

3D PRINTER SAFETY

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1. Introduction

Three-dimensional (3D) printers are gaining popularity. 3D printing is commonly used for rapid prototyping and for small scale manufacturing in aerospace, defense and health care. 3D printers are now common in homes, schools, libraries and office settings, as low-cost desktop versions have made this technology widely accessible. Several departments of Concordia University are already using 3D printers. Even though the use of 3D printers is increasing, yet there are no real guidelines on sound industrial hygiene controls.

As with all technology, 3D printers have hazards that user must be aware of. This document highlights hazards associated with 3D printer usage, and discusses safety procedures to be followed by users in order to prevent injuries and near-misses related to 3D printing processes. As well, the information in this document can help in the selection of the most appropriate 3D printer for your workspace. If you have any additional questions, please do not hesitate to contact the Environmental Health & Safety office (EHS) at ehs@concordia.ca or at 514-848-2424 ext. 4788.

2. 3D Printer Owner's Responsibilities

3D printers must be registered upon purchase by filling up and sending to EHS the 3D Printer Registration Form (EHS-FORM-113). EHS will be responsible for conducting a risk assessment review and therefore approval of all 3D printer purchases. Risk assessment will consider the type of printer, the type of print media to be used and the proposed location of the printer set-up before approval is granted.

3D printer users shall receive training in the correct and safe operation of the 3D printer, which may include also WHMIS training relevant to the media and other chemical products used in the printing process. Principal Investigators or 3D printer managers are responsible for the enforcement of any safety compliance regarding the proper use of 3D printers by users.

EHS may halt any 3D printer operations or procedures that are considered dangerous and unsafe.

3. 3D Printing Filaments

There are different types of 3D printing technology, however the majority of commercially available 3D printers utilize an additive manufacturing technique called fused filament fabrication (FFF), also known as fused deposition modeling or molten polymer deposition (MPD). This technology makes use of a solid thermoplastic filament which is forced through a computer-driven heated extrusion nozzle. Following a computer-generated image, the 3D printer uses heat to melt and place layers of filament on top of one another onto a moving bed. A 3D replica of the image is then formed as the filament material cools and hardens.

A wide variety of filament materials are now being used in desktop FFF 3D printers, including:

- Poly(lactic acid) (PLA);
- Acrylonitrile Butadiene Styrene (ABS);
- Polyethylene Terephthalate (PET) or Polyethylene Terephthalate Glycol-modified (PETG);
- Nylon Polyamide
- Polyvinyl Alcohol (PVA);

- Polycarbonate (PC);
- Polypropylene (PP);
- High-Impact Polystyrene (HIPS);
- Polyphenylsulfone (PPSF or PPSU)
- Other polymer, metal, wood or ceramic materials.

Filaments are melted at a variety of extruder nozzle temperatures and bed temperatures (Table 1) and manufacturers typically recommend ranges of optimal temperatures for each filament material and thickness. ABS and PLA filaments are currently the most commonly used in desktop 3D printers, although others are also gaining in popularity.

Table 1: 3D Printing Filaments and Associated Characteristics

Filament Type	Extruder Temp (°C)	Bed Temp (°C)	Characteristics
Poly(lactic acid) (PLA)	180–230 (356–446°F)	20–60 (68–140°F)	<ul style="list-style-type: none"> • one of the most commonly used filaments • usually made of corn starch or sugar cane • useful in a broad range of printing applications • odorless and low-warp • does not require a heated bed • wide range of filament colors • non-toxic, biodegradable and compostable in industrial composters (and through Concordia’s compost initiative)
Polyvinyl Alcohol (PVA)	180–230 (356–446°F)	45 (113°F)	<ul style="list-style-type: none"> • non-toxic • water soluble • low flexibility and safe for food • mainly used to print supports with dual extruder 3D printers
High-Impact Polystyrene (HIPS)	210–250 (410–482°F)	50–60 (122–140°F)	<ul style="list-style-type: none"> • similar to ABS but less likely to warp • can be dissolved using limonene • can bend without cracking when cool • mainly used to print supports with dual extruder 3D printers • requires a heated bed
Acrylonitrile Butadiene Styrene (ABS)	210–250 (410–482°F)	80–120 (176–248°F)	<ul style="list-style-type: none"> • one of the most commonly used filaments • petroleum-based non-biodegradable plastic • less brittle and more ductile than PLA • makes durable parts that can withstand higher temperatures • can be post-processed with acetone to provide a glossy finish • does not require a heated bed • wide range of filament colors • produces fumes when melted
Polyethylene Terephthalate (PET) or Polyethylene Terephthalate Glycol (PETG)	230–255 (446–491°F)	55–70 (131–158°F)	<ul style="list-style-type: none"> • usually composed of PET along with other copolymers • combines the ease of use of PLA filament with the strength and durability of ABS filament • barely warps and produces no odors or fumes when printed • recyclable

Polypropylene (PP)	230-260°C (446-500°F)	60-110°C (140-230°F)	<ul style="list-style-type: none"> • high level of flexibility • great toughness; elastic without being too soft • resistant to many chemicals • high resistance to electricity making it useful in electronic components • notoriously difficult to print with, presenting heavy warping and poor layer adhesion
Nylon Polyamide	235-270 (455-518°F)	60-80 (140-176°F)	<ul style="list-style-type: none"> • strong, lightweight, flexible and durable • less brittle than PLA or ABS • often used for living hinges and other functional parts • usually available as a bright natural white with a translucent surface but can absorb post-processed color dyes • requires a heated bed • extremely sensitive to moisture • when heated will break down and emit toxic fumes
Polycarbonate (PC)	270-310 (518-590°F)	90-105 (194-221°F)	<ul style="list-style-type: none"> • strong and very resistant to impact • very resistant to temperature • can bend without cracking when cool • requires a heated bed • may emit toxic fumes when heated

Thermoplastic filaments are potentially hazardous and can pose a risk to the health and well-being of individuals who use 3D printers and those in close proximity. It is important to understand the hazards associated with the filaments to be used PRIOR to purchasing and installing a 3D printer on university property. A risk assessment can be conducted by EHS and will ensure that the appropriate controls are put in place for the printer such that the risks are properly mitigated.

4. Potential Risks of 3D Printing

4.1. Heat

Temperatures of 190 to 270°C are typically used at the end of the extrusion nozzle in order to melt plastic to the right consistency for 3D printing. The nozzle temperature depends on the type of material used and the kind of finish required.

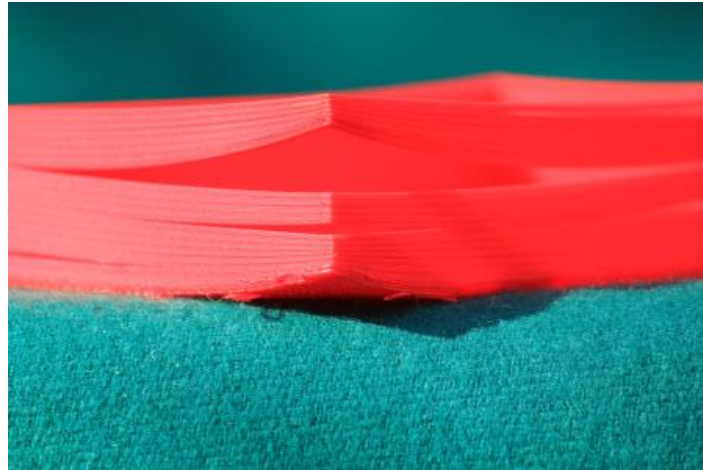
Temperatures of such magnitudes can create skin burns if users get in contact with the instrument's heated parts. Skin burns are also common when 3D printer users try to remove melted plastic from the nozzle while the nozzle is still hot.

Some 3D printers also have heat beds. Heat beds are used because they improve print quality by keeping the extruded plastic warm and thus preventing warping. When plastics are printed, they initially expand slightly and then contract as they cool down. If the plastic contracts too quickly much, it can cause the printed object to bend up from the build plate – referred to as warping (Figure 1).

Heat beds work to prevent the warping effect by keeping the 3D printed object at or above heat-deflection temperature during the whole printing process. Some materials shrink more than others, meaning that there is a larger chance of warping when using it. Typical bed temperatures, according to

filament type, are shown in Table 1. While bed temperatures are much lower than extrusion ones, some of them can still potentially cause skin burns. It is recommended to power off the heat bed and to wait 10 minutes before touching it. Furthermore, some 3D printer heat beds were reported to catch fire when left unattended for an extended period of time.

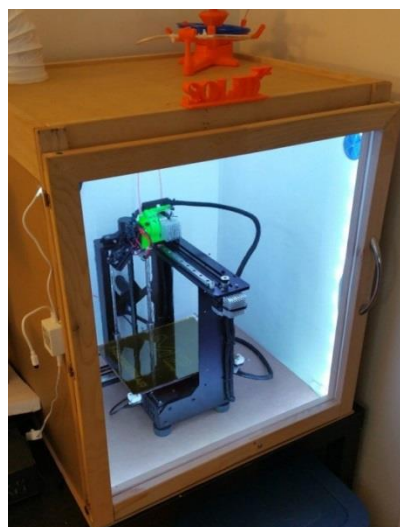
Figure 1: Plastic warp from 3D printing (taken from *3DPrintingIndustry.com*)



A 3D printer is considered heat-safe when contact with the nozzle and heated bed is prevented by surrounding it with for instance an aluminium cover or having it installed in a closed environment (Figure 2).

In order to prevent burns, 3D printers should be operated within an enclosure that prevents the user to come into contact with the various parts which pose a risk of burn, such as the nozzle and heated bed. As well, adequate signage should be present to warn the user not to tamper with the enclosure or attempt the touch the printer as it operates.

Figure 2: 3D printer located within enclosure (taken from *3dprinting.com*)



4.2. Mechanical Risks / Moving Parts

3D printers contain many moving parts: stepper motors, pulleys, threaded rods, carriages and small fans. Even though most use stepper motors that do not have enough power to cause serious injuries, they can still trap a user's finger, long hair, loose clothing, head coverings or head scarves. 3D printers operating within an enclosure are much safer since they protect users from any moving parts.

3D printers with enclosure should be equipped with an interlock system which pauses any printing when the enclosure access is opened.



If no interlock system is present, users must always disengage the printer by turning off the printer main power before manually moving the printer carriage along the X, Y and Z axis.

Furthermore, users should **confine long hair, loose clothing, head coverings or head scarves** before using any 3D printing devices.

4.3. Electrical Risks

The voltages in the exposed parts of any 3D printer usually do not exceed 12V to 24V, which is generally considered safe. Most voltages in tabletop 3D printers are also lower. Users should never remove instrument covers in order to do repairs or modifications; the instrument's manufacturer should be contacted instead.

When removing equipment covers, users might expose themselves to much higher voltages (up to 220V). Users must always switch off a 3D printer and unplug it completely from the main power supply if equipment covers are to be removed. The majority of desktop 3D printers do not have any added electrical safety features beyond regular internal fuses or external transformers.

All 3D printers used should be protected against short-circuit, overload, over voltage and over temperature. Other electrical safety features could include that the hot end of the printer contains thermal runaway protection.

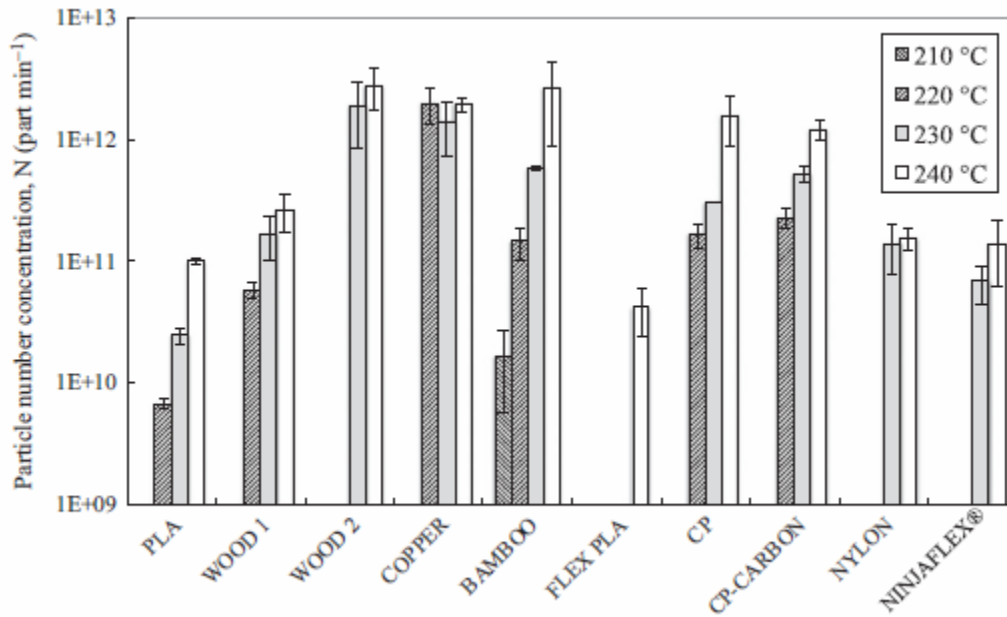
4.4. Toxic Emissions

Studies on thermal processing of plastic show that industrial extrusion equipment emit hazardous substances. Even at moderately high temperature (e.g. 170-240°C), gaseous substances are emitted during thermal processing of thermoplastic. These substances are usually referred as VOCs (Volatile Organic Compounds) and UFPs (ultrafine particles, particles with a diameter less than 100 nm). Particles and gaseous substances harmful to human health are generated, including substances such as ammonia, hydrogen cyanide, phenol, benzene.

Laboratory tests monitored the concentration of VOCs during 3D printing of plastics have shown, for example, that ABS is more toxic than PLA, but that PLA under certain conditions is not free of emissions harmful to health, especially if melted at temperatures over 200°C. A recent study compared particle emission as functions of extruder temperature and filament material by printing the same object on a

printer in a room using 10 filaments and various extruder temperatures. The results found particles emitted from all filaments were mainly UFPs with mean particle sizes between 10 – 30 nm. Higher extruder temperatures led to higher emission rates (Figure 3).

Figure 3: Particle number emission rates as a function of the extrusion temperature (taken from L. Stabile *et al.*, *Indoor Air*, 2017, Vol. 27, 398-408)



Both VOCs and UFPs can be inhaled by users through their olfactory system. The UFPs are deposited mainly in the cells of the respiratory system and through the olfactory nerves of the nasal mucosa it reaches the brain. Skin exposure allows a partial absorption. The most common diseases caused by the absorption of VOCs and UFPs produced during the 3D printing process are those related to lungs (bronchitis, tracheitis, asthma, etc.).

4.4.1. Volatile Organic Compound (VOC) Emissions

Individual VOCs emitted in the largest quantities include caprolactam from nylon-based and imitation wood and brick filaments (ranging from ~2 to 180 µg/min), styrene from ABS and HIPS filaments (ranging from ~10 to 110 µg/min), and lactide from PLA filaments (ranging from ~4 to 5 µg/min). Here are the main dangers of these 3 substances:

- caprolactam is toxic by inhalation, oral exposure or skin exposure, causes serious eye damage/eye irritation and is toxic to the respiratory system;
- styrene is toxic by inhalation, toxic to the nervous system through repeated exposure, toxic for reproduction and causes serious eye damage;
- lactide causes serious eye irritation.

Figure 4 shows the estimates of emission rates for VOCs as well as the sum of the top 10 detectable VOC emissions for different combinations of 3D printers and filaments.

In another recent study, commercially available 3D printer filaments (ABS, PLA, PET and nylon) were heated up to 240°C-250°C. Analyses revealed the presence of several VOCs, styrene, being the major component of ABS, while methylmethacrylate was the main emitted pollutant for PLA (Figure 5).

Figure 4: Estimates of emission rates for VOCs from 3D printing
(taken from P. Azimi *et al.*, Environmental Science & Technology, 2016, Vol. 50, 1260-1268)

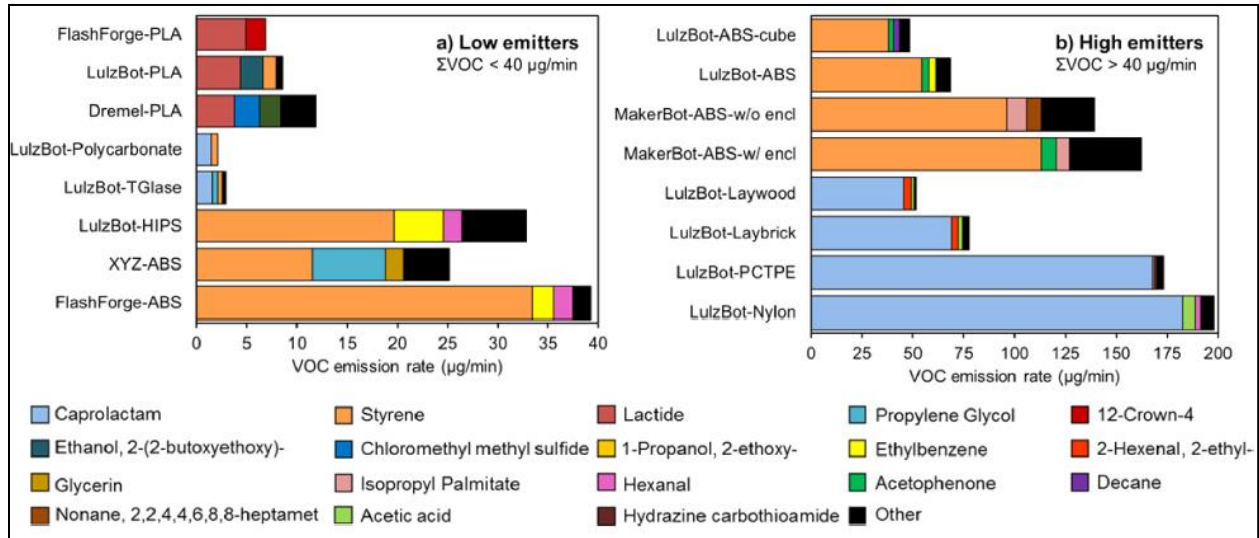
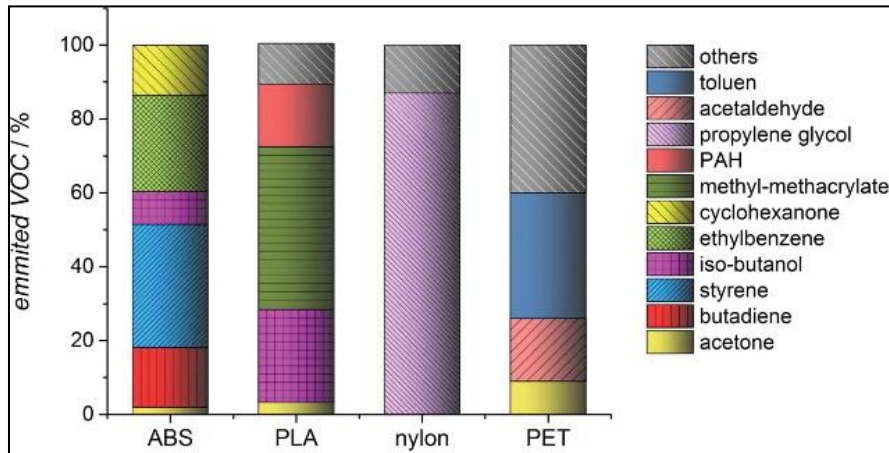


Figure 5: Emission of VOC during thermal treatment of ABS, PLA, nylon and PET
(taken from S. Wojtyla *et al.*, Journal of Occupational and Environmental Hygiene, 2017, Vol. 14, D80-D85)



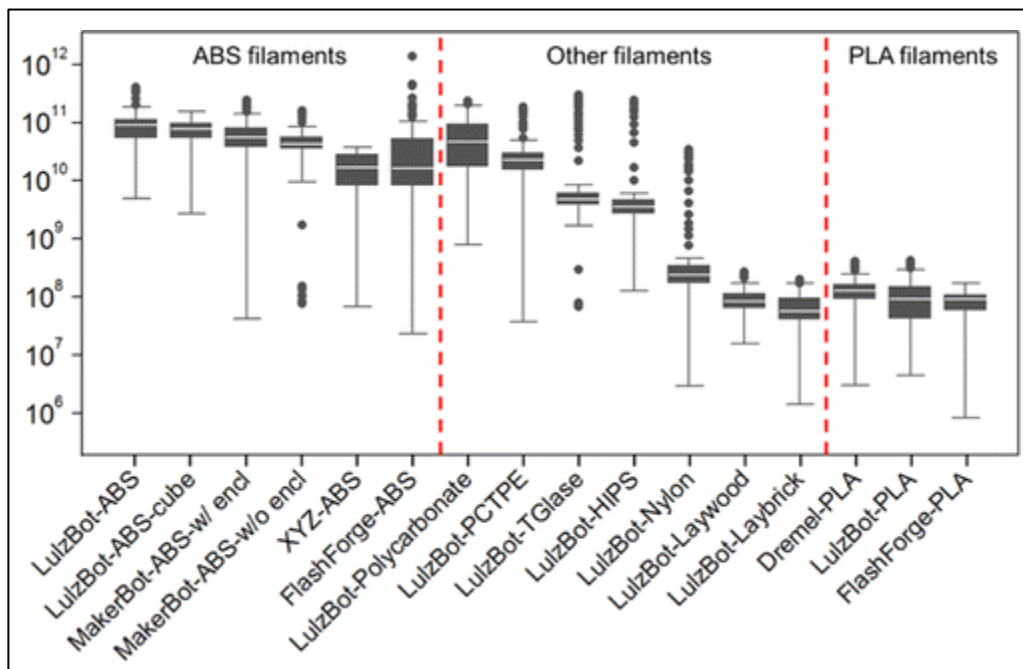
4.4.2. Ultra-Fine Particle (UFP) Emissions

Desktop 3D printers have also recently been identified as “high emitters” of UFPs and raising the temperature seems to increase their emissions. A study showed that UFP emission rates varied substantially depending on make and model of the printer, type and color of filament material, nozzle and bed temperatures and time of printing. The highest UFP emission rates typically occurred with printers utilizing ABS filaments, with median values ranging from 20 billion to 90 billion particles emitted

per minute across all ABS printers with or without enclosures. The lowest UFP emission rates occurred with printers utilizing PLA filaments, with median UFP emission rates of 0.1 billion particles per minute. The emissions peaked a few minutes after printing began, and they did not return to baseline until about 100 minutes after printing ended.

Figure 6 shows a summary of time-varying UFP emission rates estimated for some commercially available 3D printer and filament combinations. It was demonstrated that particle number concentration (from printing with PLA in a well-ventilated room was $\sim 10^3$ #/cm³; while it was $\sim 10^4$ #/cm³ for ABS in a poorly ventilated room

Figure 6: Summary of time-varying UFP emission rates from 3D printing
(taken from P. Azimi *et al.*, Environmental Science & Technology, 2016, Vol. 50, 1260–1268)



Another study compared the effect of room ventilation and 3D printer enclosure on the air distribution and concentrations of UFPs generated during 3D printing. Breathing zone (BZ) number concentration maps from a well-ventilated laboratory (10 m X 10 m X 6 m, 20 AC/hr) during a routine (1h) 3D printing operation, using PLA, showed air concentrations reaching a nominal 3,000 particle number concentration close to the printer, but fell off rapidly with distance from the printer. Approximately 3/4 of the room maintained particle concentrations at or near background levels.

When the test was repeated in poorly ventilated room (3 m X 9 m X 6 m, 1.8 AC/hr) using ABS, there was a rapid particle built-up in the BZ near the printer to 10^4 particle number concentration. With increased printing time (middle to end of the 60 min printing cycle), the surrounding room reached 10^4 particle number concentration as well.

Furthermore, that study also demonstrated the effectiveness of 3D printer enclosures, reducing the particle count in the BZ during the different stages of the 3D printing operation (Table 2).

Table 2: Aerosol Parameters Measured Inside and Outside Test Printer Enclosure During Printing
(taken from T.L. Zontek *et al*, J. Chem. Health Saf., 2017, Vol. 24, 15–25)

Printer Function	Parameter	Inside Printer Enclosure					Outside Printer Enclosure in BZ				
		dp ₅₀ (nm)	Mode (nm)	GSD	#/cc	µg/m ³	dp ₅₀ (nm)	Mode (nm)	GSD	#/cc (reduction)	µg/m ³ (reduction)
Heating		24.2	16.4	20.7	522,000	83.3	14.7	9.3	1.79	1,860 (0.996) ^a	0.0237 (0.999) ^a
		3.5	2.4	0.34	582,258	70.2	2.9	2.5	0.56	640	0.0410
Printing		30.5	34.1	1.95	71,450	7.6	16.3	9.4	1.71	3,780 (0.947) ^a	0.0013 (0.999) ^a
		4.6	13.2	0.12	45,068	6.2	0.5	2.1	0.01	283	0.0019
Cooling		16.3	14.3	1.50	66,308	0.4					
		1.1	1.0	0.05	38,234	0.2					
Door open		25.6	19.2	2.17	834	0.2					
		3.3	4.7	0.21	33	0.1					

Where ^a values inside parentheses represents the enclosure reduction factor; n = 10 for both sample sets; #/cc is the particle concentration measurements, dp₅₀ is the mobility median diameter; mode is the diameter value that appeared the most.

4.4.3. Safety requirements regarding 3D printers' VOC and UFP emissions

Since most 3D printers do not have exhaust ventilation or filtration accessories, EHS recommends that caution must be used when operating many 3D printer and filament combinations. **Furthermore, the following mitigation measures must be present when operating a 3D printer:**

- Always use the manufacturer's supplied controls when present; use the manufacturer's enclosure to minimize room air distribution and concentrations of UFPs.
- Maintain a safe distance from the 3D printer and your work station/desk to minimize possible exposure to VOCs and UFPs.
- Choose a low-emitting filament (such as PLA) instead of styrene- and nylon-based filaments.
- Carefully consider placement of the printer and selection of printing materials: non-laboratory or workshop environments such as offices, classrooms and libraries are usually designed for occupant comfort, not exposure mitigation.
- Use 3D printers only in well ventilated areas (>4 volume exchanges per hour), with no air-recirculation; 3D printers should then preferentially located within wet lab areas.
- Place 3D printers in an enclosure, or use the manufacturer's enclosure to minimize room air distribution and concentrations of UFPs.
- Local exhaust of the 3D printer must be performed in areas where room ventilation is poor, limited or recirculated within buildings and where filaments having toxic emissions (e.g. ABS) are used. Use either an extrusion and/or an enclosure system directing the air out of the building or through an activated carbon /HEPA filtration unit (Fig. 7).

Some new 3D printers equipped with photocatalytic filtration systems are also commercially available. Photocatalytic filters do not adsorb pollutants but rather degrade them to small safe molecules, such as H₂O and CO₂, offering odorless and safe printing.

Figure 7: 3D printers equipped with filtration unit



4.5. Other Chemical Risks

4.5.1. Bed Preparation

Chemicals can be used as part of the bed preparation such as hairspray or other glues. Hairspray is an effective airborne glue which is flammable and toxic. Always prepare the bed in a well ventilated area.

4.5.2. Post-Processing

Chemicals can also be used in post-printing processes, such as in material surface finishing or for support material removal. Solvents such as acetone or tetrahydrofuran (THF) are also often used for applying guilders paste or vapour polishing 3D prints. Vapour polishing is the process of gently heating a solvent (or similar chemical) to create a vapour around the final 3D printed object. This melts the surface slightly, allowing the natural surface tension to smooth the surface of the object. Acetone and THF are toxic and highly flammable and create dangerous fumes when heated.

Some support materials used in 3D printing are to be removed by dissolving them in an alkaline (basic) bath containing a 2% solution of sodium hydroxide at pH 13. Sodium hydroxide is corrosive and can cause chemical burns, scarring and blindness. To avoid chemical exposure while using the corrosive base bath, personal protective equipment (PPE) including a laboratory coat or smock, closed shoes, corrosion-resistant rubber gloves and splash goggles must be worn. Furthermore, an emergency eyewash is required in the immediate vicinity of the work. A spill kit capable of neutralizing the caustic components of the alkaline bath must also be available.

5. General Safety Guidelines

The following precautions shall be taken when operating a 3D printer:

- Consult EHS for a hazard risk assessment when considering installation, modifications or novel uses for the 3D printing equipment;
- All printers must be installed according to the manufacturer's requirements;

- Ensure proper ventilation or exhaust system for any 3D printer (please refer to section 4.4);
- Wear non-permeable gloves (e.g. nitrile) and dust mask (P100) when accessing the stage area of the printer after printing;
- Operators must be protected from hot surfaces associated with the printers;
- Safety Data Sheets (SDS) must be provided for all print media and for any other chemical product used in the printing process;
- Follow all PPE recommendations found in the Safety Data Sheet (SDS) for the specific printer media used;
- Eye protection is required during any activity where airborne projectiles may be present (i.e. cutting off rough edges of a printed item);
- If UV light is used in the curing process, PPE and/or shielding must be utilized to protect personnel;
- Once a printing job has been started, do not open the cover, defeat or override the interlock switch. If the interlock safety switch fails, do not use the printer;
- Uncured printing material is hazardous; wear nitrile gloves when handling it. Dispose of any uncured material as hazardous waste;
- In the event of leak or spill of printing material or other chemicals, use solvent-absorbent pads. Dispose of clean up materials as hazardous waste;
- In the event of an injury related to 3D printing, contact Security at x3717 for immediate medical assistance. Advise your supervisor and complete an [Injury / Near-Miss Report \(EHS-FORM-042\)](#).

If you have any concerns about 3D printers at Concordia University, please email EHS at ehs@concordia.ca.

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Reviewed: August 2017

6. References

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