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Reducing ultrafine particulate emission from multiple 3D printers in an office environment using a prototype engineering control

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Abstract

Recent studies have shown that high concentrations of ultrafine particles can be emitted during the 3D printing process. This study characterized the emissions from different filaments using common fused deposition modeling printers. It also assessed the effectiveness of a novel engineering control designed to capture emissions directly at the extruder head. Airborne particle and volatile organic compound concentrations were measured, and particle emission rates were calculated for several different 3D printer and filament combinations. Each printer and filament combination was tested inside a test chamber to measure overall emissions using the same print design for approximately 2 h. Emission rates ranged from 0.71 × 10^7 to 1400 × 10^7 particles/min, with particle geometric mean diameters ranging from 45.6 to 62.3 nm. To assess the effectiveness of a custom-designed engineering control, a 1-h print program using a MakerBot Replicator+ with Slate Gray Tough polylactic acid filament was employed. Emission rates and particle counts were evaluated both with and without the extruder head emission control installed. Use of the control showed a 98% reduction in ultrafine particle concentrations from an individual 3D printer evaluated in a test chamber. An assessment of the control in a simulated makerspace with 20 printers operating showed particle counts approached or exceeded 20,000 particles/cm^3 without the engineering controls but remained at or below background levels (< 1000 particles/cm^3) with the engineering controls in place. This study showed that a low-cost control could be added to existing 3D printers to significantly reduce emissions to the work environment.

Keywords

3D printing; Air sampling; Printer emissions; Engineering controls; Exposure assessment; Occupational health effects

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Compliance with ethical standards

Conflict of interest The authors declare that they have no conflict of interest.

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Introduction

The use of desktop 3D printers continues to increase rapidly with 500,000 units sold worldwide in 2017 and an estimated growth in sales of up to 1–1.5 million units by 2020 (Adams 2018). Questions have been raised about potential health effects from exposure to emissions due to the increased use of fused deposition modeling (FDM) three-dimensional (3D) printers in many different settings. Typical settings may include hobby shops, research and development labs, office environments, public makerspaces at libraries or at school learning centers, and in “print farms” that include cells of multiple 3D printers. These varied-use environments allow for a wide range of potential personal exposure scenarios with differences in use rate, facility ventilation design, and underlying user health status.

Published studies have characterized the rates and composition of the particles emitted during FDM 3D printing, which can include ultrafine particle and volatile organic compound (VOC) emissions (Vance et al. 2017; Zontek et al. 2017; Stefaniak et al. 2018a). Other studies have measured or predicted potential emission rates in office environments (Zhang et al. 2017; Stefaniak et al. 2018b). A recent meta-analysis of 3D printer emission studies concluded the following: FDM printers used with acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) materials would likely result in respirable particle exposure; ABS had greater overall emissions than PLA filaments; and lower nozzle temperatures reduced emission rates (Byrley et al. 2019).

Additional studies of particle emissions from laser printers showed that particle emission rates are printer type–specific and could be divided into categories such as non-emitters, and low, medium, and high emitters (He et al. 2007; Byeon and Kim 2012; Scungio et al. 2017). Other studies compared the emission rates of 3D printers with those of laser printers and found certain filaments used in 3D printers resulted in particle emission rates similar to the higher emitting laser printers (Stefaniak et al. 2017). A health survey of the employees of seventeen 3D printing companies showed strong associations between working 40-h per week with 3D printers and a respiratory-related diagnosis such as asthma or allergic rhinitis; although, it was noted that practices varied significantly by location (Chan et al. 2010). Another study of 26 healthy adults measured cytokines and eosinophil cationic protein in nasal secretions, exhaled nitric oxide, and urinary 8-isoprostaglandin before and after 3D printer emission exposure. These researchers found that the acute effects of exposure to FDM emissions from ABS and PLA filaments were not significant under the tested conditions (Gümperlein et al. 2018).

Concerns about ultrafine particle and chemical exposures to users of 3D printers in environments such as offices, schools, and libraries and other workplace settings have been expressed many times in recent years. Although multiple studies have evaluated emissions from desktop 3D printers, previous studies have not evaluated a retrofit engineering control solution designed to reduce emissions at the source of particle generation in collaboration with a 3D printer manufacturer. Our study took place at the MakerBot Industries, LLC, a facility in Brooklyn, NY. About 200 employees worked at the 31,000 square foot facility, developing printer technologies, design projects, and printing demonstration models for the MakerBot brand. The study objectives were to assess the emissions of several printer

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and filament combinations and to evaluate the effectiveness of a custom-designed, low-cost engineering control used for capturing emissions directly at the extruder head.

Methods

Emissions test chamber description

The emissions test chamber (Fig. 1) (referred to as “chamber” for the remainder of this paper) was placed over each 3D printer and filament combination to evaluate particulate and VOC emissions. The design of the chamber allowed for assembly in multiple configurations to accommodate printers of different sizes. A 0.22-m^3 (8 ft^3) chamber was placed over each 3D printer and filament combination during the initial 2-h printer/filament emissions tests. A 0.45 m^3 (16 ft^3) chamber configuration with dimensions 0.6 m (2 ft) deep by 0.6 m (2 ft) wide by 1.2 m (4 ft) high was used for the larger Replicator Z18 3D printer. The 0.22 m^3 configuration was also used to test emissions with and without the engineering control using the Replicator+ with Slate Gray Tough PLA filament and a 1-h print program. Air sampling was conducted by placing the sampling equipment through the outlet of the chamber.

A portable fume extractor (Model SS-300-PYT, Sentry Air Systems Inc., Cypress, TX) equipped with a high-efficiency particulate air (HEPA) filter and a 4-pound carbon filtration bed (to remove volatile emissions) was connected to the inlet of the chamber using a 20-cm (8 in) diameter flexible hose (Model D3890, Woodstock International Inc., Bellingham, WA) to clean the inlet air. Volumetric airflow through the chamber was measured by placing an airflow hood (Model EBT731, TSI, Inc., Shoreview, MN) over the 20-cm (8-in) diameter outlet duct. An airflow of 71 m^3/h (42 ft^3/min [cfm]) was measured from the chamber during all tests.

Simulated makerspace (conference room) description

Twenty MakerBot Replicator+ 3D printers were placed in a conference room to simulate a makerspace where multiple printers would be collocated (Fig. 2). The conference room was 12.5 m (41 ft) long by 4.7 m (15.5 ft) wide, with a ceiling height of 2.6 m (8.7 ft). Supply air was delivered to the conference room through six slot diffusers in the ceiling. Each slot diffuser was 1.2 m (4 ft) long by 3.1 cm (1.25 in) wide. Doors to the conference room were kept closed during print tests. Room supply air measurements were taken using an airflow hood (Model EBT731, TSI, Inc.). The airflow hood was configured with a 0.3 by 1.2 m (1 by 4 ft) skirt to measure airflow through each slot diffuser. Two or more airflow measurements were taken during each test, showing that the overall airflow was stable throughout testing. The supply airflow in the conference room ranged from 2166 to 2435 m^3/h (1275 to 1433 ft^3/min) during the eight tests.

VOC and particle measurement methods

Concentrations of 20 VOCs were evaluated using an evacuated canister method for emissions in the chamber. Air samples were collected to quantify specific VOCs using 450 mL Silonite® coated evacuated canister samplers (Entech Instruments). A single canister was used to sample each run throughout the entire print time, up to 2 h. These air samples were analyzed at NIOSH using a pre-concentrator/gas chromatograph/mass spectrometer

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system described by LeBouf et al. (2012) but modified to use a Model 7200 (Entech Instruments, Inc.) pre-concentrator.

The TSI NanoScan scanning mobility particle sizer (SMPS) (Model 3910, TSI Inc., Shoreview, MN) directly measured ultrafine particle numbers and sizes (ranging from 10 to 420 nm in diameter) in 13 size channels using electrical mobility with a 0.75 L/min sample flow rate. The lower and upper particle concentration measurement limits range from 100 to 1,000,000 particles/cm^3. During all tests, the NanoScan SMPS logged the total number concentration and size distribution each minute.

Emission tests in the chamber

Different 3D printer/filament combinations were tested inside the chamber as shown in Fig. 1. Each test consisted of printing the same roughly 2-h print job on each printer. These printers and filaments are commonly used and were selected based on availability and dependability for producing the sustained print during testing. Particle and VOC emissions were measured during the following 3D printer and filament combinations:

- Replicator 2X printer using True Yellow acrylonitrile butadiene styrene (ABS) filament
- Replicator+ printer using True Orange polylactic acid (PLA) filament
- Replicator+ printer using Slate Gray impact-resistant PLA (IMPLA) filament
- Replicator Z18 printer using Slate Gray IMPLA filament
- Replicator+ with Slate Gray Tough PLA filament, 1-h print job with and without LEV control

The NanoScan SMPS was configured to sample through a 0.5-m (1.6 ft) long conductive tube placed into the chamber through the exhaust outlet duct.

Particulate emission rate calculations

Emission rates were calculated from the 3D printer in the chamber using the method published by Mendes et al. (2017). The method assumes that the high airflow rate through the chamber results in turbulent well-mixed air and that measured particle concentrations correspond to fresh emissions. When the airflow rate through the chamber is known, the particle emission rate, E, can be calculated using Eq. 1:

$$E = NQ \tag{1}$$

where N is the particle number concentration and Q is the air flow rate at the outlet of the chamber. The particle concentrations were adjusted for diffusion losses in the sampling line using the methods outlined by Kulkarni et al. (2011). Diffusion losses in the 0.5-m (1.6 ft) long sampling tube were less than 9% at the smallest size bin (corresponding to the highest loss of any particle size by percentage). Geometric mean particle size and geometric standard deviations were computed using the NanoScan software program (NanoScan manager software version 1.0.0).

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Engineering control evaluation

Prior to this study, engineers at the National Institute for Occupational Safety and Health (NIOSH) designed a low-cost engineering control to fit the MakerBot Replicator+ printers. To accomplish this, the detachable Smart Extruder was removed from a MakerBot Replicator+3D printer and the existing plastic cover that supplied cooling air to the extruder from three directions was replaced with a NIOSH-designed extruder head capture hood that supplied cooling air in only one direction and captured emissions through an exhaust port (see Fig. 3). This design allows the emissions to be captured directly at the source, providing local control with the least amount of airflow required. A commercially available computer-aided design software package was used to design the NIOSH extruder head capture hood. In addition, a hose connection and an expanded slot for air suction were added to the capture hood (see Fig. 3).

The remaining parts of the NIOSH-designed ventilation control included the following:

- High-efficiency particulate air (HEPA) vacuum filter (Model 923480–01 Dyson Inc., Chicago, IL);
- 12-V radial blower (Model JT-FS-0002–1232-12, UTUO, Shenzhen, China);
- Lightweight, smooth bore tubing (CPAP Hose, Model B01MU5XLUC, RespLabs Medical Inc., Ferndale, WA); and
- 3D-printed housing to assemble a low-cost air cleaner to connect to the modified extruder cover for the engineering control (see Fig. 4).

An exhaust airflow rate of 3.4 cfm was measured through the assembled control by connecting the continuous positive airway pressure (CPAP) hose to a 2-in diameter pipe fitted with a mass flow meter (Model 620S-RFQ-4710, Sierra Instruments, Monterey, CA).

The control was evaluated in two phases, which included measuring ultrafine particle emissions with and without the control installed in the chamber and then with and without controls on the 20 MakerBot Replicator+ printers in the simulated makerspace (conference room). These tests were performed using a uniform 1-h print job for all conditions. A set of at least three replicates were completed with and without controls in place.

Results

Printer/filament emissions—chamber tests

The canister analyses from chamber samples identified the following predominant VOCs: acetone, ethanol, and isopropyl alcohol (see Table 1). Concentrations of all 20 VOCs targeted were below 50 ppb for all canister air samples collected in the chamber tests, as shown in Table 1. The highest VOC concentration that we measured in the test chamber was 40.3 ppb for ethanol during a 2-h build using ABS, and the next highest concentration was for acetone, which was measured at 38.9 ppb using IMPLA.

During the chamber tests, the highest peak ultrafine particle concentration measured by the NanoScan SMPS was 90,000 particles/cm^3 involving a Replicator+3D printer using

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IMPLA filament. These concentrations decreased to less than 10,000 particles/cm^3 after 15 min of printing (see Fig. 5). The particle size distributions and emission rates for each printer/filament combination are shown in Table 2. The geometric mean diameter of emitted particles ranged from 46 to 62 nm, with the smallest being from the Replicator+/IMPLA combination and the largest from the Replicator+/True Orange PLA combination. The emission rates ranged from 0.71 × 10^7 particles/min for the Replicator+/True Orange PLA combination to 1400 × 10^7 particles/min for the Z18/IMPLA combination (see Table 2).

During chamber tests of the extruder emission controls, the average emission rate of the 1-h prints using the Replicator+/Slate Gray Tough PLA was 199 × 10^7 particles/min with the extruder emission control off, compared with the emission rate of 3.21 × 10^7 particles/min with the control on. This equates to a 98% capture efficiency for the NIOSH print head capture hood (see Table 3). Additional bends in the flexible exhaust hose of the engineering control may have reduced the fan airflow and capture efficiency of the print head capture hood during chamber tests. During chamber emission testing, the peak concentration of particles, measured by the NanoScan SMPS, was 26,000 particles/cm^3 without the extruder emission control, compared with the peak concentration of 390 particles/cm^3 with the control (see Fig. 6). During the operation of 20 printers concurrently in the simulated makerspace (conference room), the particle concentration measured in the room air approached or exceeded 20,000 particles/cm^3 without extruder emission controls in place on all printers but remained at or below background levels (< 1000 particles/cm^3) with the controls attached and operational (see Fig. 7; Table 4).

Discussion

Emission rates found in our chamber studies were comparable with those of other published studies using similar materials for 3D printing (Azimi et al. 2016; Steinle 2016; Mendes et al. 2017; Stefaniak et al. 2017). However, results from the conference room tests indicate that many variables, such as room design, ventilation type and rate, workers moving around in the room, and changing characteristics of the emission source itself, make it difficult to predict exposure levels to printer emissions based on chamber studies alone. We found that particulate concentrations in the simulated makerspace (conference room) with multiple operating printers were much lower than those measured in the test chamber. This was likely due to the room’s greater volume and supply air ventilation, as compared with the enclosed test chamber. Time weighted average (TWA) exposure limits for the VOCs measured are based on full-shift exposure scenarios; if the concentrations found in these tests were assumed for an entire work shift, the resulting calculated exposures would be well below applicable TWAs (see Table 1).

A key finding of this study is that the development and implementation of a low-cost extruder head capture hood effectively reduced printer emissions by at least 98%. This reduced the peak ultrafine particle concentration measured in a conference room with 20 printers operating simultaneously from greater than 20,000 p/cm^3 to less than background (< 1000 p/cm^3). When equipped with a high-efficiency particulate air (HEPA) and charcoal filter, this control could potentially be retrofitted onto a 3D printer to reduce both particle

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and VOC emissions. Further research on extending this approach to other types of 3D printers could help in providing a solution both for new and in-service printers.

A second key finding of this study was the identification of True Orange PLA as a filament that produces lower ultrafine particle emissions than the other filaments we tested. It also produces lower ultrafine particle emissions than filaments tested in other 3D printing studies (Azimi et al. 2016; Steinle 2016; Mendes et al. 2017; Stefaniak et al. 2017). For example, emission rates for True Orange PLA were three to four orders of magnitude lower than the emission rates for the True Yellow ABS and IMPLA filaments evaluated during our study. Emission rates of True Orange PLA were also at least three orders of magnitude lower than those measured during a recent study of eight different PLA and ABS filaments by Stefaniak et al. (2017). Other researchers have shown that ABS filaments, in general, produce much higher particle number yields when compared with PLA (Zhang et al. 2017). Other factors such as filament color, brand, and printer brand also affect particle emissions but to a lesser effect.

Conclusions

This study evaluated a low-cost control that could be added to existing 3D printers to effectively reduce emissions to the work environment. The development of ventilation control options and guidance for the safe use of 3D printers in multiple environments should be a priority. An assessment of different filament/printer combinations showed that, while emission rates varied greatly between different filaments, the possibility of exposure to these ultrafine particles and VOCs exists for all of the configurations tested. Our testing of printers and filaments was not exhaustive and indicates that it would be prudent for manufacturers to consider the emissions when selecting the materials used in their filaments and printers. The development and use of standardized emission testing of filaments could help identify low-emitting filaments, allowing substitution as a potential exposure control for 3D printing environments. In addition, the growing body of literature on the factors affecting emissions can help assist users in selecting lower emitting filaments. Finally, implementing common sense approaches such as placing printers in an area away from other workstations and activities also provide a ready approach for reducing the potential for exposure.

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References

Adams S. (2018) Market insights: half million 3D printers sold in 2017 – on track for 100M sold in 2030. Available at https://3dprintingindustry.com/news/half-million-3d-printers-sold-2017-track-100m-sold-2030-131642/ (accessed 19 Feb 2019)

Azimi P, Zhao D, Pouzet C, Crain NE, Stephens B (2016) Emissions of ultrafine particles and volatile organic compounds from commercially available desktop three-dimensional printers with multiple filaments. Environ Sci Technol 50:1260–1268 [PubMed: 26741485]

Byeon JH, Kim J-W (2012) Particle emission from laser printers with different printing speeds. Atmos Environ 54:272–276

Byrley P, George BJ, Boyes WK, Rogers K (2019) Particle emissions from fused deposition modeling 3D printers: evaluation and meta-analysis. Sci Total Environ 655:395–407 [PubMed: 30471608]

Chan FL, House R, Kudla I, Lipszyc JC, Rajaram N, Tarlo SM (2010) Health survey of employees regularly using 3D printers. Occupational Med 68:211–214

Gümperlein I, Fischer E, Dietrich-Gümperlein G, Karrasch S, Nowak D, Jörres RA, Schierl R (2018) Acute health effects of desktop 3D printing (fused deposition modeling) using acrylonitrile butadiene styrene and polylactic acid materials: an experimental exposure study in human volunteers. Indoor Air 28:611–623 [PubMed: 29500848]

He C, Morawska L, Taplin L (2007) Particle emission characteristics of office printers. Environ Sci Technol 41:6039–6045 [PubMed: 17937279]

Kulkarni P, Baron PA, Willeke K (eds) (2011) Aerosol measurement: principles, techniques, and applications, 3rd edn. Wiley, New York

LeBouf RF, Stefaniak AB, Virji MA (2012) Validation of evacuated canisters for sampling volatile organic compounds in healthcare settings. J Environ Monit 14:977–983 [PubMed: 22322315]

Mendes L, Kangas A, Kukko K, Mølgaard B, Säämänen A, Kanerva T, Flores Ituarte I, Huhtiniemi M, Stockmann-Juvala H, Partanen J, Hämeri K, Eleftheriadis K, Viitanen A-K (2017) Characterization of emissions from a desktop 3D printer. J Ind Ecol 21:S94–S106

Scungio M, Vitanza T, Stabile L, Buonanno G, Morawska L (2017) Characterization of particle emission from laser printers. Sci Total Environ 586:623–630 [PubMed: 28196755]

Stefaniak AB, LeBouf RF, Duling MG, Yi J, Abukabda AB, McBride CR, Nurkiewicz TR (2017) Inhalation exposure to three-dimensional printer emissions stimulates acute hypertension and microvascular dysfunction. Toxicol Appl Pharmacol 335:1–5 [PubMed: 28942003]

Stefaniak AB, Johnson AR, du Preez S, Hammond DR, Wells JR, Ham JE, LeBouf RF, Menchaca KW, Martin SB Jr, Duling MG, Bowers LN, Knepp AK, Su FC, de Beer DJ, du Plessis JL (2018a) Evaluation of emissions and exposures at work-places using desktop 3-dimensional printers. J Chem Health Saf 26:19–30

Stefaniak AB, Johnson AR, du Preez S, Hammond DR, Wells JR, Ham JE, LeBouf RF, Martin SB Jr, Duling MG, Bowers LN, Knepp AK, de Beer DJ, du Plessis JL (2018b) Insights into emissions and exposures from use of industrial-scale additive manufacturing machines, safety and health at work. Saf Health Work 10(2):229–236 [PubMed: 31297287]

Steinle P (2016) Characterization of emissions from a desktop 3D printer and indoor air measurements in office settings. J Occup Environ Hyg 13:121–132 [PubMed: 26550911]

Vance ME, Pegues V, Van Montfrans S, Leng W, Marr LC (2017) Aerosol emissions from fuse-deposition modeling 3D printers in a chamber and in real indoor environments. Environ Sci Technol 51:9516–9523 [PubMed: 28789516]

Zhang Q, Wong JPS, Davis AY, Black MS, Weber RJ (2017) Characterization of particle emissions from consumer fused deposition modeling 3D printers. Aerosol Sci Technol 51: 1275–1286

Zontek TL, Ogle BR, Jankovic JT, Hollenbeck SM (2017) An exposure assessment of desktop 3D printing. J Chem Health Saf 24:15–25

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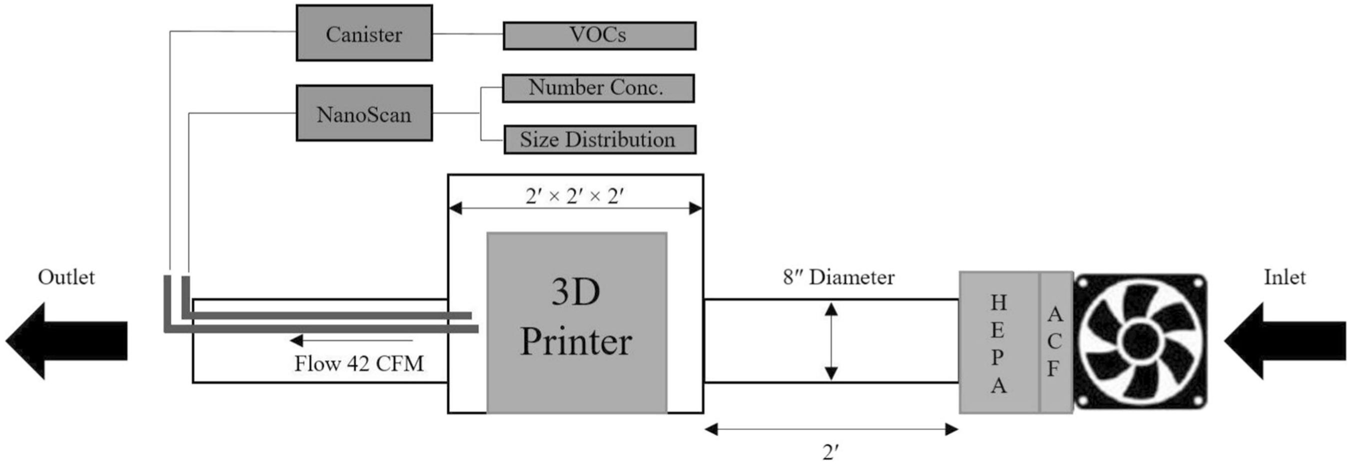

Fig. 1.
Printer emission test chamber showing dimensions and sampling equipment. Schematic by NIOSH

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Fig. 2.
Twenty MakerBot Replicator+3D printers with LEV engineering controls in a simulated makerspace (aka conference room). Photo by NIOSH

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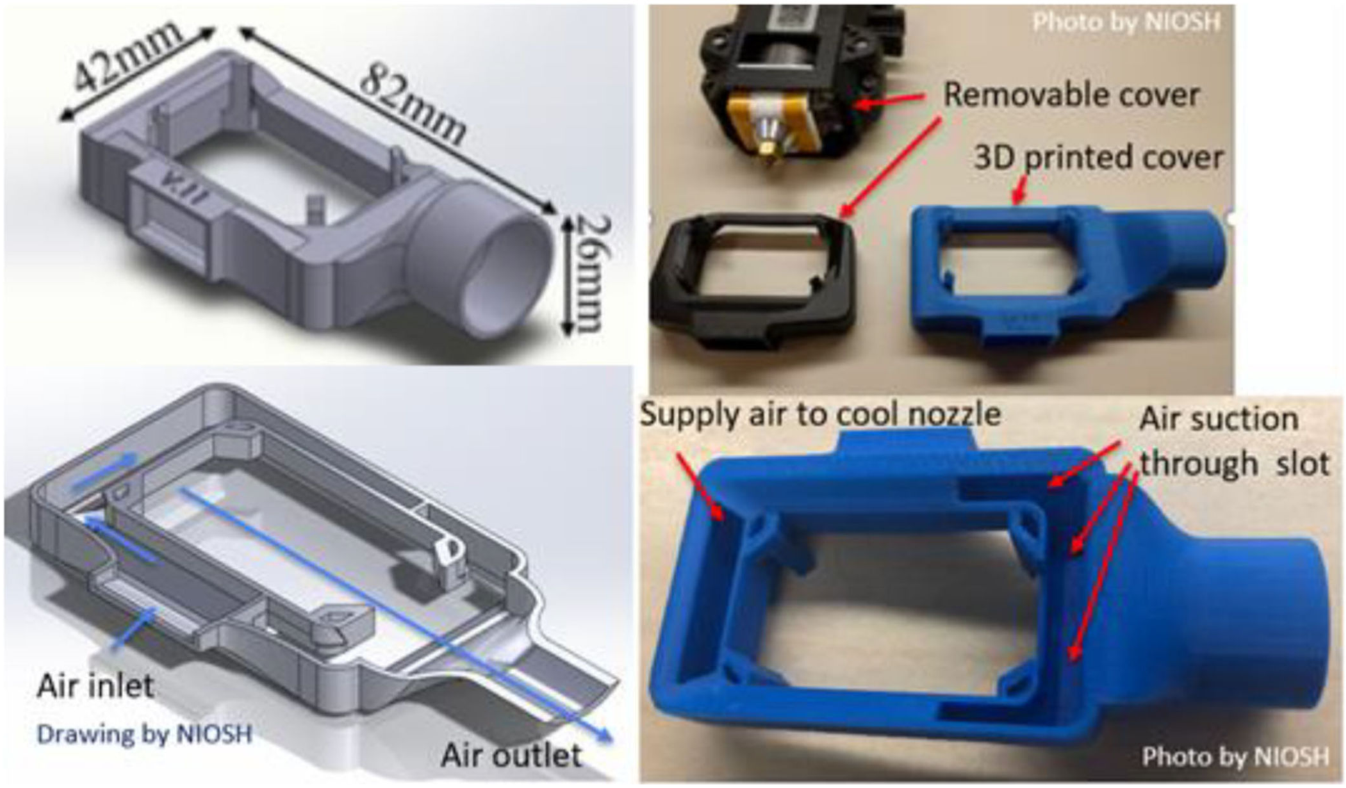

Fig. 3.

Extruder head emission control design developed to capture emissions at the point of release. Design drawings and photos by NIOSH

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Fig. 4.
Low-cost air cleaner assembly connected to a modified smart extruder cover. The HEPA filter is 14 cm (5.5 in) in diameter and 2.5 cm (1 in) in thickness

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Fig. 5.

Total number concentration of ultrafine particles from 10 to 420 nm from chamber tests with individual printer and filament combinations

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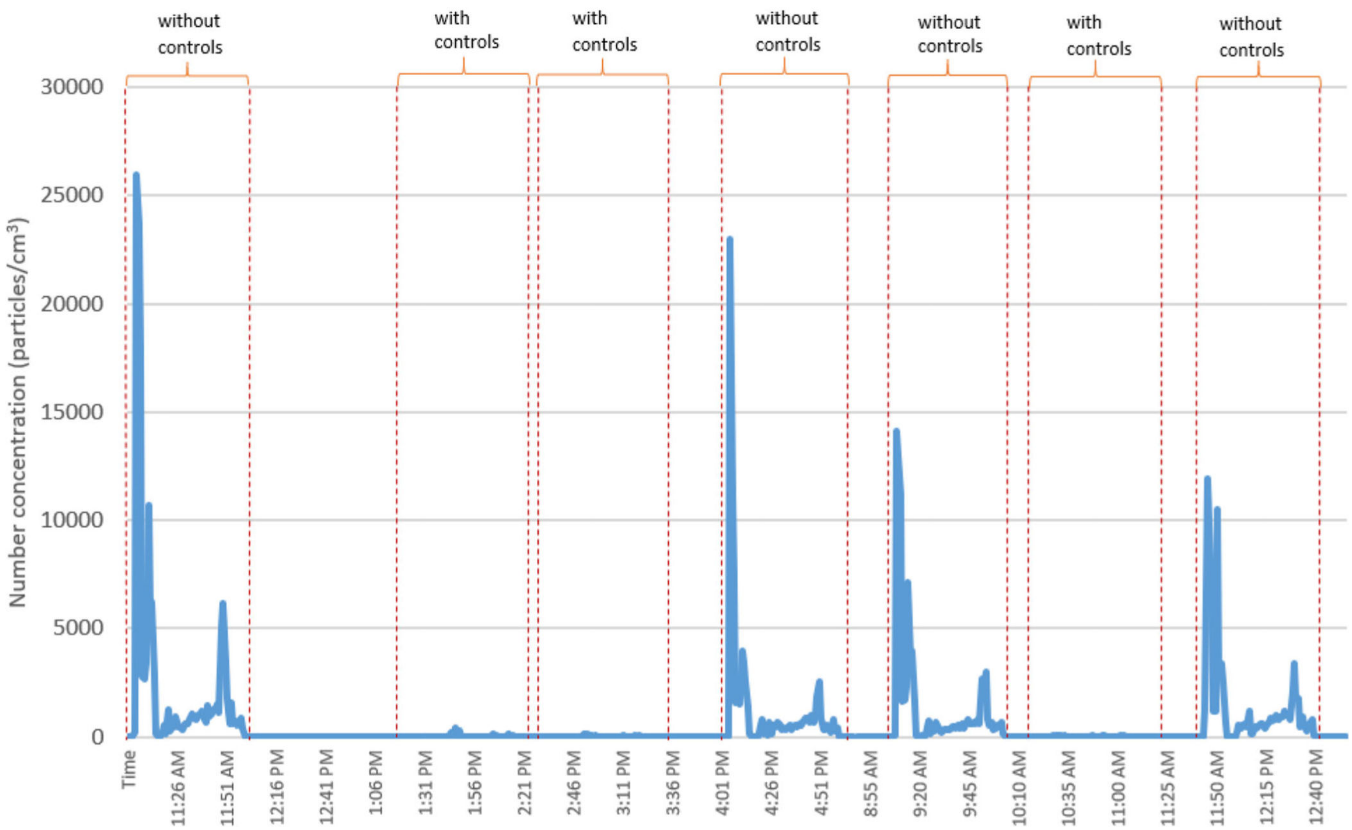

Fig. 6.
Total number concentration of particles from an individual 3D printer in the chamber with and without extruder emission control

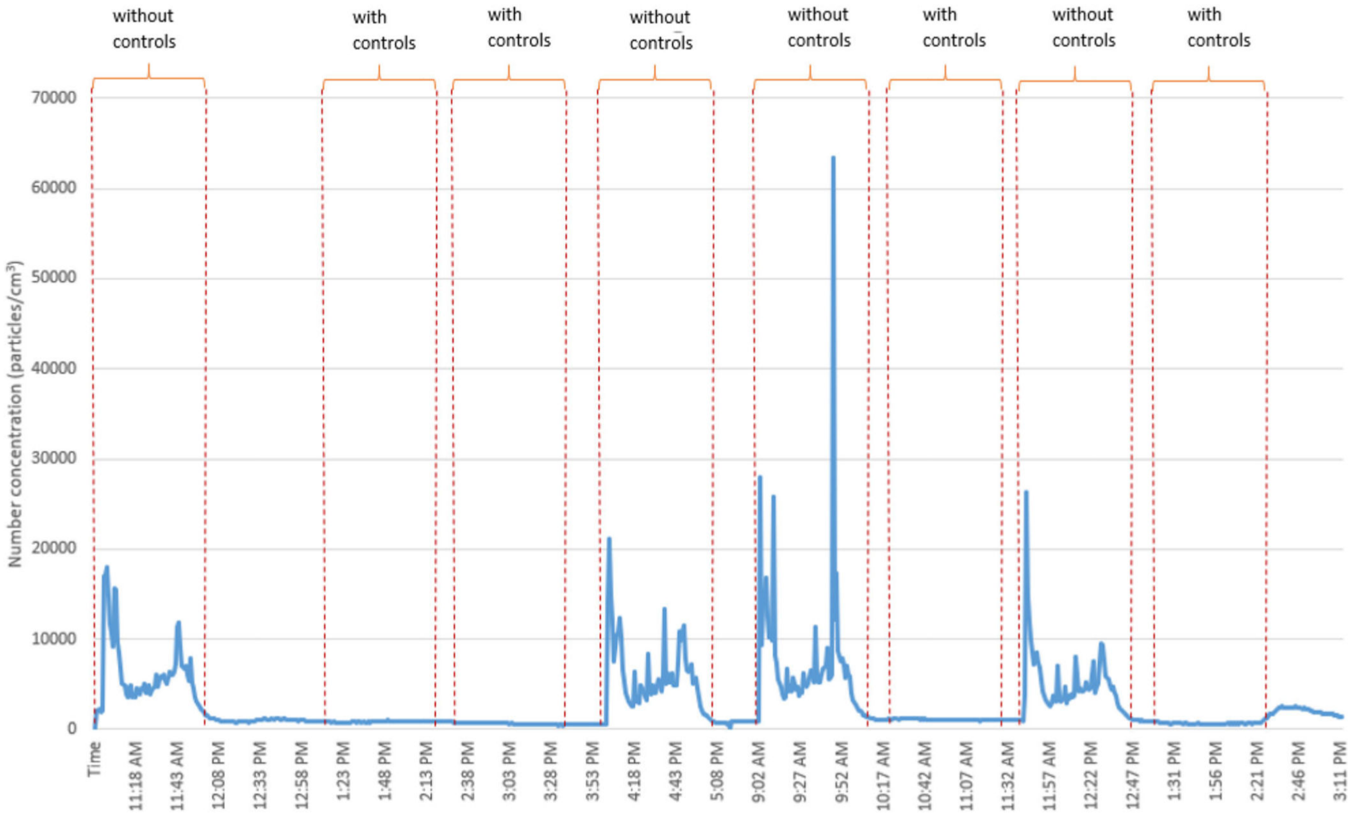

Fig. 7.
Total number concentration of particles from 20 3D printers in the conference room with and without extruder emission control

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Table 1

Individual test chamber VOC air samples collected in canisters in parts per billion (ppb)

3D printer type Filament type	BG* None	Rep 2X True Yellow ABS	Rep+ True Orange PLA	Rep+ IMPLA	Z18 IMPLA
Analyte (OEL in ppb**)					
2,3-Butanedione	0.0	0.0	0.0	0.0	0.0
2,3-Hexanedione	0.7	0.0	0.0	0.0	0.0
2,3-Pentanedione	0.0	0.0	0.0	0.0	0.0
Acetaldehyde (25,000 C)	7.7	0.0	0.0	12.5	0.0
Acetone (250,000 TWA)	5.3	9.4	6.7	38.9	7.5
Acetonitrile (20,000 TWA)	0.3	0.8	0.3	0.4	0.3
alpha-pinene	0.0	0.0	0.0	0.0	0.0
Benzene (500 TWA)	0.0	0.0	0.0	0.7	0.1
Chloroform (10,000 TWA)	0.0	0.0	0.0	0.0	0.0
D-Limonene	0.0	1.4	1.2	2.5	3.0
Ethanol (1000,000 STEL)	5.9	40.3	29.0	18.4	17.6
Ethylbenzene (20,000 TWA)	0.7	0.6	0	0.7	0.7
Isopropyl alcohol	4.5	4.7	4.5	26.7	30.1
m,p-Xylene	0.2	0.1	0.0	0.5	0.4
Methyl methacrylate (50,000 TWA)	0.7	0.0	0.0	0.0	0.0
Methylene chloride (50,000 TWA)	0.6	0.1	0.0	0.1	0.1
n-Hexane (50,000 TWA)	0.0	0.0	0.0	0.0	0.0
o-Xylene (100,000 TWA)	0.8	0.0	0.0	0.9	0.8
Styrene (20,000 TWA)	1.0	1.0	1.0	0.0	1.0
Toluene (20,000 TWA)	.2	0.1	0.1	1.2	1.2

* BG = instantaneous background air sample collected using the canister method from the outlet of the chamber

** American Conference of Governmental Industrial Hygienists (ACGIH) 8-h time-weighted average (TWA), when available or denoted as STEL for a 15-min short-term exposure limit or C for a ceiling limit

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Table 2

Particle size distributions and emission rates from the printer/filament combinations

Location	Filament	Printer type	Geometric mean diameter (nm)	Geometric standard deviation (nm)	Emission rate (particles/min)
Chamber	True Yellow ABS	Rep 2X	53.6	1.22	283×10^7
Chamber	True Orange PLA	Rep+	62.3	1.97	0.71×10^7
Chamber	IMPLA	Rep+	45.6	1.71	817×10^7
Chamber	IMPLA	Z18	49.6	1.08	1400×10^7

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Table 3

Emission rates measured with the extruder emission control on and off during 3D printing in the chamber with IMPLA filament on a Rep +

Trial number	Extruder controls (on/off)	Emission rate, particle/min	Average and 95% confidence interval
1	Off	295×10^7	199×10^7 (136×10^7−262×10^7)
2	Off	164×10^7	
3	Off	171×10^7	
4	Off	166×10^7	
5	On	3.95×10^7	3.21×10^7 (2.49×10^7−3.94×10^7)
6	On	2.91×10^7	
7	On	2.78×10^7	

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Table 4

Simulated makerspace (conference room) particle concentrations during 3D printing with 20 Rep+3D printers

Filament type	Printer type	With extruder emission controls	Average number concentration particles/cm^3	3-min avg. pretrial background particles/cm^3	Background-corrected particles/cm^3*
Slate Gray Tough PLA	20 Rep+	No	6949	2104	4845
Slate Gray Tough PLA	20 Rep+	No	6172	556	5616
Slate Gray Tough PLA	20 Rep+	No	7499	893	6606
Slate Gray Tough PLA	20 Rep+	No	5373	1011	4362
Slate Gray Tough PLA	20 Rep+	Yes	882	825	57
Slate Gray Tough PLA	20 Rep+	Yes	662	930	−268
Slate Gray Tough PLA	20 Rep+	Yes	1118	1119	−1
Slate Gray Tough PLA	20 Rep+	Yes	690	1041	−351

* Negative background-corrected results are reported when the average number concentration during a trial was lower than the pretrial background concentration