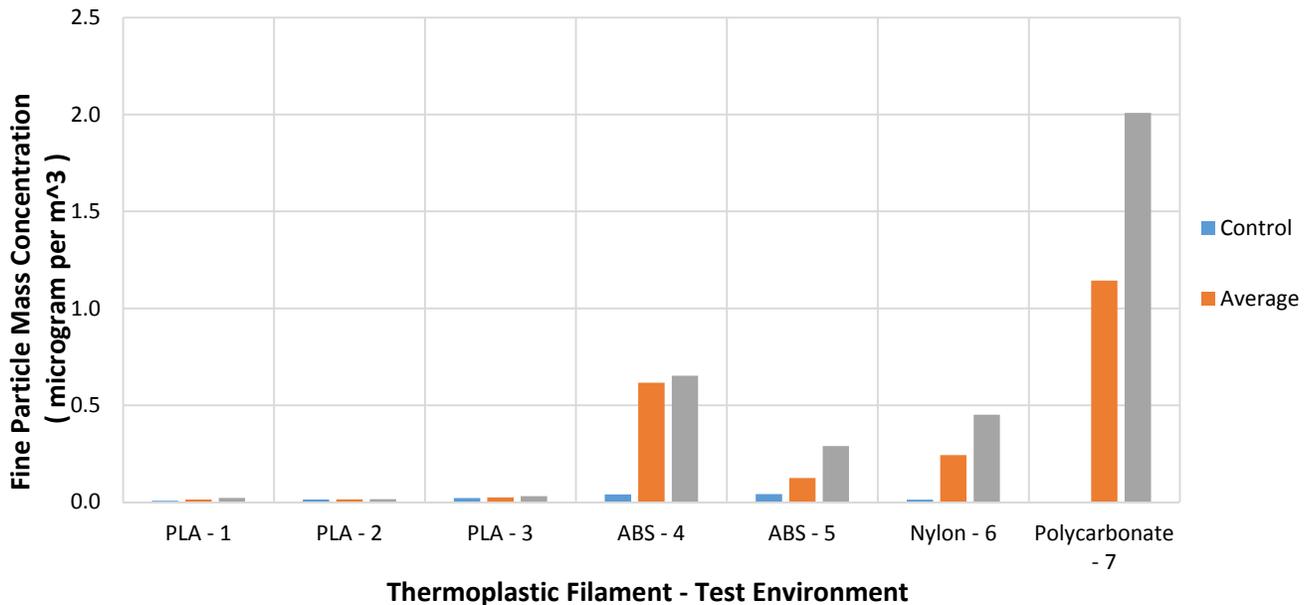


Figure 5. Fine Particle Mass Concentrations for All Test Locations

Total Particle Count

When compared against control data, total particle count per minute does not change as significantly as total fine particle count per minute. The relatively small change between control data and total particle count per minute for all seven test environments is shown in Figure 6. The largest total particle count per minute increase compared to control data occurs in Environment 7 (Polycarbonate), increasing by a factor of 1.1. This increase is two orders of magnitudes lower than the 437x increase found between control data for average fine particle count per minute for the same filament. Total particle count per minute in Environment 3 (PLA-3), when compared against control data, decreased by a factor of 0.99 during printing. The remaining total particle

counts per minute increased by multiplying factors ranging from 1.0 and 1.1. When 3D printing, the largest total particle count per minute variation was between PLA-1 and Polycarbonate-7: total particle count per minute for PLA-1 was 53.6% higher than total particle count per minute for Polycarbonate-7. Because the scale for total particle count per minute and average fine particle count per minute differ significantly, a comparison of the two would be insignificant.

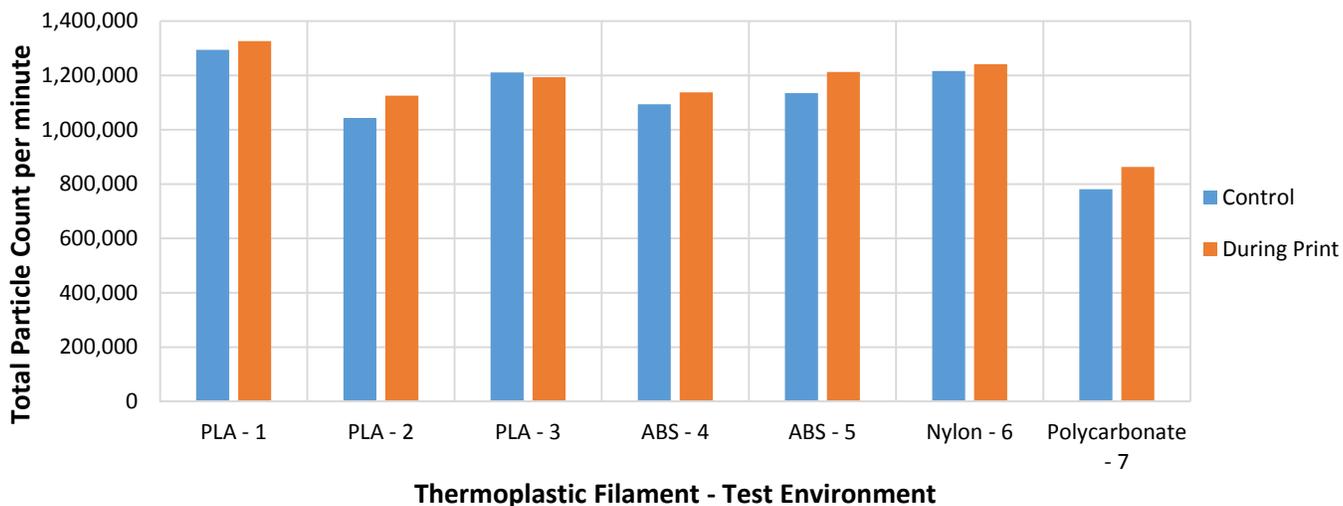


Figure 6. Total Particle Count for All 7 Test Environments

Volatile Organic Compound Emission

In all 7 test environments, total VOC concentration increased during printing. Figure 7 shows the trend of increased total VOC concentration during 3D printing. Environments printing with PLA and ABS were all towards the lower end, staying under 0.75 ppm. Nylon-6 reached a maximum of 2.96 ppm, and polycarbonate-7 reached a maximum of 2.57 ppm. Total VOC emissions for both nylon and polycarbonate were more than three times larger than the maximum VOC concentrations for both PLA and ABS. While total VOC emission is a good indicator of overall emission characteristics, a more telling indicator is the primary emitted VOC. Table 4 shows the control, average, and maximum VOC concentration for the primary VOC emitted in each test environment. The numerical values in Table 4 are not as important relative to each other as they are to the exposure limits for the respective primary VOC emitted in each test environment. Exposure limits for the primary VOCs emitted in each test environment are discussed in the next section.

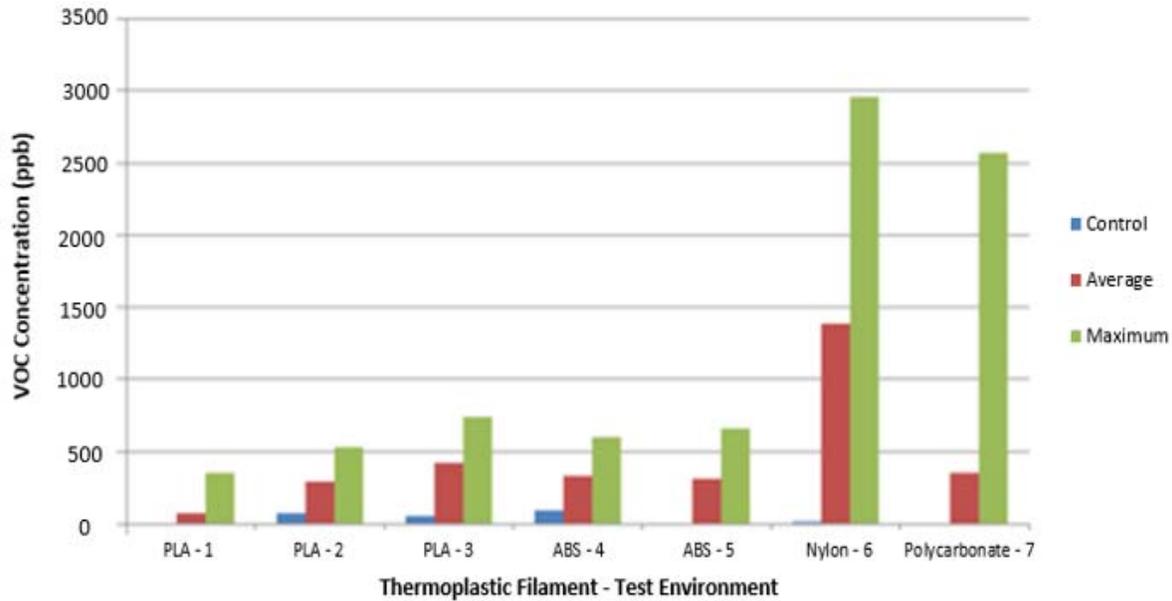


Figure 7. Total VOC Concentration Levels in Each Test Environment

Table 4. VOC Concentrations for Maximums VOCs Emitted at each Test Environment [5]

Location	Filament	Chemical Sampled	Primary VOC Concentration (ppm)		
			Control	Average	Maximum
1	PLA	Lactide	0.0000	0.0443	0.2090
2	PLA	Lactide	0.0700	0.1780	0.3200
3	PLA	Lactide	0.0342	0.2520	0.4440
4	ABS	Styrene	0.0280	0.0810	0.1450
5	ABS	Styrene	0.0000	0.0750	0.1590
6	Nylon	Caprolactam	0.0160	1.1200	2.6600
7	Polycarbonate	Caprolactam	0.0000	0.3390	1.5400

Discussion

One of the main areas of concern with respect to emissions from material extrusion printers, particularly FDM systems, is fine particles. Fine particles are a criteria air pollutant (CAP) and are respirable [8]. While exact health effects of inhaling fine particle emissions from 3D printers are unknown, fine particle emissions from other sources have been shown to be carcinogenic and cause major health problems [12]. ABS, nylon and polycarbonate, all of which are commonly used thermoplastic filaments, are known to release the carcinogenic VOCs styrene and formaldehyde when melted [13]. The National Ambient Air Quality Standards (NAAQS) has set exposure limits for fine particle emissions at thirty-five $\mu\text{g}/\text{m}^3$ during a 24-hr exposure period and twelve $\mu\text{g}/\text{m}^3$ for consistent exposure over the course of one year [9]. Of the tested filaments, the most significant emitters of fine particles were polycarbonate, ABS, and nylon. While maximum concentrations for all three do not exceed twelve $\mu\text{g}/\text{m}^3$, a longer print time could lead to a higher maximum concentration. Figure 8 contains a plot of particle mass

concentration, in micrograms per cubic meter, for Polycarbonate-7 with respect to printing time. If polycarbonate filament were used to print over eight hours, which is not uncommon, particle mass concentrations could increase from two to above twelve micrograms per cubic meter.

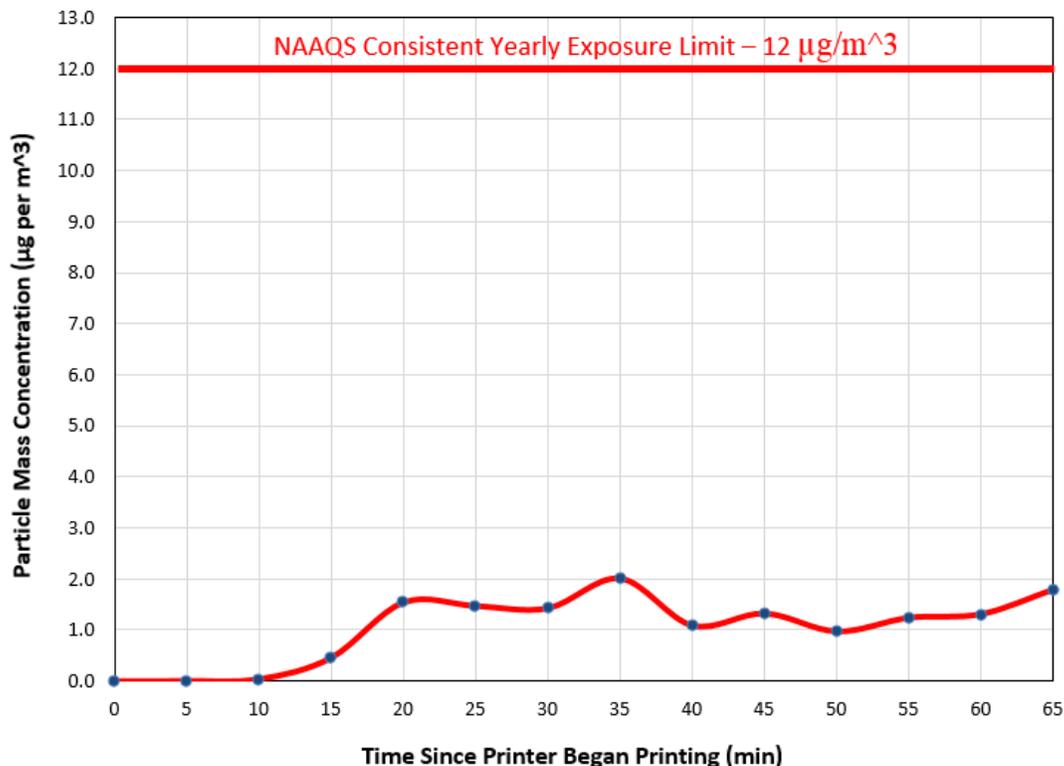


Figure 8. Particle Mass Concentration versus Print Time for Polycarbonate-7 Filament

Another area of concern is VOC emission. When collecting emissions data, Environment 6 was found to have hazardous VOC concentration levels from using nylon thermoplastic filament in an inadequately ventilated room. Environment 6 had an average VOC concentration of 1.1 ppb and a maximum VOC concentration 2.66 ppb. The primary VOC emitted during FDM printing with nylon filament is caprolactam [5]. VOC concentration levels in Environment 6 are higher than the NIOSH short term (ST) and time weight average (TWA) exposure limit of 0.660 ppm and 0.220 ppm, respectively, for caprolactam. Inhalation of caprolactam can cause dizziness, headaches, nosebleeds, vomiting, liver and kidney damage, and confusion [10]. It has also been documented that caprolactam inhalation can cause skin and eye irritation, as well as central nervous system damage [11].

Total VOC emissions for ABS filament tested in Environment 5 came to 0.336 ppm and 0.605 ppm for average and maximum concentration levels, respectively. The primary VOC emission for ABS, styrene, did not exceed the NIOSH styrene exposure limit of 100 ppm TWA or 600 ppm ST [5, 11] in Environment 5; however, some of the organic chemicals comprising the total VOC emission remain unknown. ABS is known to emit formaldehyde, and while we do not know the exact concentration of formaldehyde emitted from these printers, we cannot conclude that the amount is safe (NIOSH limits for formaldehyde are very low, at 0.016 ppm

TWA and 0.100 ppm ST). Only 2.4% of the maximum VOC emissions would need to be composed of formaldehyde to exceed the TWA limit.

What made this experiment unique was that testing was conducted in open, or natural, printing environments, what we call 3D printing “in the wild”. Similar experiments have been conducted at other institutions in more controlled environments using either a flux chamber or some other form of contained testing environment [1, 5, 10]. The goal of testing in natural environments was to gauge what emissions are like in everyday FDM printing environments, specifically at locations around a large college campus that offers many 3D printing options. Environment 5, a student dorm, and Environment 7, a graduate research office, are great examples of unregulated environments. Both locations are small rooms with no purpose built ventilation to accommodate FDM printers. Additionally, both locations used filaments well-known for emitting harmful VOCs and high levels of fine particles. An indicator that a plastic filament is emitting high concentrations of VOCs or fine particles is odor. Nylon, ABS, and especially polycarbonate filament had strong, distinct odors, which can be used as indicators that a specific filament is emitting fine particles or VOCs at a high rate.

Closing Remarks

This paper presents emission data and statistics for multiple thermoplastic filaments used in natural environments or 3D printing “in the wild”. Air quality testing in natural 3D printing environments was done in an attempt to replicate what a printer operator or bystander might be exposed to in terms of PM and VOCs. PM and VOCs emitted during use of PLA filament were relatively low when compared to ABS, nylon, and polycarbonate filament. VOC emissions from nylon were significantly higher than the exposure limit set by NAAQS for caprolactam [9]. Fine particle concentrations for polycarbonate did not exceed NAAQS exposure thresholds during testing [9]; however, longer print jobs could push concentration levels above the NAAQS exposure threshold, which would result in a hazardous operating environment for the users and bystanders.

When operating a printer with nylon or polycarbonate filament, certain safety procedures should be followed. The work area should be properly ventilated to help reduce VOC and PM concentration levels. Additionally, individuals in close proximity to the printer should wear a respirator to avoid inhalation of caprolactam. When operating a FDM printer in spaces without adequate ventilation, fans should be turned on and nearby windows should be opened to allow for clean air to flow around the printer and circulate in the room. Enclosed 3D printing spaces should make use of carbon filters to help reduce harmful emissions produced when printing. When educating students about 3D printing, particularly FDM systems, proper methods of ventilation and filtration should be discussed to make them aware of these safety issues.

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