# UL 200B

## GUIDANCE DOCUMENT

Safe Use of 3D Printing for Institutions of Higher Education

Guidance Document on the Safe Use of 3D Printing for Institutions of Higher Education, UL 200B

First Edition, Dated May 8, 2023

***SUMMARY OF TOPICS***

***This guideline publication of UL 200B dated May 8, 2023 provides a resource for the safe use of 3D printing in institutions of higher education.***

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# UL 200B

# Guidance Document on the Safe Use of 3D Printing for Institutions of Higher Education

**First Edition**

**May 8, 2023**

A Chemical Insights Research Institute of UL Research Institutes and
Campus Safety, Health, and Environmental Management
Association (CSHEMA) Collaboration

These guidelines (The Guide) provides a resource for the safe use of 3D printing in institutions of higher education.

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## About the Task Force

Additive manufacturing, or 3-dimensional (3D) printing, is a valuable tool that has transformed research, instruction, and the student experience in higher education. The use of 3D printing in education recently tripled within two years.[1] As with so many new technologies, there are unintended consequences and safety considerations that must be managed in higher education settings. Research shows that steps can be taken to mitigate these unintended consequences and allow users to leverage the benefits and innovative capabilities of 3D printing safely with fewer impacts on human health.

To address this issue and provide a resource for institutions of higher education, discussions and reviews were facilitated among an expert group of volunteers convened by Chemical Insights Research Institute (CIRI) and the Campus, Safety, Health, and Environmental Management Association (CSHEMA). This group is known as the CIRI + CSHEMA Task Force on 3D Printing in Higher Education. The task force consists of chemical exposure experts and campus environmental health and safety (EHS) professionals from a variety of universities in the United States.

The following volunteers are acknowledged for their participation in the discussions, collaborations, and material reviews involved in the creation of this guidance document.

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## Table of Abbreviations

| | |
|---|---|
| 3D | Three-dimensional |
| 3DP | 3D printing |
| CSHEMA | Campus Safety, Health, and Environmental Management Association |
| CIRI | Chemical Insights Research Institute |
| ABS | Acrylonitrile Butadiene Styrene |
| ACH | Air Changes per Hour |
| AQG | Air Quality Guidelines |
| ASA | Acrylonitrile Styrene Acrylate |
| ASHRAE | American Society of Heating, Refrigeration and Air Conditioning Engineers |
| DLP | Digital Light Processing |
| DMLS | Direct Metal Laser Sintering |
| EBAM | Electron Beam Additive Manufacturing |
| EBM | Electron Beam Melting |
| FDM | Fused Deposition Modeling |
| FFF | Fused Filament Fabrication |
| HEPA | High Efficiency Particulate Air |
| LEED | Leadership in Energy and Environmental Design |
| LENS | Laser Engineered Net Shaping |
| LMD | Laser Metal Deposition |
| LOM | Laminated Object Manufacturing |
| MJ | Material Jetting |
| MJM | Multi-Jet Modeling |
| NIOSH | National Institute for Occupational Safety and Health |
| PA | Polyamide |
| PBIH | Powder Bed and Inkjet Head |
| PC | Polycarbonate |
| PEEK | Polyetheretherketone |
| PEI | Polyetherimide |
| PETG | Polyethylene Terephthalate with added Glycol |
| PLA | Polylactic Acid |
| PP | Polypropylene |
| PPE | Personal Protective Equipment |
| PPS | Polyphenylene Sulfide |
| PVDF | Polyvinylidene Fluoride |
| SDS | Safety Data Sheet |
| SHS | Selective Heat Sintering |
| SLA | Stereolithography |
| SLS | Selective Laser Sintering |
| SOP | Standard Operating Procedure |
| SVOC | Semi-volatile Organic Compound |
| TBBPA | Tetrabromobisphenol A |
| TPA | Thermoplastic Polyamide |
| TPC | Thermoplastic Copolyester |

| | |
|---|---|
| TPU | Thermoplastic Polyurethane |
| TVOC | Total Volatile Organic Compounds |
| UC | Ultrasonic Consolidation |
| UFP | Ultrafine particle |
| UV | Ultraviolet |
| VOCs | Volatile Organic Compounds |

## Glossary of Terms

Aerosol – system of particles (solid and/or liquid) suspended in gas.

Air exchange rate (ACH) – ratio of the volume of clean air at room temperature and pressure brought into a space per hour to the space volume.

Aldehydes – low molecular weight organic compounds containing a functional group with the structure –CHO.

Course particles – particles having a diameter greater than 2.5 μm and less than or equal to 10 μm.

Feedstock – 3D printer media consumed to create a printed object, for example, filament and liquid resin.

Fine particles – Particles having an aerodynamic diameter smaller than 2.5 μm and greater than 0.1 μm.

Makerspace (or academic makerspace) – a communal workshop where students, faculty, and staff can work on projects. These facilities provide tools and machines that enable designing, creating, problem solving, and collaboration. The organizational and operational models of makerspaces can vary widely across institutions, but their common value is enabling innovation and hands-on project-based learning.

Particles – small discrete solid or liquid objects that can be chemically homogeneous or heterogeneous and are suspended in air or gas with specified physical parameters.

Particle size/particle diameter – the physical dimension of a particle. The term particle size is often used as a synonym for particle diameter. The term particle diameter is also used to classify particles in particle size classes.

$PM_{2.5}$ – inhalable fine particles with diameters that are generally between 0.1 μm and 2.5 μm.

$PM_{10}$ – inhalable particles with diameters that are generally between 2.5 μm and 10 μm.

Print time – the length of the 3D printing process.

Total volatile organic compounds (TVOC) – the sum value of all compounds within the C6 to C16 range (those that elute between hexane and hexadecane) as measured by gas chromatography/mass spectrometry (GC/MS) techniques such as U.S. EPA Method TO-17 or ASTM D6196.

Ultrafine particles (UFP) – inhalable particles having a diameter less than or equal to 0.1 μm. UFPs have a diameter larger than nominally 7 nm or the minimum size that the aerosol measurement instrument can detect, which should be at least 10 nm.

Volatile organic compound (VOC) – nonpolar and moderately polar organic chemicals with boiling points between 60ºC and 290ºC that are amenable to monitoring, based on sorbent collection/thermal desorption/GC/MS analysis. The volatility range of chemicals amenable to the method will depend on the sorbent cartridges and thermal desorption chromatographic system used by the laboratory.

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## Purpose of the Guidance Document

The purpose of this guidance document is to provide a resource for the safe use of 3D printing in institutions of higher education. Recommendations in this document may not apply to all the diverse 3D printing technologies available or to manufacturing and industrial printing spaces. Recommendations in this document will be most relevant to material extrusion and vat photopolymerization applications but some may be generalized for the safe use of other types of 3D printing processes in higher education. This document focuses on best practices and makes evidence-based recommendations but is not meant to be an exhaustive resource nor is it meant to provide strict, quantitative guidance or suggestions for individual campus policies around 3D printing.

## Audience for the Guidance Document

The audiences for this document are those that purchase, use, and/or oversee the use of 3D printers at institutions of higher education. This document focuses on smaller, commercial-grade 3D printing units that are most often seen on campuses in makerspaces, design labs, research labs, and dormitories. These units most often make use of material extrusion technologies and vat photopolymerization printing methods.

## Overview of 3D Printing in Higher Education

The use of additive manufacturing technologies (or 3D printing) has revolutionized the marketplace by streamlining product design and development and expediting product time to market. 3D printing is now widely used in a variety of industries including electronics, architecture, medicine and medical sciences, dentistry, aerospace and defense, automotive and manufacturing industries, consumer products, arts, and entertainment.[2] Moreover 3D printing is an exciting innovation that is transforming research, manufacturing, and student learning experiences throughout higher education. 3D printers have become a valuable tool in non-industrial environments because they inspire creativity and problem-solving by bringing students' ideas and designs to life. Thanks to the development of affordable, compact, and user-friendly 3D printers, use of this amazing innovation is booming particularly in institutions of higher education. As with so many new technologies, providing and encouraging best practices for safe use and managing safety and health considerations effectively will help maximize the benefits and innovative potential of 3D printing on campuses.

On most college campuses, it is not unusual to find 3D printers in such places as classrooms, makerspaces, and labs. CIRI recently conducted a survey of CSHEMA members and found that for those who responded to the survey makerspaces and research/educational labs were the most common locations for 3D printers on campus. However, as shown in Figure 1, 3D printers are found in a variety of settings on these campuses including libraries and residence halls where best practices for safe use may not be well understood. Members of the task force have also raised the issue that 3D printing has become so prolific on many college campuses that it can be difficult to effectively track 3D printer usage and locations to support the safe use of these technologies.

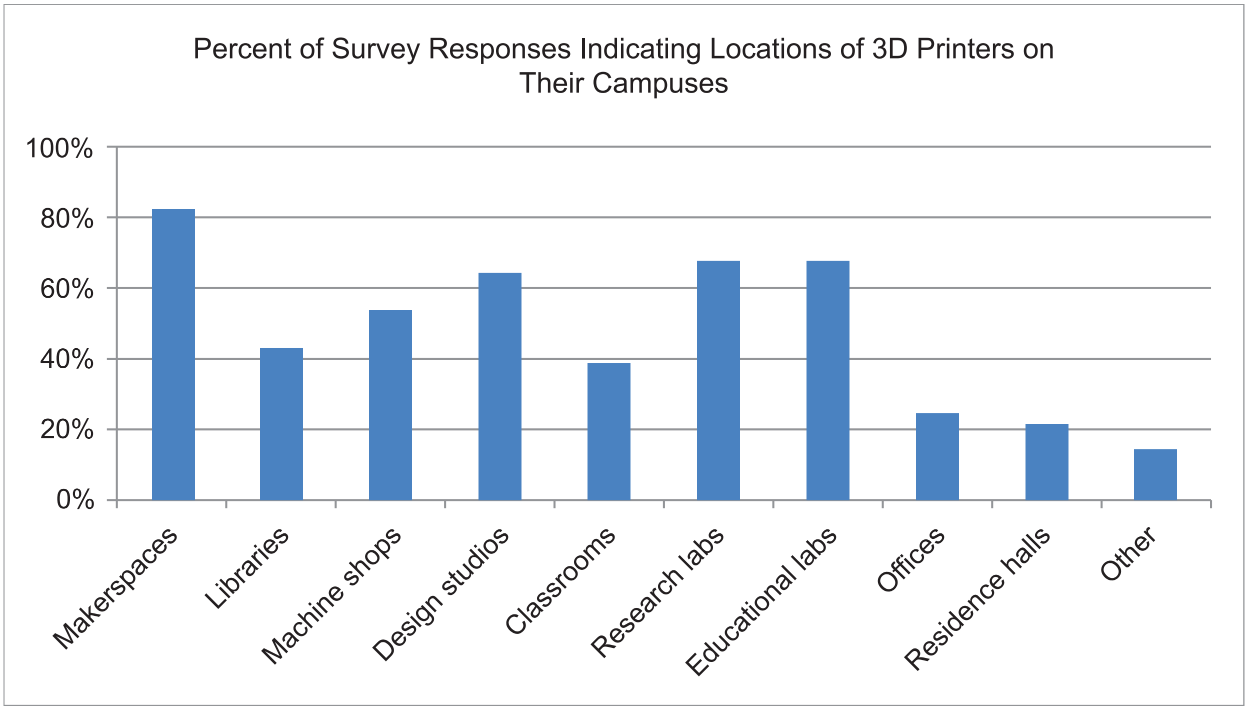



**Figure 1**

**Results From A Survey of CSHEMA Members On Locations of 3D Printing Technologies on University Campuses (n=29 with 28 campuses represented)**

Fundamentally, 3D printers use a digital file to build a 3D solid object. This process can be replicated in different ways using a variety of technologies. Safe use and risk management strategies must consider the utilization of a specific type of 3D printing as well as the hazards associated with each.[3,4] The American Society for Testing and Materials (ASTM) has classified additive manufacturing processes into seven categories.[5] Table 1 below lists these common 3D printing processes along with descriptions, materials, and general hazards associated with each.

**Table 1**
**The Seven Most Common 3D Printing Processes**

| Process Type | Description | Technologies | Materials | Potential Hazards |
|---|---|---|---|---|
| Powder Bed Fusion | Thermal energy selectively fuses regions of a powder bed. | Selective Laser Sintering (SLS)<br>Direct Metal Laser Sintering (DMLS)<br>Electron Beam Melting (EBM)<br>Selective Heat Sintering (SHS) | Metals, Polymers, Ceramics in powder or wire forms | Exposure to airborne powder, explosion, laser/radiation exposure |
| Directed Energy Deposition | Focused thermal energy is used to fuse materials by melting as they are being deposited. | Laser Metal Deposition (LMD)<br>Laser Engineered Net Shaping (LENS)<br>Electron Beam Additive Manufacturing (EBAM) | Metals<br>In wire or powder forms | Exposure to airborne metal powders, burns, laser/radiation exposure |
| Material Extrusion | Heated material (filament) is selectively dispensed through a nozzle or orifice to build an object layer by layer. | Fused Deposition Modeling (FDM)<br>Fused Filament Fabrication (FFF) | Thermoplastics, Possible additives and/or composites<br>In spooled, pellet, or granular forms | Exposure to volatile organic compounds (VOCs) and ultrafine particles, burns |
| Vat Photo-polymerization | Liquid photopolymer in a vat is selectively cured by light-activated polymerization. | Stereolithography (SLA)<br>Digital Light Processing (DLP) | Photopolymers<br>In liquid resin form | Exposure to VOCs, dermal exposure to resins and solvents, UV exposure |
| Binder Jetting | A liquid bonding agent is selectively deposited to join powder materials. | Powder Bed and Inkjet Head (PBIH)<br>Plaster-based 3D Printing | Metals, Polymers, Ceramics, Sand<br>In powder form | Exposure to VOCs and airborne powder, dermal exposure to powder and binders |
| Material Jetting | Droplets of build material are selectively deposited. | Material Jetting (MJ)<br>Multi-Jet Modeling (MJM)<br>Wax Casting | Photopolymers, Waxes<br>In liquid ink form | Exposure to VOCs, dermal exposure to resins and solvents, UV exposure |
| Sheet Lamination | Sheets of material are bonded to form an object. | Laminated Object Manufacturing (LOM)<br>Ultrasonic Consolidation (UC) | Paper, Metal, Plastic, Ceramics<br>In sheet, film, or ribbon forms | Exposure to VOCs, laser/radiation exposure |

As seen in Table 1, the general hazards associated with 3D printing are related to the specific processes and materials used. These health and safety concerns can be associated with the specific type of equipment and may include electrical hazards, mechanical forces from moving parts, ultraviolet light (UV), laser/radiation exposure, noise, and/or burn hazards from hot surfaces. Health and safety concerns may also be associated with the materials used in a specific 3D printing process. These can include burns from molten materials, cuts and dermal exposures, flammability or explosion risk from metal powders, chemical burns from solvents used in post-processing, as well as health hazards associated with inhalation of ultrafine particles, VOCs and/or toxic smoke, fumes, and dust.

Recommendations in this document will focus on smaller 3D printing units that involve material extrusion or vat photopolymerization printing methods. These technologies are typically the most common 3D printing methods on university campuses because of their affordability and user-friendliness. In the previously mentioned survey of CSHEMA members, 100% of survey participants indicated that material extrusion printers were present on their campuses and 83% indicated the presence of vat polymerization printers. Figure 2 also shows the prevalence of other 3D printing technologies based on CSHEMA member responses.

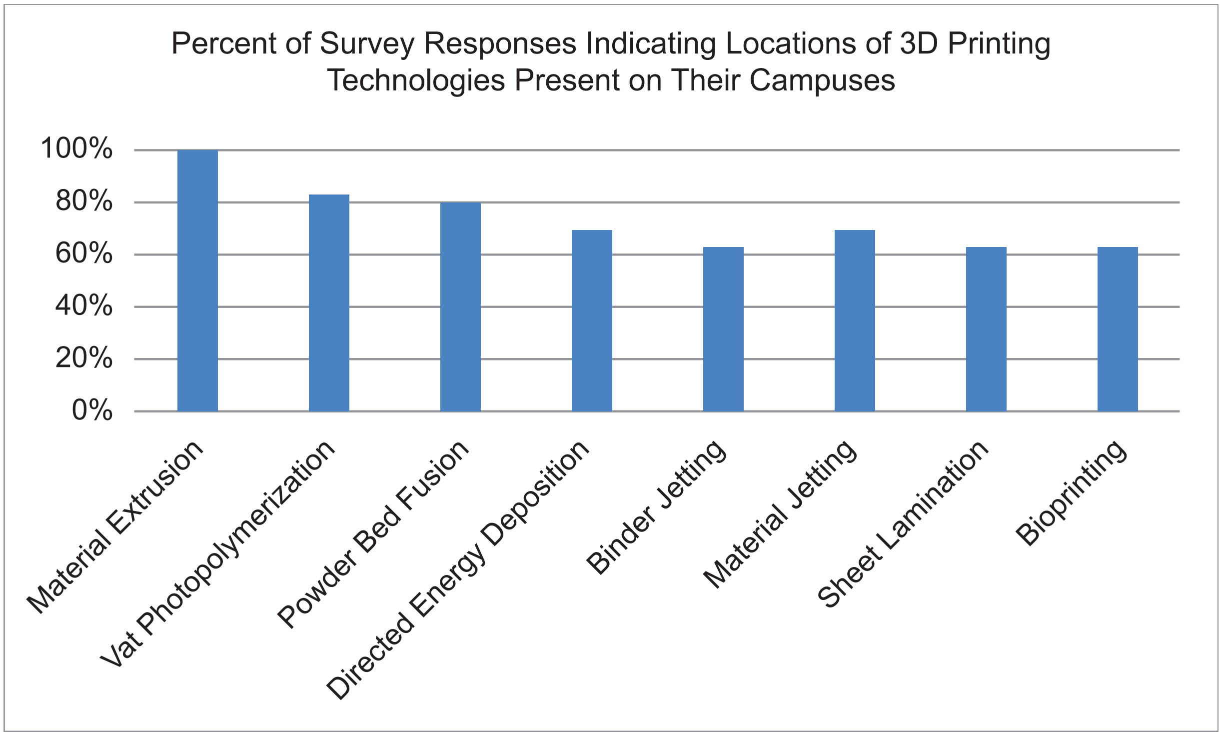



**Figure 2**

**Results From A Survey of CSHEMA Members On 3D Printing Technologies Present on University Campuses (n=29 with 28 campuses represented)**

## Primary 3D Printing Technologies in Higher Education Settings

### Material Extrusion Printing

The most common consumer-grade 3D printers use a material extrusion process. In this process, a filament material is delivered through a heated nozzle controlled by computer software. The nozzle moves along a print bed, that is sometimes heated, to deposit material in layers and create the shape of the desired object. Due to the affordability of material extrusion printers and the user-friendliness of this process, material extrusion printers are very popular among students and in higher education settings in general. A schematic of the material extrusion 3D printing process may be seen in Figure 3.[6] Post processing of finished parts from material extrusion involves removing the part from the print bed (or build plate) which may involve scraping with tools and the removal of any support material that was used during printing.

Thermoplastics such as polylactic acid (PLA), acrylonitrile butadiene styrene (ABS), and nylon are common filament materials, but composite material filaments are also frequently used as feedstock in material extrusion printers. Choice of feedstock often depends on the desired physical properties of the final product. In the previously mentioned survey of CSHEMA members, PLA and ABS were the most common filament materials used across campuses. Other commonly used filament materials on these campuses are in Figure 4.

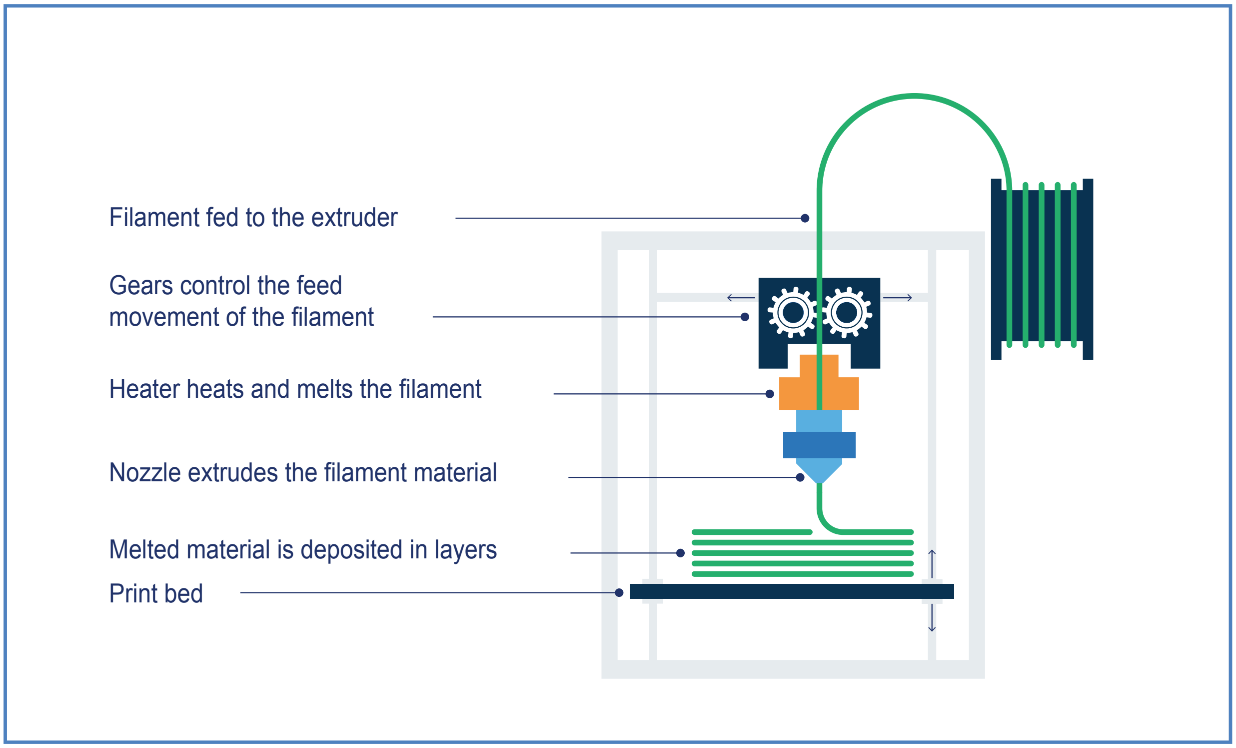



**Figure 3**

**Material Extrusion 3D Printing Process**

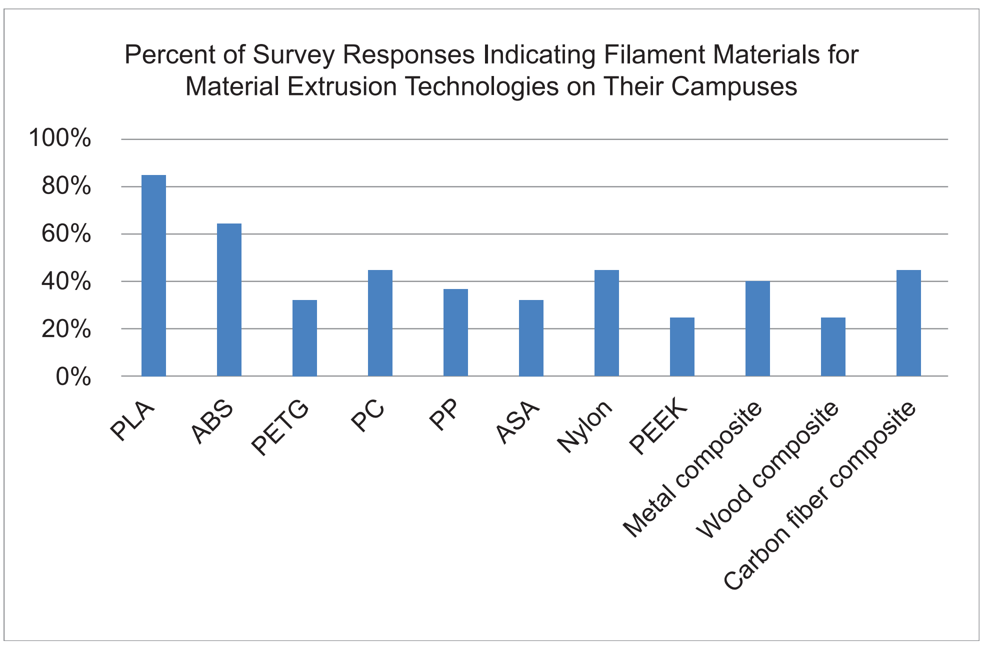



**Figure 4**

**Results From A Survey of CSHEMA Members On Material Extrusion Filament Materials Used on University Campuses (n=29 with 28 campuses represented). PLA =polylactic acid, ABS=acrylonitrile butadiene styrene, PETG=polyethylene terephthalate with added glycol, PC=polycarbonate, PP=polypropylene, ASA=acrylonitrile styrene acrylate, and PEEK=polyetheretherketone.**

### Vat Photopolymerization Printing

Vat photopolymerization is also a common consumer-grade technology. This method uses a vat of liquid photopolymer resin to create a 3D printed object. The resin is selectively cured or hardened (polymerization) layer by layer using a light source. Laser UV light sources are typically used to cure the photopolymer, but digital light sources are also available. This process represents chemical reaction bonding to form the object rather than the thermal reaction bonding seen in material extrusion.[7] A schematic of the vat photopolymerization 3D printing process is shown in Figure 5.[8] Vat photopolymerization processes can create highly accurate parts with smooth surface finishes.

Support structures and post curing with additional UV light are often required to create the final product's desired structural strength. Post-processing can be more involved with vat photopolymerization as compared to material extrusion. Support structures need to be removed using a knife or sharp implement. Methods for removing excess resin and supports include the use of an alcohol rinse followed by a water rinse. The post processing may require additional scrubbing to completely remove material. Parts are then dried naturally or by using compressed air.[8]

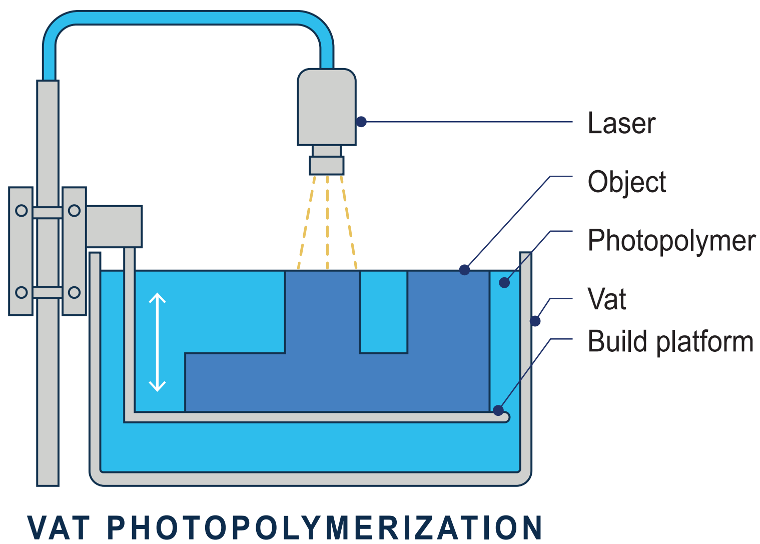



**Figure 5**

**Vat Photopolymerization 3D Printing Process**

## 3D Printer Emissions and Health Impacts

### Material Extrusion Printing

CIRI, along with researchers from Georgia Institute of Technology, conducted a multi-year research initiative on emissions from material extrusion 3D printers. The research found that during operations, 3D printers emit small particles and volatile organic compounds (VOCs), some of which are known irritants, carcinogens and odorants. This means that exposure may present a human health hazard, in particular when a person stands next to the printer with minimal ventilation (<4 ACH).[9] Emissions from material extrusion printers varied based on filament type and print conditions. In a different study where nozzle temperature and the structural characteristics of the printed product were considered for their impact on emissions, nozzle temperature was found to be a main determinant of the magnitude of emissions. [10]

3D printing emits particles, a mixture of very small solids and liquid droplets suspended in the air. Fine and ultrafine particles (UFPs, smaller than 100 nanometers in size) can act as a gas that can penetrate deep into the lungs, and potentially even enter the bloodstream. These particles can cause eye, nose, and throat irritation; aggravate coronary and respiratory disease symptoms; and contribute to premature death in people with heart or lung disease. Overall, CIRI research found that particle emissions could reach up to one trillion particles per hour and are mostly UFPs.[11] In fact, $PM_{2.5}$ (fine particulate matter, smaller than 2.5 μm in size) levels (μg/$m^3$) could exceed those of environments near a busy highway.[12-14]

CIRI has also performed research to assess the toxicological properties of emitted particles from material extrusion 3D printers and to determine the toxicity of popular filaments using primary small airway epithelial cells.[13,14] In general, this research found that 3D printing emissions, even at low levels, may contribute to cellular injury, inflammation, and oxidative damage of important biomolecules including DNA and phospholipids that serve critical roles in living cells. Exposure to 3D printing emissions using both PLA and ABS filaments was associated with a decline in cell viability, oxidative stress, an increase in DNA damage, and high levels of metabolites (products of metabolism) that are associated with cellular injury and inflammation.[15] These preliminary studies present the potential for health impacts from 3D printing emissions but additional studies are needed to fully understand the effects of long-term exposure.

VOCs are organic (meaning they contain carbon) chemical compounds that evaporate easily into the air and can be inhaled. VOCs can be found in a number of products including building materials like paint, varnishes, adhesives, flooring and carpet as well as in consumer products like cleaners, air fresheners, and personal care products. Certain activities in addition to 3D printing can be a source of VOCs. These include smoking, cooking, laser printing, dry cleaning, wood burning, and vehicle emissions. VOCs pose several health risks such as: eye, nose, and throat irritation, headaches, loss of coordination and nausea from short term exposure (on the order of hours or days); damage to the liver, kidney, and central nervous system, cardiovascular disease, cancer, and asthma as a result of long-term exposure (on the order of months or years). CIRI research found more than 200 different VOCs in 3D printer emissions, many of which are known irritants, carcinogens and odorants. The most frequently detected and highest emitting VOCs included styrene, caprolactam, benzaldehyde, ethylbenzene, and acetaldehyde, depending on material type. Formaldehyde, a known human carcinogen, was also detected from a variety of filaments.[16]

A consensus standard, “ANSI/CAN/UL 2904 Standard Method for Testing and Assessing Particle and Chemical Emissions from 3D Printers”, has been developed from CIRI research, establishing test protocols and acceptable emissions criteria for 3D printers.[17] An interactive, data visualization tool that allows a user to see research results for a variety of thermoplastic and composite filaments with various print conditions may be accessed at https://chemicalinsights.org/data-portal/. This tool includes data collected by CIRI (2015-present) on particle and VOC emissions from fused filament fabrication (FFF) 3D printing using a chamber test method aligning with the ANSI/CAN/UL 2904 Standard. This tool provides particle emission rates, identifies the individual VOCs released as well as their emission rates and health or indoor air quality concerns, pinpoints the effect of print conditions on emissions, provides high vs. low emitting conditions and comparison to emission criteria from the ANSI/CAN/UL 2904 Standard.

### Vat Photopolymerization Printing

Emissions from vat photopolymerization processes have not been studied as extensively as those from material extrusion. CIRI has initiated a study on particle and VOC emissions from the printing and post-processing wash and cure stages of vat photopolymerization using the standard test protocol in the ANSI/CAN/UL 2904 Standard.[18] This test protocol is described in Appendix E.

Based on CIRI's work, both printing and post-processing showed very limited particle emissions but high levels of VOC emissions. These findings were consistent with other studies.[19,20] However, other researchers have observed metal containing particle emissions at levels similar to those of material extrusion printers indicating that emission characterizations depend on experimental design, studied materials and conditions, and measurement and analysis methods.[21]

In CIRI's research, the total VOC (TVOC) emission rates from vat photopolymerization printing were three to six times higher than the average from material extrusion. Individual VOCs emitted differed from those measured with material extrusion 3D printing due to the differences in print materials and methods. Before printing began, the TVOC levels in the chamber were over 10 times higher than that of the empty chamber background indicating that the printer vat itself with resin loaded is a source of VOC emissions without preheating or operating. This is likely associated with the TVOC emissions from resin volatilization at room temperature. During the printing phase, the TVOC concentration further increased to over 4000 μg/m$^3$. This is well above the U.S. Green Building Council Leadership in Energy and Environmental Design's (LEED's) maximum TVOC concentration of 500 μg/m$^3$ for green buildings.[22] The TVOC concentration in the chamber also increased over the course of one hour after printing was complete indicating a continuous release of VOCs even after printing has finished. Note that, in this study, the printer cover was kept closed during the sampling period. Therefore, it is expected that the concentration levels are higher when opening the printer cover during the loading resin stage and while unloading the printed part. Likely due to the absence of the resin tank, wash and cure processing units yielded lower TVOC levels than operations studied with the printer running. However, the TVOC concentrations were still over 600 μg/m$^3$ inside the chamber during wash and cure post-processing.

The top five chemicals with the highest emission rates are shown in Figure 6. Data were collected based on the ANSI/CAN/UL 2904 Standard method with a four hour print duration followed by washing (10 minutes) and curing (15 minutes). These top five chemicals accounted for 88%, 100% and 91% of the sum of VOC emissions for print, wash, and cure processes respectively. 2-Hydroxypropyl methacrylate, associated with the resin chemical compositions, was detected from all processes with the highest or second highest emission rates. Isopropanol accounted for over 97% of the sum of VOC emission rates for wash treatment, due to the use of isopropyl alcohol as the reagent in the wash tank. The washed part was further treated with light during cure post-processing, and isopropanol was also detected at a relatively high emission rate during the cure treatment. Other top emitting chemicals included hydrocarbons, alcohols, esters, and aldehydes, including formaldehyde. TVOC emission rates from all processes were below the maximum allowable emission criterion listed in ANSI/CAN/UL 2904 Standard (10.4 mg/h). However, this complex mixture of alcohols, aldehydes, and acrylates could present a strong irritation response among those exposed.

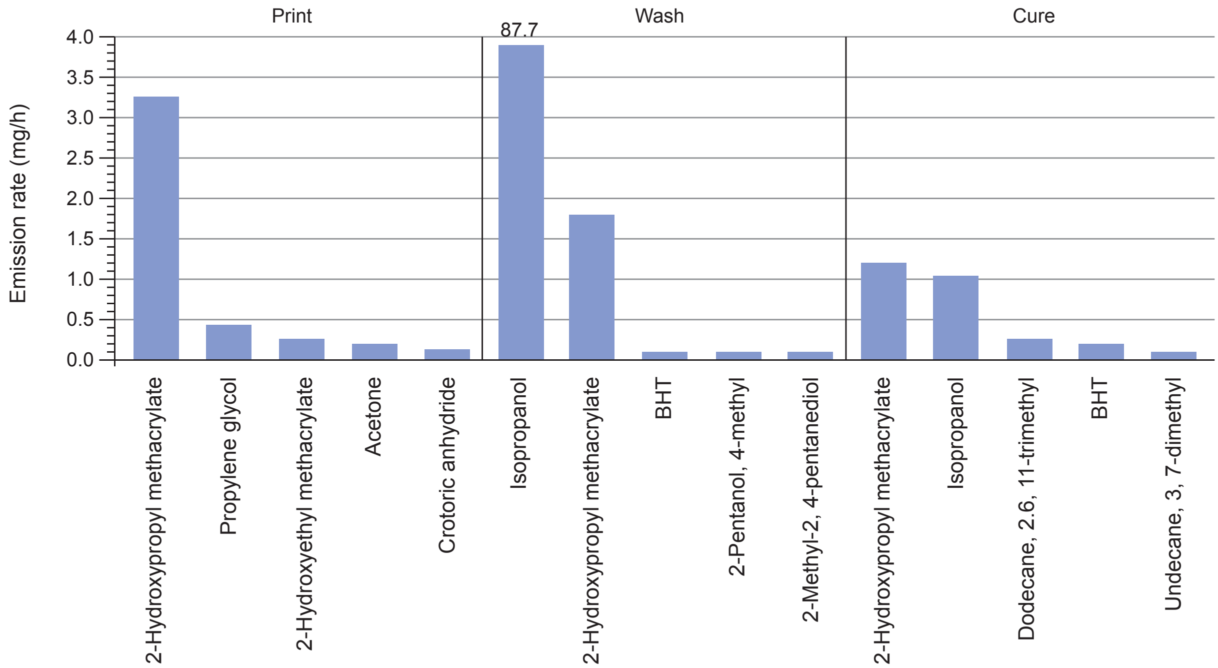



**Figure 6**

**Top five VOCs emitted from a vat photopolymerization process.**

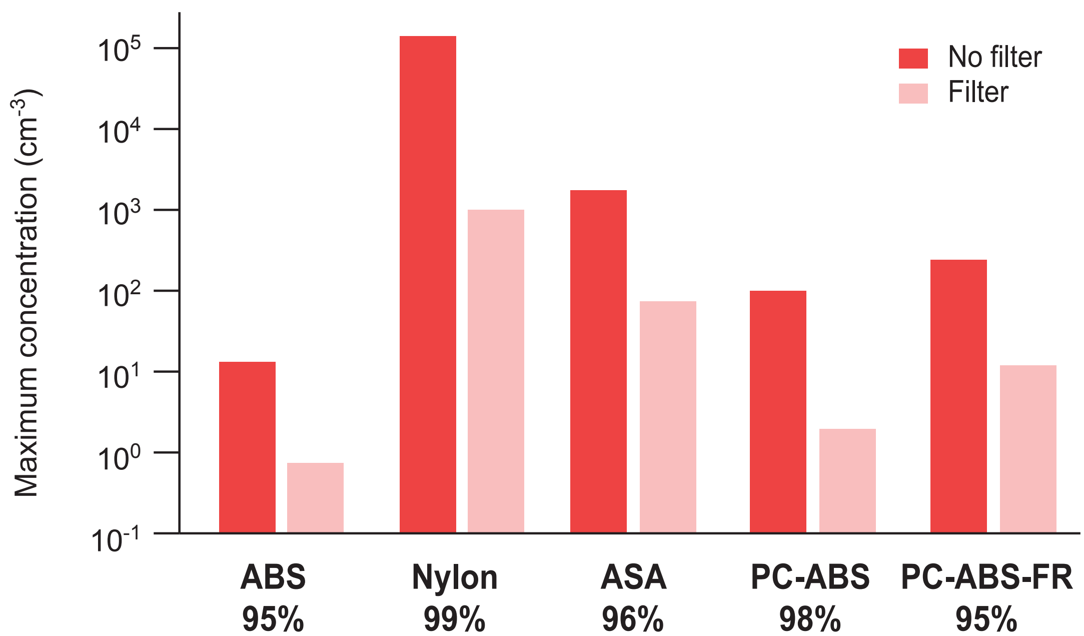
There are no regulated standards for acceptable indoor air pollutant levels in nonindustrial environments such as homes, offices, and schools. Appendix B provides a list of some U.S. and global organizations which recommend exposure limits and odor thresholds for common air pollutants in environments where a range of people with various vulnerabilities and sensitivities may exist. In general, emission hazards from 3D printing should be minimized using a hierarchy of controls as described later in this document due to the known health impacts of UFPs and VOCs as well as the current need for further studies related to long-term exposure to the complex mixtures of 3D printing emissions.

**Selection and Purchasing (Printer)**

Before selecting and purchasing a printer, it is crucial to think through the logistics of the printer location as this may determine or limit the type of printer that can be bought. Based on the recommendations in the “Printer Installation Location” section, only purchase printers that a chosen space can accommodate or discuss changes that might be needed to the chosen space with facility management on your campus.

There are several key steps consumers and institutions can take to mitigate risks when purchasing 3D printers such as purchasing equipment that has been certified for product safety compliance according to standards such as UL 60950 and UL 62368-1. Consider selecting printers that meet ANSI/CAN/UL 2904 Standard criteria and requiring compliance with the standard in the bidding and purchasing process, if applicable.[6] ISO and ASTM International are other standards development organizations that are working on developing a comprehensive set of standards for 3D printing processes around materials, processes and equipment, and the treatment of finished parts. This work is ongoing and a global agreement on complete standards for 3D printing has not yet been realized.[23]

Other important printer safety features to consider when purchasing include integrated enclosures, direct exhaust lines, and/or local active filtration systems equipped with HEPA (high efficiency particulate air) filtration for particles and activated carbon filters for VOCs.[6] CIRI's research has shown that the use of a filtration system attached to the printer significantly reduced particle emissions for all filament types studied. As seen in Figure 7, filtration was able to reduce maximum particle concentrations by at least one order of magnitude, and the reduction rates were 95% or greater.[24]




Percentage indicates the reduction due to filtration. ABS= acrylonitrile butadiene styrene, ASA= acrylonitrile styrene acrylate, PC-ABS= polycarbonate-ABS, PC-ABS-FR= PC-ABS with flame retardant (FR).

**Figure 7**

**Particle maximum concentration during printing for with and without filtration.**

**Selection and Purchasing (Print Media)**

In addition to the printer itself, consumers and institutions also need to consider the safety of the type of print media that will be used when purchasing 3D printers.

**Material Extrusion Printing**

In the case of material extrusion printers, many manufacturers specify the thermoplastic filaments that should be used with their printers. Only purchase the brands specified by the printer manufacturers or those from reliable suppliers. There is little dependable information about the chemical compositions or quality controls of lower-cost filaments or unidentified brands.[6]

CIRI's published research and studies of a similar nature indicate that, among the commonly used filaments present in the study, printing with PLA plastic filaments tends to be a safer option. Filaments such as ABS and nylon usually print at higher temperatures, and therefore release more UFPs and VOCs in general.[11,25] However, PLA has some limitations related to final product properties. PLA is relatively weak unlike ABS which is used to produce more long-lasting, durable items such as aircraft parts and prosthetics. PLA also absorbs moisture from the air and can become brittle over time, a factor which also applies to PLA printed items.[9]

Composite filaments that are made from more than just one material are also used in material extrusion processes. These filaments are usually made of a solid powder like wood, metal, or carbon fiber embedded in a plastic matrix. For common composite filaments, PLA is used for the plastic matrix, which allows composite filaments to be printed at relatively low temperatures.[26] CIRI has measured emissions from material extrusion printing using metal/PLA and nylon/chopped carbon fiber composite filaments. Metal/PLA composite filaments had comparable to higher particle and TVOC emissions than pure PLA polymer filaments, dependent on print temperatures while the nylon composite filament had comparable emissions to a pure nylon polymer filament when printing at similar temperatures.[27]

Many new polymer filaments for material extrusion printing have entered the marketplace in recent years. These include but are not limited to sustainables, flame retardants, and flexibles. Sustainables include filaments containing recycled feedstocks and plant-based or non-petroleum-based feedstocks. If post-consumer recycled plastics are used as feedstock, the variability of the composition of the feedstock needs to be known since the presence of plasticizers or low molecular weight polymers can increase the risk of formation of UFPs from semi-volatile organic compounds (SVOCs) as well as VOC emissions. On the other hand, reusing previously printed filaments as feedstock, a common practice on university campuses, can reduce UFP and VOC emissions for some polymers because SVOCs and VOCs become depleted with successive use.[28] If recycled filaments are used, proper categorizing and segregating of materials must be done carefully so that different types of polymers are not mixed together for printing. This mix could result in some filaments being used at higher than recommended temperatures potentially resulting in higher emissions. Plant-based or non-petroleum-based filaments may emit different compounds and/or particles and should be tested for emission properties before use.

Flame retardant additives can be incorporated into thermoplastics to slow the rate of combustion, reduce smoke, and/or limit dripping upon melting. Some 3D printing filaments have inherent flame-retardant properties including polyphenylene sulfide (PPS), polyvinylidene fluoride (PVDF), polyetherimide (PEI), and polyether ether ketone (PEEK). Others need added flame retardants if flame resistant properties are required for the final product. These include polyamide (PA), acrylonitrile butadiene styrene (ABS), nylon, polycarbonate (PC), and thermoplastic polyurethane (TPU). Additives might include halogenated flame retardants like tetrabromobisphenol A (TBBPA) and dichloromethane, non-halogenated organic flame retardants like organophosphates or bisphenol A, and inorganic flame retardants like hexaboron dizinc undecaoxide. While they may be incorporated at low percentages, some of these additives are known to be toxic or carcinogenic. [29,30]

Thermoplastic elastomers are used as flexible filaments when the final product needs to be elastic or stretchy. Common types of flexible filaments include thermoplastic polyurethane (TPU), thermoplastic copolyester (TPC), thermoplastic polyamide (TPA) and soft PLA (a mix of PLA with TPE or TPU). Emissions testing results using flexible filaments have been mixed but these filaments could emit particles and VOCs at levels similar to more traditional thermoplastic filaments.[31,32]

In general, when choosing a print media for material extrusion, the desired properties of the final product must be considered while balancing health and safety concerns. Always consult the Safety Data Sheets (SDS) to understand and evaluate the specific health and safety hazards associated with the 3D print materials used and any additives that may be present in these materials.

## Vat Photopolymerization Printing

Vat photopolymerization uses photo-sensitive polymer liquids (resins) that cure when exposed to light resulting in a solid part. A wide variety of liquid resins are used to accomplish the desired surface finish, and these resins consist of various chemicals and additives designed to produce specific properties in the printed piece. Therefore, the resin chosen will depend on the finish, mechanical properties, and biocompatibility of the finished product.[33] Photopolymer materials are generally divided into seven classifications: structural; tough and durable; flexible and elastic; castable wax and ceramic; biocompatible; and bioink. Each classification has unique mechanical and chemical properties and specific uses.[34]

Many of the resins contain sensitizers so prolonged exposure can cause an allergic reaction. The chemicals that make up most resins are also skin irritants and are absorbed quickly into the skin which can lead to more severe reactions.[35] When deciding to purchase, it is important to consult the SDS to understand and evaluate the specific health and safety hazards associated with the resin materials used and any additives that may be present in these materials. As with material extrusion, when choosing a print media for vat photopolymerization, the desired properties of the final product must be considered while balancing health and safety concerns.

## Printer Installation Location

Indoor air quality around 3D printers is an important part of managing risk on campus since 3D printers have been shown to emit UFPs and a complex mixture of VOCs when operating. The first choice for the location of 3D printing activities should be in spaces with dedicated ventilation in accordance to ASHRAE 62.1[36] to ensure acceptable indoor air quality; contaminants should be vented from the room to the outside without recirculating them within the building.[6]

Examples of dedicated ventilation controls include single unit local exhaust ventilation systems (fume hoods), snorkel fume extractors, or for situations where multiple printers are used, operating 3D printers within enclosed ventilated racks that exhaust to the outdoors. In a study done by the National Institute for Occupational Safety and Health (NIOSH) on the use of ventilated enclosures containing multiple material extrusion printers, closing the doors to the enclosure and turning on the vent fan reduced the particle number concentration in the print room by 99.7% and the TVOC concentration by 69.5% within 30 minutes.[37]

If dedicated ventilation is not available, the second option is to exhaust the air from printers through a room air cleaner equipped with HEPA filtration for particles and activated carbon filters for VOCs[38] or to purchase a benchtop, single-unit fume extraction system to be used while the printer operates.

The third option is to choose a location with sufficient existing ventilation that has been measured and validated as a low-cost way to mitigate risks. However, the ventilation rates of offices, libraries and general classrooms may not be sufficient to remove contaminants generated by 3D printing and air within these spaces is usually recirculated. To increase ventilation, printers can even be positioned next to air vents that exhaust to the outside or near operable windows that can be opened to naturally ventilate the space. Be sure to keep printers away from any return air vents. Many university EHS policies require dedicated ventilation for printing and post-processing activities unless material extrusion printing is being done with PLA filaments only. For PLA printing without dedicated ventilation, EHS policies generally recommend minimums between 4-12 ACH, but this requirement is often reduced if dedicated ventilation or HEPA/carbon filtration is present.[9]

A location with a sprinkler system is always recommended for fire safety concerns. For vat photopolymerization, avoid placing a 3D printer over carpeted areas or use a barrier to avoid the possibility of carpet damage.[39] If possible, 3D printers should only be operated in well-ventilated spaces away from high-traffic areas.

## Recommendations for Safe Operation

Always follow the manufacturer's guidelines when operating a 3D printer and consult campus EHS professionals for a hazard assessment especially if modifications or novel uses of the 3D printing process are considered. Always use appropriate personal protective equipment (PPE) when using a 3D printer and during post-processing activities. These may include lab coats, safety glasses, face shields, and/or safety goggles, and gloves. Standard protective dust masks are not effective at preventing inhalation of the VOCs and UFPs emitted by 3D printers. Some commercial respirators approved by NIOSH provide adequate protection from chemical and particle contaminants, but they can be cumbersome, expensive, and require enrollment in a campus respiratory protection training program.[6] In general, the use of dedicated ventilation, enclosures, and filtration are preferred to mitigate inhalation hazards.

For vat photopolymerization, wear appropriate chemical-resistant gloves (nitrile or neoprene) and do not use latex gloves when handling uncured resins. Also, with vat photopolymerization, use safety glasses/goggles with UV protection features. Contact campus EHS professionals with questions and guidance related to PPE and/or first aid procedures related to 3D printing operation. In addition to recommendations made here and in the above sections regarding purchasing, print media, and installation, the following additional guidelines in Table 2 are recommended for safe operation of 3D printing processes and post-processing activities.[6,39,40]

**Table 2**
**Additional Recommended Guidelines for Safe 3D Printing**

| | Material Extrusion | Vat Photopolymerization |
|---|---|---|
| **Before printing** | • Ensure the 3D printer nozzle and build plate are clean before each use.<br>• Follow manufacturer instructions for base plate glue or tape application.<br>• Avoid excessive application of glue or tape on the build plate especially if heated.<br>• Set the nozzle and base plate temperatures at the lowest recommended settings that produce desired print quality. | • Do not expose UV curable resin to heat, flames, sparks, or any source of ignition.<br>• If UV curable resin comes in a sealed cartridge: Inspect the cartridge before loading it into the printer. Do not use a cartridge that is leaking or damaged.<br>• Avoid spills and drips of resin when pouring resins.<br>• Wear gloves when loading the resin tank. |
| **During printing** | • Limit time spent observing close to the 3D printer while it is operational. Do not hover near the printer but consider cameras or observation windows for observation.<br>• If the printer malfunctions, stop the print job but let the printer cool and emissions dissipate before troubleshooting or restarting. | • Limit time spent observing close to the 3D printer while it is operational. Do not hover near the printer but consider cameras or observation windows for observation.<br>• Do not look directly into the UV lamp. |
| **After printing** | • Wait until the printer has cooled and emissions have dissipated before accessing the product or cleaning up.<br>• Clean the 3D printer nozzle and build plate after each use.<br>• Clean the printer and enclosure surfaces with a damp cloth to remove deposited particles.<br>• Vacuum floors, surfaces, and furniture frequently using a vacuum with high efficiency particulate filtration (HEPA).<br>• Wash hands to avoid hand-to-mouth transfer of chemicals and particles, especially before eating. | • Wear gloves when handling parts directly from the printer.<br>• Clean any surfaces that have been exposed to resin with window cleaner, or a denatured or isopropyl alcohol, followed by washing with soap and water.<br>• Tools that may be contaminated with uncured resin material should be cleaned with window cleaner, or denatured or isopropyl alcohol, followed by washing with soap and water.<br>• Do not pour used, uncured resin back into new resin bottles.<br>• Do not leave printer or post-printing unit open when loaded with resins/chemicals. |

**Table 2 Continued on Next Page**

## Table 2 Continued

| | Material Extrusion | Vat Photopolymerization |
|---|---|---|
| **Post-processing** | • Wear appropriate cut-resistant gloves when scraping the build plate or removing support materials with tools.<br>• Wear appropriate chemical-resistant gloves when removing support materials with chemical dissolution.<br>• If the space does not have a dust collection system, wear a dust mask when sanding or post-finishing parts. | • Wash the parts before post-cure using a manufacturer’s recommended solvent like isopropyl or rubbing alcohol. Wear gloves when handling chemical solvents. Be careful dealing with alcohols since they are flammable.<br>• Post-curing using UV light should follow the wash step before the printed object is handled without gloves.<br>• Ensure that all 3D printed objects are fully post-cured by exposure to a UV light source according to the manufacturer’s instructions.<br>• Wear appropriate cut-resistant gloves when removing support materials with tools.<br>• If the space does not have a dust collection system, wear a dust mask when sanding or post-finishing parts. |
| **Handling Waste** | • Waste products from the printing process may be hazardous waste. Consult your material SDS and/or campus EHS guidelines on proper handling and labelling of waste products from the printing process.<br>• Check with your campus EHS guidelines for recommendations on disposal or recycling of unused filament or feedstock materials. | • Do not pour used, uncured resin back into new resin bottles.<br>• Waste products from the printing process may be hazardous waste. Consult your material SDS and/or campus EHS guidelines on proper handling and labelling of waste products from the printing process. |
| **Storage** | • Store filaments in sealed containers with desiccant to prevent changes due to environmental exposure.<br>• Check with material SDS and/or campus EHS guidelines for proper storage of devices, accessories, and printing filaments or feedstock materials.<br>• Follow all manufacturer recommendations for proper maintenance and cleaning procedures including relevant filter maintenance and replacement schedules. | • Keep UV curable resins sealed tightly in containers out of direct sunlight and within the temperature range suggested by the manufacturer.<br>• Do not leave printer or post-printing unit open when resins/chemicals are loaded.<br>• Check with material SDS and/or your campus EHS guidelines for proper storage of devices and accessories.<br>• Follow all manufacturer recommendations for proper maintenance and cleaning procedures including relevant filter maintenance and replacement schedules. |
| **General Safety** | • 3D printers should be listed or labelled by a Nationally Recognized Testing Laboratory (NRTL) to meet electrical safety and fire codes.<br>• Beware that malfunctions of the heated build platform, printer nozzles, or internal electrical components could result in fire.<br>• 3D printers and related equipment should be connected directly to a safety certified electrical receptacle with verified ground.<br>• Do not modify any electrical components such as the build platform heater.<br>• Do not operate 3D printers unattended due to fire risk.<br>• Unguarded electrical components in some 3D printers could pose a risk of electrical shock.<br>• Beware that moving parts can cause injury while the 3D printer is operating.<br>• Contact with hot surfaces can result in burns. | • 3D printers should be listed or labelled by a Nationally Recognized Testing Laboratory (NRTL) to meet electrical safety and fire codes.<br>• Beware that malfunction of internal electrical components could result in fire.<br>• 3D printers and related equipment should be connected directly to a safety certified electrical receptacle with verified ground.<br>• Do not modify any electrical components.<br>• Do not operate 3D printers unattended due to fire risk.<br>• Unguarded electrical components in some 3D printers could pose a risk of electrical shock.<br>• Beware that moving parts can cause injury while the 3D printer is operating.<br>• Contact with the UV lamp can result in burns.<br>• Exposure to the UV light source can damage eyes and skin.<br>• Do not expose UV curable resin to heat, flames, sparks, or any source of ignition. |

## Risk Management for Campus EHS Professionals

### Initiating A Risk Management Program

Members of the task force have raised the issue that 3D printing has become so prolific on many college campuses that it can be difficult to track 3D printer usage and support the safe use of these technologies. In this case, an initial recommendation for beginning risk management is to conduct a campus wide survey on the use of 3D printing technologies to allow for an inventory and registration of what types of 3D printers currently exist on campus and the locations and environments of these printers. The questions CIRI used to survey CSHEMA members on the use of 3D printing on their campuses is found in Appendix A for reference and could be modified or function as a starting point for campus use. This kind of inventory could form the basis for creating a risk management program and setting risk management policies around guidance on purchasing new 3D printers, identifying appropriate locations and providing safety recommendations, and requiring regular training for those involved with 3D printing technologies. Some additional questions that could also be asked as part of starting a risk management program are provided after the survey shown in Appendix A. The questions shown in Appendix A could be adapted for use in a variety of campus settings.

As a part of understanding the landscape of 3D printing on campus, EHS departments have been able to better understand the spaces that house 3D printers and are able to make recommendations and influence campus policies where 3D printers are safe to use. For example, many universities are now prohibiting the use of 3D printers in residence halls because of fire and indoor air quality risks, and have added language to student housing contracts indicating these policies.[41] Also, 3D printers on campuses are often found in large makerspaces that may house a variety of additional tools and activities such as laser cutters, soldering irons, welding, mills and routers, lathes, drill presses, saws, vinyl cutters, woodworking tools, and various electronics. Knowing this, campuses should be aware of what other activities are happening in a space and what combination of hazards may be present.

Indoor air quality around 3D printers is an important part of managing risk on campus since 3D printers have been shown to emit UFPs and a complex mixture of VOCs when operating. As mentioned previously. Appendix B provides a list of some U.S. and global organizations which recommend exposure limits/odor thresholds for common air pollutants in environments where a range of people with various vulnerabilities and sensitivities may exist. In general, emission hazards from 3D printing should be minimized using a hierarchy of controls as described below, due to the known health impacts of UFPs and VOCs and the current lack of data related to the health impacts of long-term exposure to 3D printing emissions.

When developing any risk management program, identifying roles and responsibilities of all stakeholders is important for setting expectations. Table 3 contains some examples of roles and responsibilities for a risk management program around 3D printing on campuses and can provide a framework for program development. The examples in Table 3 have been adapted from EHS department guidelines at Carnegie Melon University.[42]

**Table 3**
**Sample Roles and Responsibilities for Managing Safe Use of 3D Printing on Campuses**[42]

| Who Is Responsible? | What Will They Do? |
|---|---|
| Environmental Health and Safety (EHS) | 1. Develop written 3D Printing Guidelines and revise as necessary. Some samples of guidelines and fact sheets from several institutions may be seen in .Appendix C[42-45]<br>2. Complete risk assessments and review manufacturer's instructions and any applicable Safety Data Sheets (SDS) when new 3D printers are obtained. An example of a risk assessment tool provided by NIOSH may be seen in Appendix D.[40]<br>3. Develop and implement a training program on the safe use and operation of 3D printers.<br>4. Conduct routine inspections including indoor air quality measurements using the methodologies shown in Appendix E to ensure the operation of 3D printers does not degrade indoor air quality. |
| Departments | 1. Understand and comply with the requirements of campus EHS guidelines.<br>2. Contact EHS when new 3D printers are obtained and provide the manufacturer's instructions and SDS documentation.<br>3. Assist in the hazard assessment review.<br>4. Ensure the safe use and operation of 3D printers within their spaces according to campus EHS guidelines.<br>5. Maintain a clean and dust free work area in spaces where 3D printers are housed.<br>6. Contact EHS if assistance is needed. |
| Faculty, Staff, and Students | 1. Complete training as required before using 3D printers.<br>2. Comply with the procedures outlined in campus EHS guidelines.<br>3. Inform the supervisor/manager of the space (faculty or staff) of any problems, defective equipment, or any other issues relating to 3D printers and associated equipment. |

## Using a Hierarchy of Controls

NIOSH outlines five levels of actions to reduce or remove hazards. This hierarchy of controls, as seen in Figure 8, can be applied to the use of 3D printing on campuses.[46] Example recommendations for each level relevant to 3D printing are given below. NIOSH has also created a useful graphic resource that can be used for risk assessment called "3D Printing with Filaments: Health and Safety Questions to Ask" based on the hierarchy of controls. This resource is shown in Appendix D.[40]

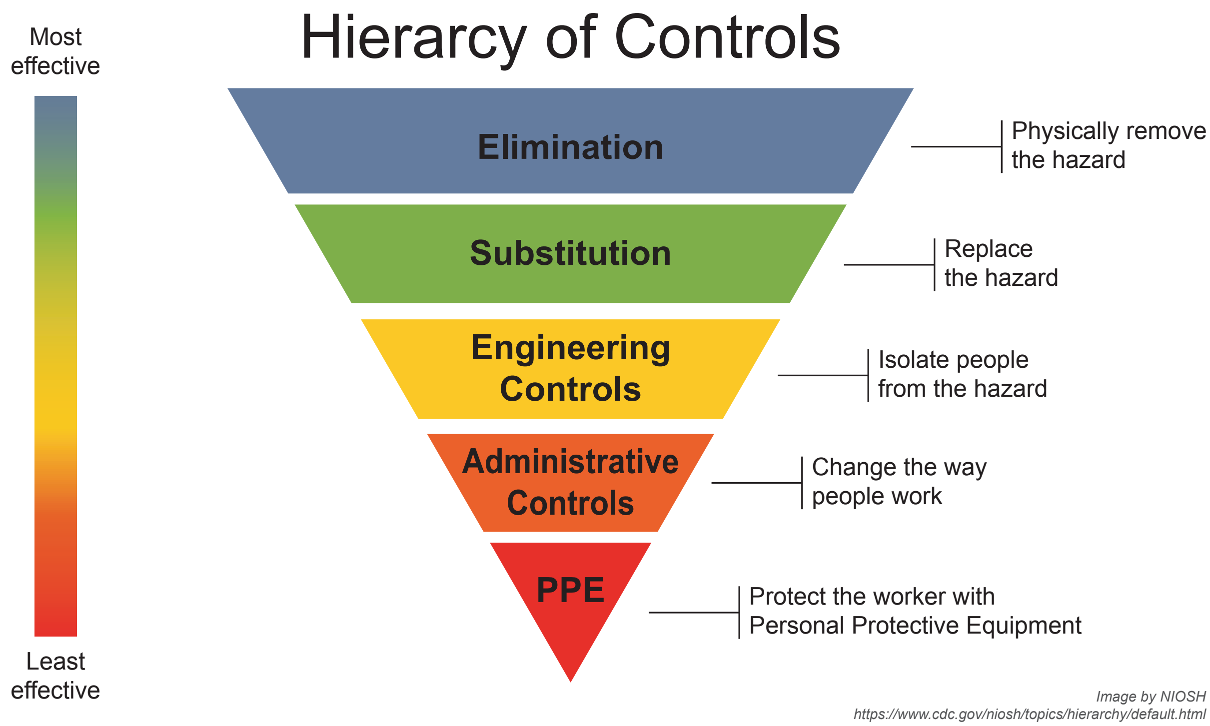



**Figure 8**

**NIOSH Hierarchy of Controls[46] Used with permission from https://www.cdc.gov/niosh/topics/hierarchy/default.html**

**Elimination**

Elimination refers to removing the hazard at the source.[46] In the case of 3D printing this could include selecting only printers and feedstock that meet 3D printing emission certifications such as ANSI/CAN/UL 2904 Standard.[17]

**Substitution**

Substitution means using a safer alternative to the source of the hazard.[46] Only using feedstocks recommended by the manufacturer and choosing lower emitting filaments whenever possible are examples of this kind of control for 3D printing.

**Engineering Controls**

Engineering controls reduce or prevent user contact with hazards by removing the hazard at the source. Engineering controls may cost more upfront than administrative controls or PPE. However, long-term operating costs tend to be lower, especially when protecting large numbers of users.[46] Engineering control recommendations can also be useful for design and construction professionals as they consider proactively incorporating these kinds of features into new designs and construction projects.

Ventilation, integrated enclosures, active filtration systems, and filter maintenance are the most important engineering controls for 3D printing processes and post-processing activities. If possible, 3D printers should only be operated in well-ventilated spaces away from high-traffic areas. The chosen location should have the recommended ventilation according to ASHRAE 62.1[47] to ensure acceptable indoor air quality. In addition, for sources of potentially hazardous emissions, capturing these emissions close to the source is often the best practice. Thus, dedicated ventilation is the preferred engineering control used on campuses to protect users from exposure to emissions. These types of engineering controls provide directed air flow to capture emissions at the source. Examples of dedicated ventilation controls include single unit local exhaust ventilation systems (fume hoods), snorkel fume extractors, or for situations where multiple printers are used, operating 3D printers within enclosed ventilated racks that exhaust to the outdoors. Other options are to exhaust the air from printers through a room air cleaner equipped with HEPA filtration for particles and activated carbon filters for VOCs[38] or purchase a benchtop, single-unit fume extraction system to use while the printer operates. If filtration is used as part of an engineering control strategy, filter maintenance and replacement schedules based on the manufacturer's recommendations must be followed.

**Administrative Controls**

Administrative controls establish work practices that can reduce the exposure to hazards.[46] The following are examples of beneficial administrative controls for 3D printing:

- Controlled access to 3D printing spaces.

- Recommendations to follow the manufacturer's guidelines and material SDS documents for safe use.

- Registration and hazard assessment processes for printer purchases and installation.

- Regular inspections of 3D printers and printing spaces on campus, including indoor air quality measurements. For reference, information on indoor air quality guidelines and measurement methods are shown in Appendix B and E, respectively.

- Guidelines, required training programs, and established standard operating procedures (SOP) for all 3D printing activities including post-processing, cleaning, waste disposal, maintenance protocols, first aid, and emergency response procedures.

**Personal Protective Equipment (PPE)**

PPE is equipment worn to minimize exposure to hazards. When other control methods are unable to reduce the hazardous exposure to safe levels, PPE must be provided to minimize inhalation, ingestion, and dermal exposures and hazards during 3D printing activities.[46] Specific recommendations for PPE related to 3D printing will depend on a specific activity's risk assessment and may include lab coats or aprons, safety glasses, face shields, and/or safety goggles, and gloves. Heat resistant and/or cut resistant gloves may need to be specified. For vat photopolymerization, appropriate chemical-resistant gloves (nitrile or neoprene) are needed when handling uncured resins and chemical solvents. Safety glasses/goggles must have UV protection features.

**Supplemental Resources**

CIRI has published several scientific journal articles and created a number of educational tools and resources related to 3D printing. These may be found at CIRI's 3D printing landing page.[48] Also, a current list of scientific publications based on CIRI's 3D printing research may be seen in Appendix F. Today, CIRI continues the work of measuring and characterizing 3D printing emissions and their impact on air quality and human health. As mentioned throughout the text, the supplied appendices contain some additional resources mentioned in the text.

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## Appendix A: Questions used in the CIRI 3DP survey of CSHEMA members

Please help us learn more about your campuses by responding to the three questions below. If you don't know the answer, please take your best guess, or indicate accordingly.

1. Where are 3D printers found on your campus? (Please check all that apply):

   □ Makerspaces

   □ Libraries

   □ Machine shops

   □ Design studios

   □ Classrooms

   □ Research labs

   □ Educational labs

   □ Offices

   □ Residence halls

   □ Other (please specify) ____________________________________________

2. Which 3D printing technologies are found on your campus including the estimated number of units:

| Check All That Apply | | | Estimated # |
|---|---|---|---|
| Yes | Not sure | | |
| | | Material Extrusion (e.g., Fused Deposition Modeling [FDM], Fused Filament Fabrication [FFF]) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Vat Photopolymerization (e.g., Stereolithography [SLA], Digital Light Processing [DLP]) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Powder Bed Fusion (e.g., Selective Laser Sintering [SLS], Direct Metal Laser Sintering [DMLS], Electron Beam Melting [EBM], Selective Heat Sintering [SHS]) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Directed Energy Deposition (e.g., Laser Metal Deposition [LMD], Laser Engineered Net Shaping [LENS], Electron Beam Additive Manufacturing [EBAM]) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Binder Jetting (e.g., Powder Bed and Inkjet Head [PBIH], Plaster-based 3D Printing [PP]) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Material Jetting (e.g., Material Jetting [MJ], Multi-Jet Modeling [MJM], Wax Casting) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Sheet Lamination (e.g., Laminated Object Manufacturing [LOM], Ultrasonic Consolidation [UC]) | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |

| Check All That Apply | | | Estimated # |
|---|---|---|---|
| | | Bioprinting | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |
| | | Other (please specify)<br>________________________________________ | o 1 – 10<br>o 10 – 25<br>o 25 – 50<br>o Over 50 |

3. For material extrusion 3D printing technologies on your campus, please identify the filament type used by providing the estimated proportion out of 100% (if applicable).

| Filament Type | Estimated proportion out of 100% (if applicable) | Does not apply |
|---|---|---|
| PLA (Polylactic Acid) | | |
| ABS (Acrylonitrile Butadiene Styrene) | | |
| PETG (Polyethylene Terephthalate with added Glycol) | | |
| PC (Polycarbonate) | | |
| PP (Polypropylene) | | |
| ASA (Acrylonitrile Styrene Acrylate) | | |
| Nylon (Polyamide) | | |
| PEEK (Poly Ether Etherketone) | | |
| Metal composite | | |
| Wood composite | | |
| Carbon Fiber composite | | |
| Other (please specify)<br>____________________________________ | | |

Additional questions that could be used for gathering information during risk management assessments:

1. Describe the space where your 3D printer(s) is/are located.

2. Who will have access to your space?

3. Who has access to 3D printing in your space?

4. What other activities occur in your space?

5. How frequently will your printers be operating (hours/day, days/week)?

6. What chemicals are used or stored near your 3D printer(s)?

7. How many of each kind of 3D printing technology do you have in your space?

8. Where are your 3D printers located within your space?

9. Do your 3D printers have integrated enclosures and and/or local active filtration systems equipped with HEPA (high efficiency particulate air) filtration for particles and activated carbon filters for VOCs?

10. What information do you have about the ventilation in your space (air exchange rates, pressure differentials, % recirculated air, air filtering)?

11. Will dedicated ventilation be used for 3D printing – such as single unit local exhaust ventilation systems (fume hoods), snorkel fume extractors, or for situations where multiple printers are used, enclosed ventilated racks that exhaust to the outdoors? If so, please describe.

12. What additional 3D printing technologies or printers do you plan to purchase?

## Appendix B: Indoor air quality guidelines

There are no regulated standards for acceptable indoor air pollutant levels in nonindustrial (non-manufacturing) environments such as homes, offices, and schools. Below is a list of some U.S. and global organizations which recommend exposure limits/odor thresholds for common air pollutants in environments where a range of people with various vulnerabilities and sensitivities may exist. The most accepted is the national consensus standard ANSI/ASHRAE/ICC/ISGBC/IES Standard 189.1-2020 that gives air testing details and acceptable criteria for ozone, carbon monoxide, $PM_{2.5}$, $PM_{10}$ and specific VOCs as shown in Table B1. Table B2 lists those organizations with additional health guidance for target indoor air pollutants. Table B3 lists those regulatory and professional organizations with recommended or regulated occupational exposure limits. Measurement methodologies for occupational measurements can be found in the NIOSH Manual of Analytical Methods.[49]

**Table B1**
**Maximum Concentration of Air Pollutants Relevant to Indoor Air Quality Based on ANSI/ASHRAE/ICC/ISGBC/IES Standard 189.1-2020[36]**

| Pollutant | Maximum Concentration (µg/m$^3$ unless specified) |
|---|---|
| Carbon monoxide | 9 ppm, no greater than 2 ppm above outdoor levels |
| Ozone | 0.075 ppm (8-hour) |
| $PM_{2.5}$ | 35 (24-hour) |
| $PM_{10}$ | 150 (24-hour) |
| **Volatile Organic Compounds (VOCs)** | |
| Acetaldehyde | 140 |
| Acrylonitrile | 5 |
| Benzene | 60 |
| 1,3-butadiene | 20 |
| t-butyl methyl ether (methyl-t-butyl ether) | 8000 |
| Carbon disulfide | 800 |
| Caprolactam | 100 |
| Carbon tetrachloride | 40 |
| Chlorobenzene | 1000 |
| Chloroform | 300 |
| 1,4-dichlorobenzene | 800 |
| Dichloromethane (methylene chloride) | 400 |
| 1,4-dioxane | 3000 |
| Ethylbenzene | 2000 |
| Ethylene glycol | 400 |
| Formaldehyde | 33 |
| 2-ethylhexanoic acid | 25 |
| n-hexane | 7000 |
| 1-methyl-2-pyrrolidinone | 160 |
| Naphthalene | 9 |
| Nonanal | 13 |
| Octanal | 7.2 |
| Phenol | 200 |
| 4-phenylcyclohexene (4-PCH) | 2.5 |
| 2-propanol (isopropanol) | 7000 |
| Styrene | 900 |

**Table B1 Continued on Next Page**

## Table B1 Continued

| Pollutant | Maximum Concentration (µg/m$^3$ unless specified) |
|---|---|
| Tetrachloroethene (tetrachloroethylene, perchloroethylene) | 35 |
| Toluene | 300 |
| 1,1,1-trichloroethane (methyl chloroform) | 1000 |
| Trichloroethene (trichloroethylene) | 600 |
| Xylene isomers | 700 |

## Table B2
## Organizations who recommend exposure limits and risks levels for common air pollutants

| Organization or Standard | Application | Additional Information | Website |
|---|---|---|---|
| ANSI/ASHRAE/CC/USGBC/IES Standard 189.1-2020 | General air/ indoor air | Standard that defines indoor air quality (IAQ) requirements for target volatile and non-volatile air contaminants. | https://www.ashrae.org/technical-resources/bookstore/standard-189-1 |
| The United States Environmental Protection Agency (U.S. EPA) | Inhalation and oral exposure of target chemicals | The U.S. EPA maintains the Integrated Risk Information System (IRIS), a database on information on noncancer and cancer health effects that may result from exposure to various substances in the environment, based on toxicological reviews. IRIS has a reference concentration for inhalation exposure (RfC) and a reference dose for oral exposure (RfD). RfC and RfD are estimates of a daily exposure of the human population that is likely to be without an appreciable risk of deleterious effects during a lifetime. | https://www.epa.gov/iris |
| CDC's Agency for Toxic Substances and Disease Registry (ATSDR) | Minimal risk levels for target chemicals | The CDC's Agency for Toxic Substances and Disease Registry (ATSDR) has developed Minimal Risk Levels (MRLs) which estimate the daily level to which a substance may be exposed without the likelihood of adverse, non-cancer health effects. MRLs are derived for acute (1 – 14 days), intermediate (>14 – 364 days), and chronic (365 days and longer) exposure durations. | https://wwwn.cdc.gov/TSP/MRLS/mrlsListing.aspx |
| CA 01350 Specification | Specific source emissions | CDPH SM 01350 sets allowable concentrations that emission levels from building products and materials must meet within 14 days after installation. Certification programs like CHPS, GREENGUARD gold, and BIFMA have adopted this requirement. | https://www.cdph.ca.gov/Programs/CCDPHP/DEODC/EHLB/AQS/Pages/AQS-Main-Page.aspx |
| U.S. Green Building Council Leadership in Energy and Environmental Design (LEED) | Indoor air and specific target chemicals | The LEED rating system specifies maximum acceptable concentrations for the clearance testing of air levels before a building or school is occupied. | https://www.usgbc.org/leed |
| California Office of Environmental Health Hazard Assessment (OEHHA) | Reference exposure levels for target chemicals | Reference exposure levels (RELs) address non-cancer health effects of volatile organic compounds (VOCs) and provide concentrations below which these health effects have been observed in studies. | https://oehha.ca.gov/air/general-info/oehha-acute-8-hour-and-chronic-reference-exposure-level-rel-summary |
| California OEHHA Proposition 65 | Allowable daily dose for target chemicals | Chemicals that are known to cause cancer or birth defects or other reproductive harm | https://oehha.ca.gov/proposition-65 |

## Table B3
## Organizations who recommend occupational exposure limits and risks levels for common air pollutants

| Organization or Standard | Application | Additional Information | Website |
| --- | --- | --- | --- |
| California The Division of Occupational Safety and Health (Cal/OSHA) | Occupational | California has the most extensive list of occupational exposure limits of all states in the US reported as permissible exposure limit (PEL). | https://www.dir.ca.gov/Title8/5155table_ac1.html |
| National Institute of Occupational Safety and Health (NIOSH) | Occupational | NIOSH recommended exposure limits (RELs) are intended to limit exposure to hazardous substances in workplace air to protect worker health. | https://www.cdc.gov/niosh/npg/pgintrod.html |
| American Conference of Governmental Industrial Hygienists (ACGIH) | Occupational | Threshold Limit Values (TLV®s) are guidelines for the level of exposure that the typical worker can be exposed to without adverse health effects. They are not quantitative estimates of risk at different exposure levels or by different routes of exposure. | https://www.acgih.org/science/tlv-bei-guidelines/ |
| Occupational Safety and Health Administration (OSHA) | Occupational | Permissible exposure limits (PELs) are how OSHA defines the maximum concentration of chemicals to which a worker may be exposed. PELs are defined in two ways: STEL (15-minute time-weighted average not to be exceeded) or an 8-hour total weight average (TWA), which is an average value of exposure over an eight-hour work shift. | https://www.osha.gov/annotated-pels |

In addition, the U.S. EPA has established standards or made recommendations on air quality guidelines (AQG) for levels of $PM_{2.5}$ and $PM_{10}$ particulate matter pollution in the outdoor as presented in Table B4.

## Table B4
## U.S. EPA Standards for PM Pollution[50]

| Pollutant | Primary/Secondary* | Averaging Time | Standard ($\mu g/m^3$) | Notes |
| --- | --- | --- | --- | --- |
| $PM_{2.5}$ | Primary | Annual | 12 | annual mean, averaged over 3 years |
| | Secondary | Annual | 15 | annual mean, averaged over 3 years |
| | Primary and Secondary | 24-hour | 35 | 98th percentile, averaged over 3 years |
| $PM_{10}$ | Primary and Secondary | 24-hour | 150 | Not to be exceeded more than once per year on average over 3 years |

*Primary standards provide public health protection, including protecting the health of "sensitive" populations such as asthmatics, children, and the elderly. Secondary standards provide public welfare protection, including protection against decreased visibility and damage to animals, crops, vegetation, and buildings.

## Appendix C: Example campus guidelines and resources on 3D printing

The following links provide examples of guidelines and fact sheets created by various campuses for use as resources for 3D printing on their campuses.

1. Carnegie Melon University
https://www.cmu.edu/ehs/Guidelines/ehs-guideline—3d-printers1.pdf

2. University of California, Los Angeles
https://ucla.app.box.com/s/yh8ikmma3h06t62d5duipjvxukh8jtr7

3. Harvard University
https://www.ehs.harvard.edu/sites/default/files/3d_printers_fact%20sheet.pdf

4. University of Pennsylvania
https://ehrs.upenn.edu/sites/default/files/2021-03/3D%20Printng%20Fact%20Sheet%20js3-21_0.pdf

# Appendix D: Example 3D printing risk assessment tool

NTRC NANOTECHNOLOGY RESEARCH CENTER
National Institute for Occupational Safety and Health

## 3D Printing with Filaments: Health and Safety Questions to Ask

Review the questions on the left and explore different control options and other information to reduce your exposure on the right

### 1 Characterization of Potential Hazards

What potential hazards are associated with 3D printing? Are there known health effects from the filaments (for example, see safety data sheets)? What is the work environment like (for example, open or isolated area)?

**Potential hazards may include:**
- Breathing and skin contact with volatile organic chemicals (VOCs) and particulates (printing) and other chemicals (post-printing)
- Hot surfaces and moving parts

**Printing considerations:**
- Printing material (e.g., use polylactic acid (PLA) filament rather than acrylonitrile butadine styrene [ABS] when possible)
- Filaments with additives (e.g., metals, nanomaterials, carbon fibers)
- Frequency and duration of printing
- Manufacturer's recommendations for bed and nozzle temperatures

**Work environment best practices:**
- Print a negative pressured area with a dedicated ventilation system, in an area away from other work
- Reduce time spent near printing process (e.g., monitor remotely or leave area)

### 2 Work Activities

Could the work activity cause exposures? What is the likelihood of exposure? Can you change the way you do the activity to reduce the likelihood of exposure (high potential to low)?

**Pre-printing**

Higher potential for exposures:
- Cleaning printer heads/nozzles
- Heating nozzles

Lower potential for exposures:
- Loading filament into printer
- Changing printer heads/nozzles
- Prepping build plate

**Printing**

Higher potential for exposures:
- Using printer in general office work area
- Working near printer
- Going to printer quickly after print failures and during start up

Lower potential for exposures:
- Using video monitoring

**Post-printing**

Higher potential for exposures:
- Removing support structures with solvents or other chemicals
- Post-processing activities with filaments containing nanomaterials

Lower potential for exposures:
- Removing part and changing filaments
- Scraping build plate with tools

**Maintenance and cleaning**

Higher potential for exposures:
- Cleaning printer head/build plate with solvents

Lower potential for exposures:
- Changing filaments
- Collecting waste
- Housekeeping

### 3 Engineering Controls

Based on the work activity, what engineering controls will reduce the likelihood of exposure? What are the key design and operational requirements for the control?

**Applies to all Printing Stages**
- High efficiency particulate air (HEPA)-filtered local exhaust ventilation placed printing
- If concerned about VOCs, add gas and vapor filters to local ventilation
- Ventilated enclosure or containment (for example, fume hood)
- Local exhaust ventilation or ventilated enclosure for post-processing activities involving chemicals (for example, cleaning or spray painting parts)
- Ventilated enclosure or downdraft table for cutting and grinding parts during postprocessing

### 4 Administrative Controls

Have you considered your workplace practices and policies? Have you set up a plan for waste management? Have you considered what to do in case of a chemical spill?

**Applies to all Printing Stages**
- Incorporate 3D printing into workplace safety plans
- Develop standard operating procedures and train workers
- Do not consume food or drinks in work areas
- Select the lowest printing temperature that achieves the desired product
- When possible, choose a filament with lower known emission rates
- Use signs to alert workers of hazards and appropriate actions to protect themselves
- Restrict access to essential personnel or use remote monitoring
- Handle and dispose of all waste materials (including cleaning materials/gloves) in compliance with all applicable federal, state, and local regulations

### 5 Personal Protective Equipment (PPE)

If the measures above do not effectively control the hazard, what PPE can be used? Have you considered PPE for other safety hazards (for example, thermal gloves to prevent burns from hot printer heads)?

**Applies to all Printing Stages**

Wear PPE that is appropriate for the activities around you (for example, a coworker cleaning a printer next to your work station may require you to wear the same level of PPE). Follow proper PPE replacement practices. Do not wear PPE outside of work areas. Examples of possible PPE are

- Nitrile or chemical resistant gloves
- Lab coat or overalls
- Safety glasses, goggles, or face shields
- Respiratory protection when indicated and when engineering controls cannot control exposures, and in accordance with federal regulations (29 CFR 1910.134)
- NIOSH guidance on respirators can be found at www.cdc.gov/niosh/topics/respirators/

Centers for Disease Control and Prevention National Institute for Occupational Safety and Health

**Learn more about working with filaments for 3D Printing** | DHHS (NIOSH) Publication No. 2020-115, https//doi.org/10.26616/NIOSHPUB2020115 | March 2020

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https://www.cdc.gov/niosh/docs/2020-115/pdfs/2020-115.pdf?id=10.26616/NIOSHPUB2020115

## Appendix E: Indoor air quality measurement in 3D printing spaces

CIRI research has shown that high concentrations of UFPs and over 200 VOC species can be emitted during 3D printing. Emission profiles vary with print conditions including printer and feedstock properties. These emissions can deteriorate indoor air quality and may result in adverse health impacts, especially when used in non-industrial indoor environments with minimal ventilation. Full research reports on identification and characteristics of the emissions can be found on CIRI's website[51]. Methodologies for measuring particles and VOCs in general indoor, non-industrial, spaces follow the guidance of outdoor air measurements and include the following methods.

**Table E1**
**Methodologies for Measuring Particles and VOCs in Indoor Air**

| Measurement | Methods |
|---|---|
| VOCs | ASTM D6196[52]<br>EPA Method TO-17[53]<br>EPA Method TO-1[54] |
| Particles | EPA 62 FR 38764[55]<br>NIOSH 0501(total particles)[49]<br>NIOSH 0600 (respirable particles)[49]<br>EPA Method 5[56] |

For a specific printer evaluation and its acceptability for an indoor space, the national standard ANSI/CAN/UL 2904[17] is available. This is a joint Canada-United States National Standard developed through UL's consensus-based Technical Committee process in accordance with the requirements of the American National Standards Institute (ANSI) and the Standards Council of Canada (SCC). The Standard provides a systematic test method to identify and characterize 3D printer emissions and includes guidance on estimating exposure levels during the printing process. Chemical and particle emissions are measured during the operation of 3D printers, enabling accurate and comparative measurement data across various machines and print media available in the marketplace. The Standard describes, in detail, processes for measuring total particle concentrations over a wide range of particle sizes (ultrafine, fine, and coarse) during printing using a combination of particle size and concentration analyzers. The particle emission rates (emission per hour) and yields (emission per mass of feedstock used) are calculated from measured particle concentrations with adjustments made to account for particle loss.

ANSI/CAN/UL 2904[17] Standard primarily applies to measuring emissions from 3D printers operating with commercially available feedstocks, in classrooms, offices, libraries, residential settings, small and medium size enterprises, and other non-industrial indoor spaces. The test protocol is beneficial to comparing and evaluating the emissions from different print material, printed objects, and printer hardware, as well as obtaining data for risk assessments. This Standard includes methods to quantify emissions and requirements on laboratory quality management systems and measurement uncertainty estimation. This Standard can be used to generate data for product development, product comparisons, certification or verification, research, and risk assessments. This Standard can be accessed on UL Standards' website.[57]

Key elements of the ANSI/CAN/UL 2904 Standard include:

- A two-day test protocol, including preparation, pre-operating, printing, and post-operating phases of the printer.

- Setup of a test environment that maintains a well-controlled background, including a test chamber and clean air supply system, along with criteria that the setup needs to comply.

- Processes for measuring total particle concentrations covering a wide range of particle sizes (ultrafine, fine, and coarse) during emission tests at reasonable frequencies.

- Procedures for calculating particle emission rates (emission per hour) and yields (emission per mass of feedstock used).

• Processes for measuring VOCs in range of C6 to C16 (boiling points between 60°C and 290°C) and aldehydes like formaldehyde.

• Method of calculating exposure levels of VOCs and particles, based on detailed environment models. Specification of the office environment model for product certification or verification.

• Maximum allowable emission rate criteria for VOCs and total particle emissions.

• A universal test method for assessing particle and VOC emissions from operating 3D printers.

• Provides a test method and criteria for third party verification or certification.