# In-Depth Lab Report

## Design and evaluation of low cost, custom, retrofitted engineering controls for 3D printing


Colleen O'Connor, MPH

LT Christopher Barnes, MS

Landen Kent

CAPT Duane Hammond, MS, PE



**Division of Field Studies and Engineering**
**Engineering and Physical Hazards Branch**
**EPHB DFSE Report No. 2022-DFSE-959**
**Alice Hamilton Laboratory**
**Cincinnati, OH**
**March 2022**

## Lab Study Site:

5555 Ridge Ave. Mailstop R-5 Cincinnati, OH 45213

## NAICS Code:

323111 Commercial Printing (except Screen and Books)

## Lab Study Dates:

May 2021 – February 2022

## Lab Study Conducted By:

Mary O’Connor, NIOSH/DFSE/EPHB

Landen Kent, NIOSH ORISE fellow

# Disclaimer

# Table of Contents

# Abstract

## Background

Multiple studies show that workers are being exposed to emissions from three-dimensional (3D) printing processes and suffering adverse health effects from the exposures. Prior to NIOSH research in this area, engineering controls that are designed to capture and filter out emissions from 3D printing processes and reduce worker exposures during 3D printing were not commonly available or they often cost more than the 3D printers themselves. In 2020, a NIOSH publication showed how a low-cost engineering control could be added to existing 3D printers to significantly reduce emissions to the work environment for a specific 3D printer model [Dunn et al. 2020]. The current laboratory study demonstrates that it is possible to develop effective low-cost engineering controls that can be added to other 3D printer models.

## Methods

NIOSH researchers used SolidWorks solid modeling computer-aided design software to design low-cost custom retrofit engineering controls for two common models of desktop 3D printers. Several components of the engineering controls were fabricated using a 3D printer and combined with an off-the-shelf fan, filter, and hose to build each control for less than $60. NIOSH researchers evaluated the effectiveness of each engineering control using an environmental test chamber to compare ultrafine particle emissions, with and without the engineering controls in place, while 3D-printing a National Institute of Standards and Technology (NIST) test artifact from black acrylonitrile butadiene styrene filament.

## Results

Average ultrafine particle concentrations measured in the outlet of the environmental test chamber while 3D Printer A was operating with and without the engineering control in place were 2 particles/$cm^3$ and 2,025 particles/$cm^3$, respectively. For 3D Printer B, average particle concentrations measured in the outlet of the environmental test chamber with and without the engineering control were 769 particles/$cm^3$ and 11,648 particles/$cm^3$, respectively. Based on these findings it can be concluded with 95% confidence that the efficiency of the local exhaust ventilation designs were greater than 99.72% and greater than 91.76% for 3D Printer A and 3D Printer B, respectively, as tested in the laboratory.

## Conclusions and Recommendations

This study showed that different designs of low-cost local exhaust ventilation controls could be added to existing 3D printers to significantly reduce emissions to the work environment. However, these results were in a controlled test environment and limited to only two 3D printers. Follow on studies should be conducted to evaluate the effectiveness of the controls in work environments. Studies should consider factors such as the location of the 3D printer, existing room ventilation, room size, workflow, printer model variation, etc.

# Introduction

## Background for Control Technology Studies

The National Institute for Occupational Safety and Health (NIOSH) is the primary Federal agency engaged in occupational safety and health research. Located in the Department of Health and Human Services, it was established by the Occupational Safety and Health Act of 1970. This legislation mandated NIOSH to conduct research and education programs separate from the standard setting and enforcement functions carried out by the Occupational Safety and Health Administration (OSHA) in the Department of Labor. An important area of NIOSH research deals with methods for controlling occupational exposure to potential chemical and physical hazards. The Engineering and Physical Hazards Branch (EPHB) of the Division of Field Studies and Engineering has been given the lead within NIOSH to study the engineering aspects of health hazard prevention and control.

Since 1976, EPHB has conducted assessments of health hazard control technologies based on industry, common industrial process, or specific control techniques. Examples of these completed studies include the foundry industry; various chemical manufacturing or processing operations; spray painting; and the recirculation of exhaust air. The objective of each of these studies has been to document and evaluate effective control techniques for potential health hazards in the industry or process of interest, and to create a more general awareness of the need for or availability of an effective system of hazard control measures.

These studies involve multiple steps or phases. Initially, a series of walk-through surveys is conducted to select plants or processes with effective and potentially transferable control concept techniques. Next, in-depth surveys are conducted to determine both the control parameters and the effectiveness of these controls. The reports from these in-depth surveys are then used as a basis for preparing technical reports and journal articles on effective hazard control measures. Ultimately, the information from these research activities builds the data base of publicly available information on hazard control techniques for use by health professionals who are responsible for preventing occupational illness and injury.

In addition to field studies, EPHB researchers also develop and evaluate the effectiveness of engineering controls in laboratory settings. Effective engineering controls developed in the laboratory setting are often later evaluated in field surveys in collaboration with partners and stakeholders.

## Background

As 3D printer technology continues to develop, it is becoming increasingly more accessible allowing it to be used as a more mainstream tool in rapid prototyping and advanced manufacturing. In 2018, the number of 3D printers purchased and shipped worldwide numbered 1.42 million units. By 2027, it is expected that units sold will reach 8.04 million [Printed Electronics Now 2020]. While industrial 3D printers make up most of the industry (77%), the market for desktop 3D printers continues to expand [Printed Electronics Now 2020]. Desktop 3D printers are becoming increasingly more accessible to a wide variety of consumers, with units available for as low as $150 [Sargent & Schwartz 2019]. With this widespread availability, 3D printing is being utilized as a tool across many applications, including academic institutions, libraries, office environments and homes [Dunn et al. 2020]. Unlike environments where industrial 3D printers are used, desktop 3D printers are typically found in non-traditional workplace settings without ventilation systems designed for exposure mitigation [Yi et al. 2016]. Most desktop 3D printers use technology referred to as fused deposition modeling (FDM) or fused filament fabrication (FFF), where a plastic filament is heated at high temperatures and extruded onto a build plate to create a 3D object. Numerous studies have shown that 3D printing processes can produce ultrafine particle (UFP) and volatile organic compound (VOC) emissions [Geiss et al. 2016; Gu et al. 2019; Vaisanen et al. 2018; Zontek et al. 2017]. Due to their size, UFPs can penetrate deeply into the alveolar regions of the lung when inhaled and can cross the lung's epithelial and endothelial cells into the blood stream [Fonseca et al. 2016]. At that point they can circulate throughout the body, reaching sensitive target organs like the heart, lymph nodes, spleen, bone marrow, liver and brain, depending on particle composition [da Costa E Oliveira, et al. 2019; Martins et al., 2010]. Breathing in high concentrations of UFPs can lead to respiratory and cardiovascular diseases as well as immune system suppression [Garcia-Hernandez et al. 2019].

Short term use of desktop 3D printers does not often lead to detectable health conditions regardless of the type of filament used [Gumperlein et al. 2018]. However, repeated exposure to 3D printing emissions has been linked to increased reports of cardiorespiratory symptoms, cutaneous symptoms, and headaches [Chan et al. 2018]. Significant increases in cytokine levels within nasal secretions has been reported after exposure to emissions from the two most commonly used 3D printing filaments, acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) [Gumperlein et al. 2017]. In some studies, exposure to 3D printing emissions was linked to development of asthma or hypersensitivity pneumonitis [House et al. 2017; Johannes et al. 2016]. Research using animal models found exposure to 3D printing emissions stimulates acute hypertension and microvascular dysfunction [Stefaniak et al., 2017]. Another study indicated persons with pre-existing respiratory and cardiovascular diseases may be at higher risk of developing adverse health effects when exposed to high levels of UFPs [Zontek et al. 2017].

Studies have also shown the effectiveness of engineering controls at capturing and reducing emissions from common 3D printing processes [Kwon et al. 2017; Dunn et al. 2020]. Additionally, NIOSH has engineering control recommendations for 3D printing that includes high efficiency particulate air (HEPA)-filtered local exhaust ventilation (LEV) placed near the 3D printing emission source and recommendations for ventilated enclosures to contain 3D printing emissions [NIOSH 2020]. Most of the commercially available engineering controls continue to cost more than the 3D printers themselves. NIOSH has previously worked to retrofit an affordable, easily produced LEV control for a commonly used desktop 3D printer [Dunn et al. 2020]. However, affordable engineering controls are needed for additional models of 3D printers.

## Background for this Study

Prior to NIOSH research in this area, engineering controls that are designed to capture and filter out emissions from 3D printing processes and reduce worker exposures during 3D printing were not commonly available or would typically cost more than the 3D printers themselves. In 2020, NIOSH published an initial study that showed how a low-cost control could be added to existing 3D printers to significantly reduce emissions to the work environment for a specific 3D printer model [Dunn et al. 2020].

In this study, NIOSH researchers applied similar design techniques developed by Dunn et al. [2020] to develop two additional NIOSH designed low-cost, custom, retrofitted engineering controls. The goal was to evaluate their effectiveness at removing emissions generated during 3D printing processes. Engineering controls developed for the two 3D printers in this study were evaluated in an environmentally controlled emissions test chamber at the CDC NIOSH Alice Hamilton laboratory.

## Control Technology

The LEV controls were designed for two commercially available desktop 3D printers representing popular open frame designs. The first control was designed to attach to 3D Printer A (Figure 1 and Figure 2). The control was designed using a commercially available computer-aided design (CAD) software program, SolidWorks (Dassault Systemes, Velizy-Villacoublay, France). The extruder attachment piece was designed and formatted to print on 3D Printer A with ABS filament. The 3D printed part was used in conjunction with a 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 a 3D-printed housing to contain the HEPA filter and provide a method to connect the 3D printed engineering control with the tubing (Figure 3).

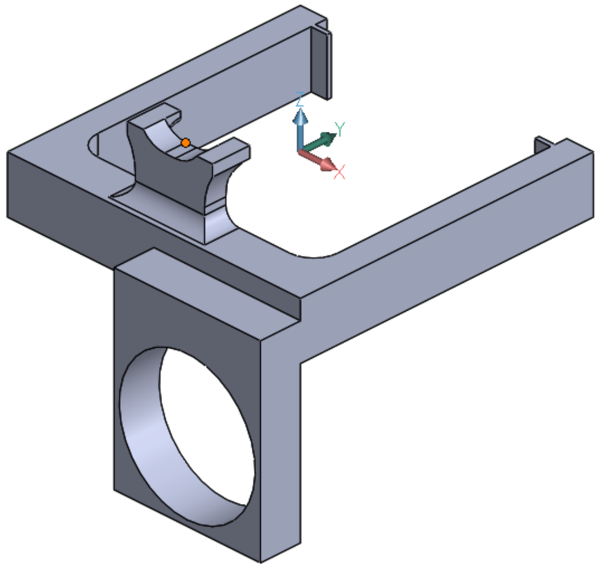

**Figure 1: LEV control designed to remove emissions from the point of origin for 3D Printer A. Design drawing by NIOSH.**

**Figure 2: 3D Printer A with LEV control attached. Photo by NIOSH.**


**Figure 3: Low-cost HEPA air cleaner assembly (left). Right picture shows the HEPA assembly connected to a 3D printed LEV capture shroud. The HEPA filter is 14 cm (5.5 in) in diameter and 2.5 cm (1 in) in thickness. Photos by NIOSH.**

3D Printer B was similarly designed using CAD software and formatted to 3D print on the desktop 3D printer using ABS filament (Figure 4 and Figure 5). The 3D printed LEV control attached to the extruder of the 3D printer and connected to the same HEPA filter unit as 3D Printer A.

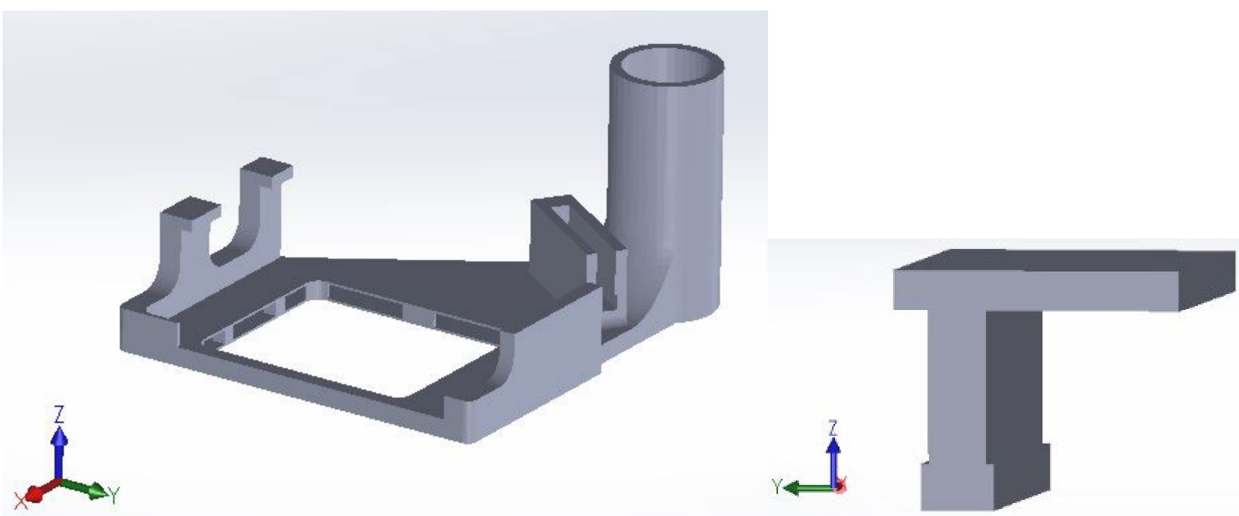


**Figure 4: LEV control designed to remove emissions from the point of origin for 3D Printer B. Left is the main body of the control, right is the tab to secure the part to the extruder head. Design by NIOSH.**


**Figure 5: 3D Printer B LEV control with tab inserted (left) and control attached to the 3D printer extruder head (right). Photos by NIOSH.**

## Occupational Exposure Limits and Health Effects

As a guide to the evaluation of the hazards posed by workplace exposures, NIOSH investigators use mandatory and recommended Occupational Exposure Limits (OELs) when evaluating chemical, physical, and biological agents in the workplace. Generally, OELs suggest levels of exposure to which most workers may be exposed up to 10 hours per day, 40 hours per week for a working lifetime without experiencing adverse health effects. It is, however, important to note that not all workers will be protected from adverse health effects even though their exposures are maintained below these levels. A small percentage may experience adverse health effects because of individual susceptibility, a pre-existing medical condition, and/or hypersensitivity (allergy). In addition, some hazardous substances may act in combination with other workplace exposures, the general environment, or with medications or personal habits of the worker to produce health effects even if the occupational exposures are controlled at the level set by the exposure limit. Combined effects are often not considered in the OEL. Also, some substances are absorbed by direct contact with the skin and mucous membranes, and thus can increase the overall exposure. Finally, OELs may change over the years as new information on the toxic effects of an agent become available.

Most OELs are expressed as a TWA exposure. A TWA exposure refers to the average airborne concentration of a substance during a normal 8- to 10-hour workday. Some substances have a recommended Short Term Exposure Limit (STEL) or ceiling values which are intended to supplement the TWA where there are recognized toxic effects from higher exposures over the short-term.

In the U.S., OELs have been established by Federal agencies, professional organizations, state and local governments, and other entities. The U.S.

Department of Labor OSHA Permissible Exposure Limits (PELs) [29 CFR 1910.1000 2003] are occupational exposure limits that are legally enforceable in covered workplaces under the Occupational Safety and Health Act. NIOSH recommendations are based on a critical review of the scientific and technical information available on the prevalence of health effects, the existence of safety and health risks, and the adequacy of methods to identify and control hazards [NIOSH 1992]. They have been developed using a weight of evidence approach and formal peer review process. Other OELs that are commonly used and cited in the U.S. include the Threshold Limit Values (TLVs®) recommended by American Conference of Governmental Industrial Hygienists (ACGIH®), a professional organization [ACGIH 2013]. ACGIH® TLVs are considered voluntary guidelines for use by industrial hygienists and others trained in this discipline "to assist in the control of health hazards." Workplace Environmental Exposure Levels® (WEELs) are recommended OELs developed by the American Industrial Hygiene Association® (AIHA), another professional organization. WEELs have been established for some chemicals "when no other legal or authoritative limits exist" [AIHA 2007].

OSHA requires an employer to furnish employees a place of employment that is free from recognized hazards that are causing or are likely to cause death or serious physical harm [Occupational Safety and Health Act of 1970, Public Law 91–596, sec. 5(a)(1)]. Thus, employers are required to comply with OSHA PELs. Some hazardous agents do not have PELs, however, and for others, the PELs do not reflect the most current health-based information. Thus, NIOSH investigators encourage employers to consider the other OELs in making risk assessment and risk management decisions to best protect the health of their employees. NIOSH investigators also encourage the use of the traditional hierarchy of controls approach to eliminating or minimizing identified workplace hazards. This includes, in preferential order, the use of: (1) substitution or elimination of the hazardous agent, (2) engineering controls (e.g., LEV, process enclosure, dilution ventilation), (3) administrative controls (e.g., limiting time of exposure, employee training, work practice changes, medical surveillance), and (4) personal protective equipment (e.g., respiratory protection, gloves, eye protection, hearing protection).

### *Occupational Exposure Limits for 3D Printing Emissions*

The focus of this study was on controlling ultrafine particle emissions. Currently there are no PELs, RELS, or TLVs® for ultrafine particle emissions from 3D printing. PELs, RELs, and TLVs® have been established for many of the VOCs emitted during 3D printing with filaments. However, past NIOSH research has shown the common VOCs generated when 3D printing with filaments are well below OELs in well ventilated spaces [Dunn et al. 2020].

# Methodology

## Evaluation Procedures

All tests were conducted inside of a HEPA filtered environmental test chamber that was located inside of a HEPA filtered room to eliminate background particles.

Specifically, each 3D printer was placed in an emissions test chamber, a 0.22 $m^3$ (8 cubic-feet ($ft^3$)) testing chamber constructed from 80/20 aluminum and acrylic sheets. The chamber was connected by a 20 centimeter (cm) (8-inch) flexible duct to a portable air cleaner with a HEPA air filter (Sentry Air Systems, Inc., Houston, TX, USA) which provided constant filtered air flow through the chamber (Figure 6 and Figure 7). Air flow rate through the chamber was measured by removing the 20 cm (8-inch) outlet duct and placing an Alnor EBT731 Balometer fitted with a 0.6 m x 0.6 m (2-ft x 2-ft) hood (TSI Inc., Shoreview, MN, USA) over the 0.6 m x 0.6 m (2-ft x 2-ft) acrylic panel that includes the 20 cm (8-inch) outlet hole of the environmental test chamber. Average air flow was measured to be 59 cubic meters per hour ($m^3$/h) (35 cubic feet per minute (CFM)). The chamber had a flexible duct connected to the side opposite from the fan to allow for collection of emission data during the tests. Data were collected using a NanoScan Scanning Mobility Particle Sizer (NanoScan SMPS 3910; TSI Inc., Shoreview, MN, USA) and a Condensation Particle Counter (CPC 3007; TSI Inc., Shoreview, MN, USA). Both instruments were used for data collection since each has different collection rates and size ranges. The Nanoscan measures particles from 10 nanometers (nm) to 420 nm in size every minute allowing for a total number concentration up to 1,000,000 particles/$cm^3$ and particle size distribution data in 13 size channels. The CPC measures a size range from 10 nm to 1,000 nm every second in a single size bin up to a maximum total number concentration of 100,000 particles/$cm^3$. Size distribution data from the Nanoscan showed that nearly all measured particles were below 200 nm in size and the total number concentration of particles measured per trial were very similar between instruments. Therefore, only results from the Nanoscan were used for the performance analyses described in this report and the CPC data were only used as a check to verify consistency with the readings from the Nanoscan. Both instruments were factory calibrated by the manufacturer prior to data collection.

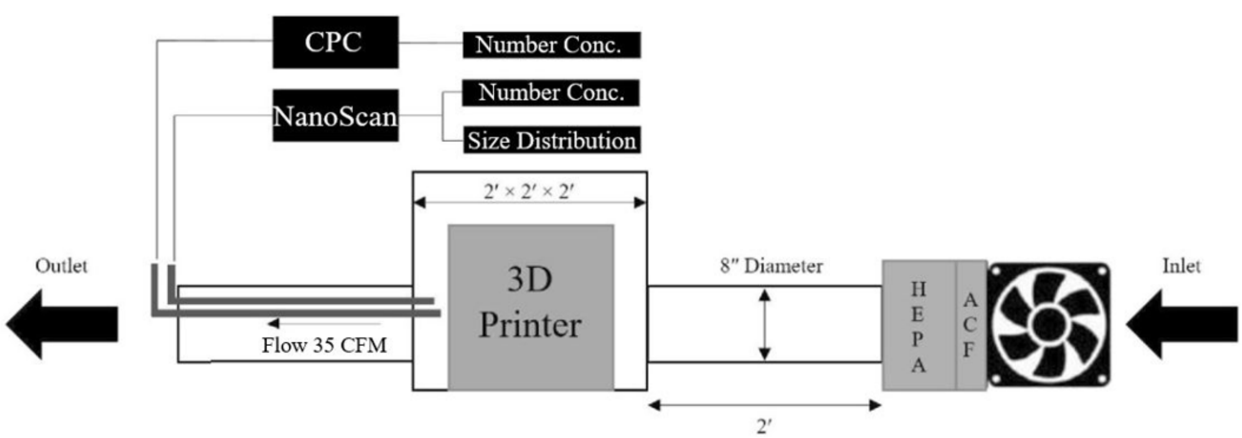


**Figure 6: 3D printer emission test chamber schematic showing dimensions and sampling equipment. Schematic by NIOSH.**

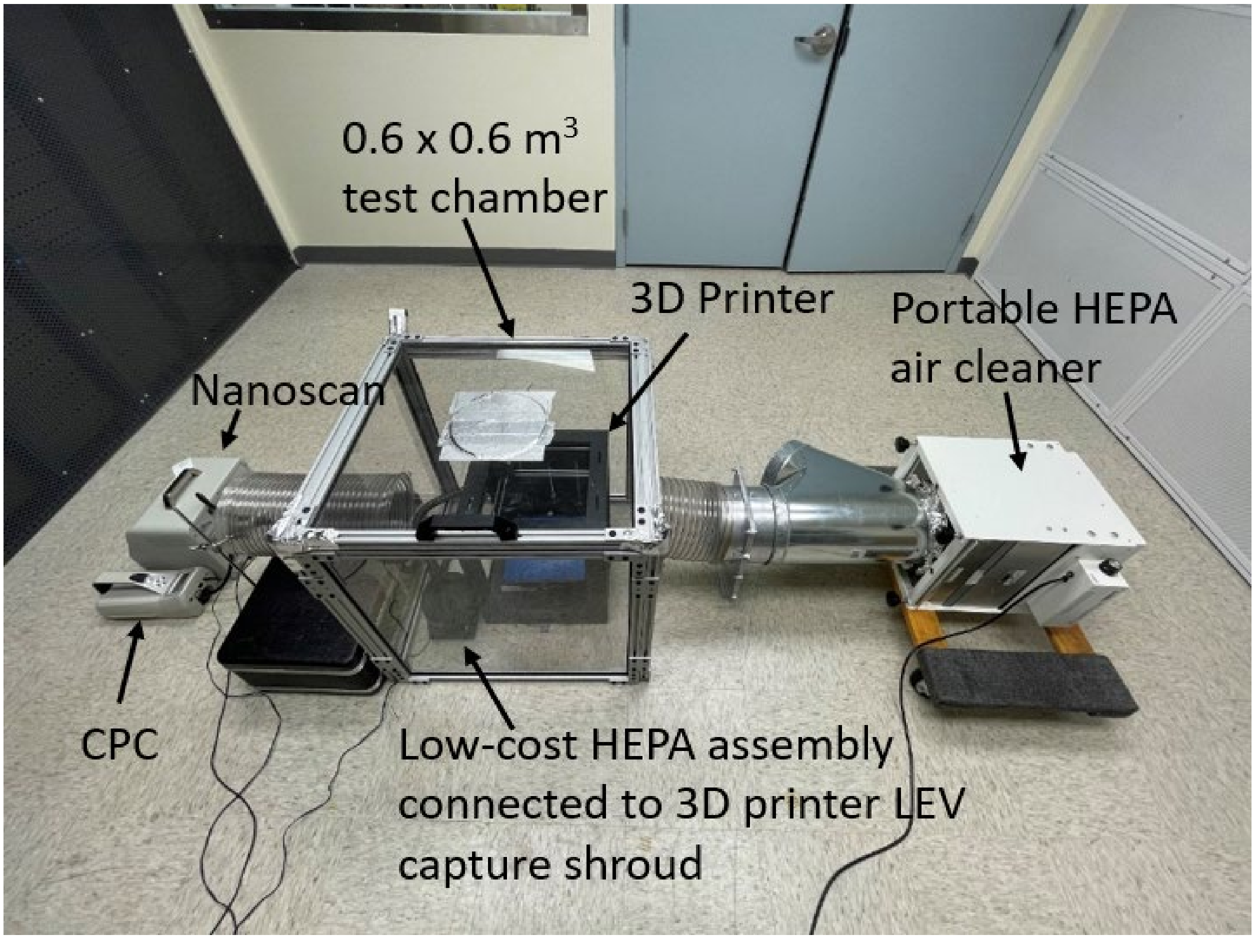


**Figure 7: Actual 3D printer emission test chamber with 3D Printer A and sampling equipment. Photo by NIOSH.**

Each LEV control was evaluated using randomized pairs of control-on versus control-off test trials. Ten test pairs (twenty individual trials) were performed for each 3D printer. All tests were conducted while 3D printing a National Institute of Standards and Technology (NIST) test artifact (Figure 8), designed to assess the performance of 3D printing systems [Moylan et al. 2014]. The test artifact was scaled down in size to reduce 3D printing time to approximately one hour. All 3D printing was performed with Matterhackers Build Series brand black ABS filament (Matterhackers Inc., Lake Forest, CA, USA).

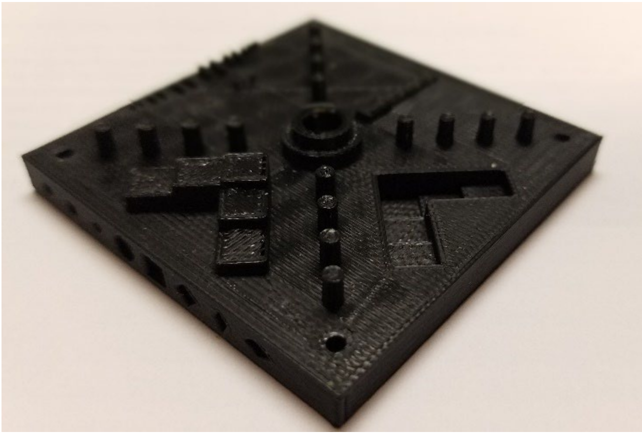

**Figure 8: NIST test artifact 3D printed in ABS. Photo by NIOSH.**

## Statistical Procedures

Once all test prints were completed, the emissions data obtained from the NanoScan and Condensation Particle Counter were analyzed using the average particle concentration measured in the outlet of the chamber for each trial. Capture efficiency was calculated for each randomized pair of control on versus control off trials using Equation 1:

Equation 1:

$$\eta = \frac{C_{off} - C_{on}}{C_{off}} \times 100$$

where

η is the capture efficiency,

$C_{off}$ is the average particle concentration measured in the outlet of the chamber during a trial when the engineering control was turned off, and

$C_{on}$ is the average particle concentration measured in the outlet of the chamber during a trial when the engineering control was turned on.

Minimum overall capture efficiency of each engineering control was calculated following the procedures described in NIOSH Publication No. 97-105 [NIOSH 1997]. Since all tests were conducted inside of a HEPA filtered environmental test chamber located within a HEPA filtered room, it was not necessary to correct for the influence of background particles. We measured a zero-particle concentration on both instruments before beginning each trial. The mean capture efficiency (m) was calculated by taking the average of ten control on versus control off capture efficiency pairs. The estimated standard deviation (s) was also calculated for the set of n=10 capture efficiency pairs.

The value for (t) was selected from the Student's t-distribution table at the 95th percentile based on the value of (n-1), i.e. (10-1). This information was then used to calculate the test statistic (T) to confirm, with 95% confidence, the minimum capture efficiency for each evaluated engineering control as shown in Equation 2.

Equation 2:

$$T = m - \frac{(t \times s)}{n^{0.5}}$$

# Results

Results confirmed that the HEPA filtered chamber located in the HEPA filtered room achieved a zero-particle concentration before each trial and background corrections of the data were not needed. The results from the chamber studies with the NIOSH-designed custom retrofit engineering controls for 3D Printer A (Table 1) and 3D Printer B (Table 2) demonstrate consistent reductions in average particle concentrations while 3D printing NIST test artifacts in a laboratory setting. As shown in Table 1, it can be concluded with 95% confidence that the efficiency of the engineering control for 3D Printer A is greater than 99.72% as tested in the laboratory. As shown in Table 2, it can be concluded with 95% confidence that the efficiency of the engineering control for 3D Printer B is greater than 91.76% as tested in the laboratory.

Without controls, average particle concentration per trial measured in the outlet of the chamber for 3D Printer A ranged from 331 to 4,408 particles/cm$^3$. With the engineering control in place, the average particle concentrations per trial ranged between 0.196 to 16 particles/cm$^3$. The average particle concentration with and without the engineering control was 2 and 2025 particles/cm$^3$, respectively, resulting in an average capture efficiency of 99.87% for 3D printer A. Table 1 summarizes the particle concentration and capture efficiency data obtained from the 3D Printer A, while Figure 9 provides a graphical representation of emission trends throughout each 3D printing trial for 3D Printer A.

**Table 1: 3D Printer A capture efficiency of ultrafine particles during 3D printing test trials**

| Test # | No Control (#/cc) | Control (#/cc) | Capture Efficiency (%) |
|---|---|---|---|
| 1 | 4408.53 | 1.46 | 99.97% |
| 2 | 2242.81 | 0.86 | 99.96% |
| 3 | 2811.58 | 0.48 | 99.98% |
| 4 | 2255.02 | 0.34 | 99.98% |
| 5 | 1743.29 | 0.75 | 99.96% |
| 6 | 1903.79 | 16.22 | 99.15% |
| 7 | 977.50 | 0.20 | 99.98% |
| 8 | 2894.19 | 0.29 | 99.99% |
| 9 | 331.85 | 0.54 | 99.84% |
| 10 | 684.23 | 0.60 | 99.91% |
| Average Particle Concentration | 2025.28 | 2.17 | |
| **Average Capture Efficiency** | | | **99.87%** |
| **Test Statistic** | | | **99.72** |

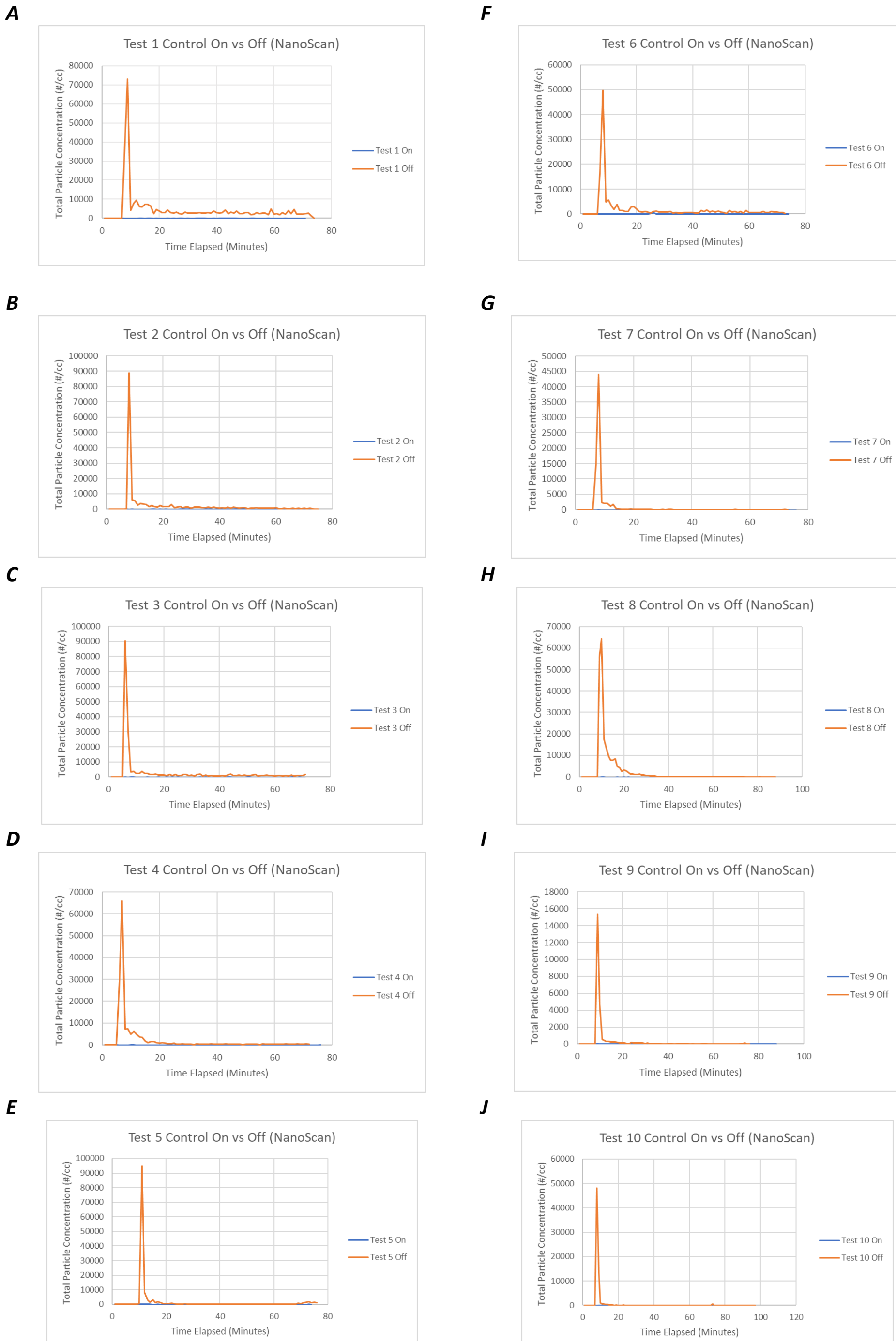


**Figure 9: 3D Printer A - total particle concentration vs time with and without the custom retrofitted engineering control.**

For 3D Printer B, the average particle concentrations per trial ranged from 918 to 85,130 particles/cm$^3$ with no control. When equipped with the NIOSH designed engineering control, average particle concentrations per trial ranged from 10 to 6,502 particles/cm$^3$. The overall average particle concentration of the ten chamber studies performed without the engineering control in place was 11,648 particles/cm$^3$. With the control in place, the overall average particle concentration was reduced to 769 particles/cm$^3$. A mean capture efficiency of 95.26% was achieved with the integration of the engineering control for 3D Printer A. It can be concluded with 95% confidence, that the capture efficiency of the engineering control for 3D Printer A is greater than 91.76%. Table 2 highlights the particle concentration data and capture efficiency calculations for 3D Printer A and Figure 10 provides graphical representation of how emissions trended up and down throughout each 3D printing trial.

**Table 2: 3D Printer B capture efficiency of ultrafine particles during 3D printing test trials**

| Test # | No Control (#/cc) | Control (#/cc) | Capture Efficiency (%) |
|---|---|---|---|
| 1 | 6719.40 | 41.75 | 99.38% |
| 2 | 1177.04 | 10.83 | 99.08% |
| 3 | 8102.86 | 20.10 | 99.75% |
| 4 | 1153.55 | 17.47 | 98.49% |
| 5 | 5175.72 | 810.51 | 84.34% |
| 6 | 2770.26 | 124.77 | 95.50% |
| 7 | 2672.49 | 19.20 | 99.28% |
| 8 | 918.10 | 138.00 | 84.97% |
| 9 | 2661.45 | 13.76 | 99.48% |
| 10 | 85130.85 | 6502.37 | 92.36% |
| Average Particle Concentration | 11648.17 | 769.88 | |
| **Average Capture Efficiency** | | | **95.26%** |
| **Test Statistic** | | | **91.76%** |

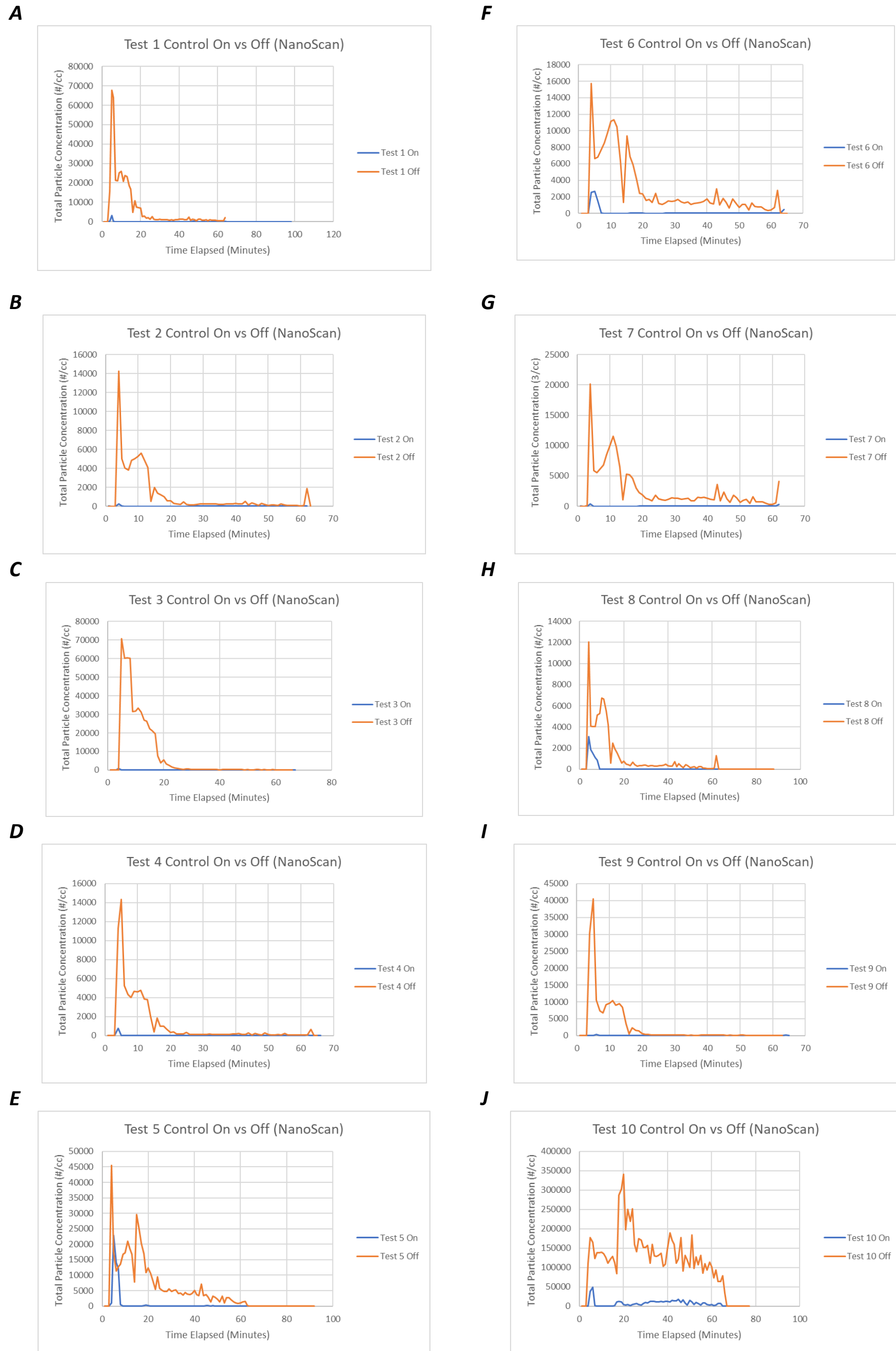


**Figure 10: 3D Printer B – total particle concentration vs time with and without the custom retrofitted engineering control.**

# Discussion

The initial spike seen in all our tests is a common phenomenon observed when evaluating particle concentrations from 3D printing with filaments. The causative reason for this is not known. Other 3D printing emission studies have found that particle concentrations increase rapidly to a peak a few minutes after 3D printing begins and decay to background while 3D printing continues [Dunn et al. 2020; Mendes et al. 2017; Yi et al. 2016].

Multiple studies have also shown that there is inherent variability in UFP emissions during repeat tests with FDM and FFF 3D printing [Azimi et al. 2016; Zhang et al. 2017]. Our study also demonstrated substantial variability during repeat tests. Average particle concentrations measured in the outlet of our environmental test chamber varied greatly between and within the two models of 3D printers used in this study. The same brand and color of filament material, 3D print object (NIST test artifact), chamber settings (air flow rate and air temperature), were all held consistent throughout the study. However, we observed substantial variability in measured particle concentrations from trial to trial during the study. Without the engineering control, particle concentrations for 3D Printer A varied by as much as 1,304% between test trials. However, even with the large variability in emissions, the NIOSH developed engineering control consistently provided a 99.15% or greater capture efficiency in 3D Printer A emissions for all trials.

Measured particle concentrations for 3D Printer B were also highly variable without the NIOSH developed engineering control in place. Particle concentrations measured in the chamber during 3D Printer B trials showed a 9,172% difference between the maximum and minimum average test trial. This variability is approximately seven times greater than what was measured with 3D Printer A. The highest particle concentration measurement occurred after a print failure in trial 10 (Table 2). This failure also resulted in the highest concentration over time than any other test print performed by 3D Printer B Figure 9 (J). The root cause of the print failure was poor adhesion of the NIST test artifact to the printing platform and the custom 3D printed engineering control became clogged as a result of the print failure. The control was removed and cleaned by carefully using tweeters and air to remove shavings of filament. Trial 10 was repeated after the failure, but elevated particle concentrations were noted for both test prints with and without the engineering control. Test trial three had the next highest particle concentration count without the engineering control. A 1,209% change in particle concentration between trial three and 10 was noted. With the engineering control, trial six had the second greatest particle concentration recorded. A change of 5,111% was observed in the particle concentration counts between trial six and 10.

Variability was also observed in the capture efficiency of the custom engineering control developed for 3D Printer B. Capture efficiencies of 84.34% and 84.97% were observed for test trials five and eight, respectively, in the test chamber studies. This is in contrast to an average capture efficiency exceeding 97.9% over the remaining 8 test trials for 3D Printer B. The inherent variability in particle concentrations observed for 3D Printer B with and without the control may have contributed to the occasional lower capture efficiencies.

It is unclear what caused the elevated particle concentrations following the print failure that occurred prior to trial 10 but it is possible that filament melted onto the hot end of the extruder emitting more particles on the following run or another unknown cause. While these print-failure events appear to have potentially contributed to moderate reductions in control efficiency, the failures also represent real-world events and the control efficiencies still exceeded 80% under these more extreme scenarios.

# Conclusions and Recommendations

3D printing is an emerging technology commonly used in traditional workplace settings, such as manufacturing plants, academic institutions, and office environments. 3D printing is also used by self-employed/freelance workers and consumers for personal applications. In this study, NIOSH researchers developed custom low cost, retrofitted engineering controls for two 3D printer models. A series of 10 paired trials with and without engineering controls while 3D printing a NIST test artifact inside an environmentally controlled test chamber were performed for both 3D printers. This was done to assess the average particle concentrations produced by the 3D printers without the control, and to analyze the capture effectiveness of the NIOSH-designed engineering control attached to the 3D printers.

With 95% confidence, our study found that the NIOSH designed custom engineering controls were able to reduce average particle concentrations by more than 99.72% for 3D Printer A and more than 91.76% for 3D Printer B. This study was conducted in a controlled laboratory environment, however, it highlights the possibility of developing, validating, and implementing low-cost engineering controls that can be retrofitted to existing 3D printers. Follow on studies should be performed in both traditional and non-traditional as-used work environments. Factors such as room ventilation, size, workflow, location, etc. should be accounted for and evaluated in these studies.

In a couple of the trials using 3D Printer B, print failure events occurred and appeared to contribute to associated variabilities in particle count generation. These events are indicative that it is important to inspect and clean the engineering control following any print failures, to prevent the control from becoming clogged with debris that may block airflow and subsequently reduce performance.

# References

Azimi, P.; Zhao, D.; Pouzet, C.; Crain, N. E.; 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(3), 1260.

Chan, F. L., House, R., Kudla, I., Lipszyc, J. C., Rajaram, N., & Tarlo, S. M. [2018]. Health survey of employees regularly using 3D printers. *Occupational Medicine, 68*(3), 211-214. doi:10.1093/occmed/kqy042

Dunn KL, Hammond D, Menchaca K, Roth G, Dunn KH [2020]. Reducing ultrafine particulate emission from multiple 3D printers in an office environment using a prototype engineering control. J Nanopart Res 22(5):112.

House, R., Rajaram, N., & Tarlo, S. M. [2017]. Case report of asthma associated with 3D printing. *Occupational Medicine (Oxford, England), 67*(8), 652-654. doi:10.1093/occmed/kqx129.

Fonseca, A. S., Viana, M., Pérez, N., Alastuey, A., Querol, X., Kaminski, H., Asbach, C. [2016]. Intercomparison of a portable and two stationary mobility particle sizers for nanoscale aerosol measurements. *Aerosol Science and Technology, 50*(7), 653-668. doi:10.1080/02786826.2016.1174329

Garcia-Hernandez, C., Ferrero, A., Estarlich, M., & Ballester, F. [2019]. Exposure to ultrafine particles in children until 18 years of age: A systematic review. *Indoor Air,* doi:10.1111/ina.12620

Geiss O., Bianchi I., Barrero-Moreno J. [2016]. Lung-deposited surface area concentration measurements in selected occupational and non-occupational environments. J Aerosol Sci. 96:24–37.

Gu J, Wensing M, Uhde E, Salthammer T [2019]. Characterization of particulate and gaseous pollutants emitted during operation of a desktop 3D printer. Environ Int. 123:476-485.

Gumperlein, I., Fischer, E., Dietrich-Gumperlein, G., Karrasch, S., Nowak, D., Jorres, R. A., & 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*(4), 611-623. doi:10.1111/ina.12458

House, R., Rajaram, N., & Tarlo, S. M. [2017]. Case report of asthma associated with 3D printing. Occupational Medicine, 67(8), 652-654. doi:10.1093/occmed/kqx129

Johannes, J., Rezayat, T., Wallace, W. D., & Lynch, J. P. [2016]. Chronic hypersensitivity pneumonitis associated with inhaled exposure to nylon powder for 3-D printing: A variant of nylon flock worker's lung disease? *D46. case reports in environmental and occupational health* (pp. A7071) American Thoracic Society.

doi:10.1164/ajrccm-conference.2016.193.1_MeetingAbstracts.A7071 Retrieved from https://doi.org/10.1164/ajrccm-conference.2016.193.1_MeetingAbstracts.A7071

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

S.P. Moylan, J.A. Slotwinski, A.L. Cooke, K.K. Jurrens, and M.A. Donmez (2012), "Proposal for a standardized test artifact for additive manufacturing machines and processes," Proceedings of the 23rd International Solid Free Form Symposium – An Additive Manufacturing Conference, Austin, TX, USA, August 2012, pp. 902-920.

NIOSH [1997]. Engineering Control Guidelines for Hot Mix Asphalt Pavers Part 1 New Highway-Class Pavers18–20. Cincinnati, OH: U.S. Dept. of Health and Human Services, Public Health Service, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 97-105.

NIOSH [2020]. 3D printing with filaments: Health and safety questions to ask. By Glassford E, Dunn KL, Dunn KH, Hammond D, Tyrawski J. Cincinnati, OH: U.S. Department of Health and Human Services, Centers for Disease Control and Prevention, National Institute for Occupational Safety and Health, DHHS (NIOSH) Publication No. 2020-115, https://doi.org/10.26616/NIOSHPUB2020115

Printed Electronics Now [2020]. GVR. Global 3D Printing Market Size was $11.58 Billion in 2019. Available at https://www.printedelectronicsnow.com/contents/view_breaking-news/2020-02-10/gvr-global-3d-printing-market-size-was-1158-billion-in-2019/#:~:text=The%20global%203D%20printing%20market,)%2C%20By%20Printer%20Type%20(Desktop (accessed 01 Feb 2020)

Sargent Jr, JF, & Schwartz, RX [2019]. 3D printing: Overview, impacts, and the federal role. Congressional Research Service, R45852, 1-15. Retrieved from https://fas.org/sgp/crs/misc/R45852.pdf

Stefaniak A.B., LeBouf R.F., Duling M.G., Yi J., Abukabda A.B., McBride C.R. [2017]. Inhalation exposure to three-dimensional printer emissions stimulates acute hypertension and microvascular dysfunction. Toxicol Appl Pharmacol. 335:1–5.

Vaisanen AJK, Hyttinen M, Ylonen S, Alonen L. [2018]. Occupational exposure to gaseous and particulate contaminants originating from additive manufacturing of liquid, powdered and filament plastic materials and related post-processes. J Occup Environ Hyg. 16:258-271.

Yi, J, LeBouf, RF, Duling, MG, Nurkiewicz, T, Chen, BT, Schwegler-Berry, D, Virji, MA, Stefaniak, AB [2016]. Emission of particulate matter from a desktop three-dimensional (3D) printer. Journal of Toxicology and Environmental Health.Part A, 79(11), 453-465. doi:10.1080/15287394.2016.1166467

Zhang, Q.; Wong, J. P. S.; Davis, A. Y.; Black, M. S.; Weber, R. J. [2017]. Chemical Composition and Toxicity of Particles Emitted from a Consumer-Level 3D Printer Using Various Materials. Aerosol Sci. Technol., 51(11), 1275.

Zontek, TL, Ogle, BR, Jankovic, JT, & Hollenbeck, SM [2017]. An exposure assessment of desktop 3D printing. Journal of Chemical Health & Safety, 24(2), 15-25. doi:10.1021/acs.chas.8b24206

# Delivering on the Nation's promise: Promoting productive workplaces through safety and health research

## Get More Information

Find NIOSH products and get answers to workplace safety and health questions:

1-800-CDC-INFO (1-800-232-4636) | TTY: 1-888-232-6348
CDC/NIOSH INFO: cdc.gov/info | cdc.gov/niosh
Monthly *NIOSH eNews*: cdc.gov/niosh/eNews