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3D PRINTING EMISSIONS: THE BASICS

THE POTENTIAL IMPACT AND CONTROL OF 3D PRINTING EMISSIONS

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Abstract

This technical paper considers the data and associated impact and control of 3D printing emissions. Two main additive manufacturing (AM) processes are examined: fused filament fabrication (FFF, sometimes referred to as fused deposition modelling (FDM)) and VAT polymerisation (VP; sub-groups of which are stereolithography (SLA) and digital light processing (DLP)). FFF and VP generate the highest number of printer sales. Their output accounts for approximately 50% of the total components produced in the AM industry (Associates, 2021). It is also considered that, given the available data and the growing process adoption and use, there is a strong requirement to ensure associated hazards are comprehensively mitigated by both users and employers.

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SYNOPSIS

This paper considers the data and associated impact and control of 3D printing emissions. Two main additive manufacturing (AM) processes are examined: fused filament fabrication (FFF, sometimes referred to as fused deposition modelling (FDM)) and VAT polymerisation (VP; sub-groups of which are stereolithography (SLA) and digital light processing (DLP)). FFF and VP generate the highest number of printer sales of any 3D printing process. Their output accounts for approximately 50% of the total components produced in the AM industry (Associates, 2021). It is also considered that, given the available data and the growing process adoption and use, there is a strong need to ensure associated hazards are comprehensively mitigated by both users and employers.

BOFA is a world leader in portable fume extraction and is investing significantly in developing a comprehensive portfolio of products specifically for the AM industry, tailored to help users manage the risks associated with the airborne emissions produced by 3D printers. BOFA believes that users have the right to understand the emissions from their 3D printers and employers deserve help in complying with their legislative responsibility to protect their employees. This paper aims to educate the market, enabling a more informed and safer use of 3D printers.

INTRODUCTION

3D printing is internationally hailed as an innovation that brings significant benefits to its users. The technology provides flat economies of scale which can disrupt supply chains – it brings processes which enable new design opportunities, reduce material wastage and eliminate tooling costs. A factor often not adequately considered is what risks this technology may present to deliver its function.

There has been consecutive year-on-year growth in the industry with more printers being sold now than ever before and more companies supplying product generated using AM processes than ever before. Even throughout the COVID-19 pandemic and subsequent market contraction, product and service revenues within the AM industry grew and the number of users was higher than ever (Associates, 2021). As the technology matures and adoption rates increase, the requirement for heightened awareness of the risks is vital.

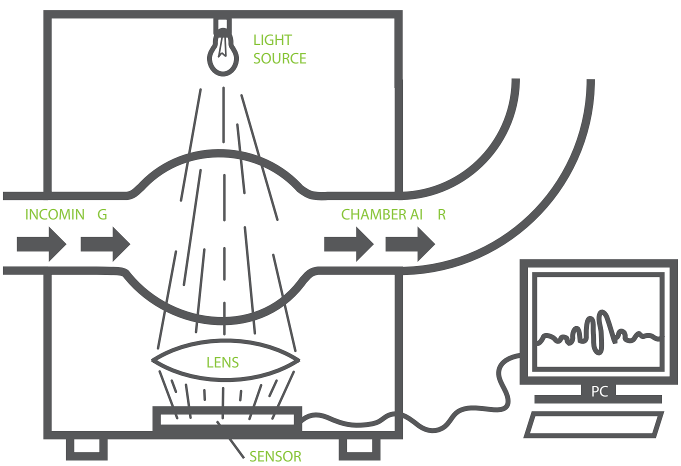
3D PRINTING EMISSIONS

Both FFF and VP processes are most popular with entry level users of AM as they offer cost competitiveness, and access to a large variety of potential materials delivering high quality printed parts. However, due to their intended customer base, their design often requires frequent manual loading, handling and process optimisation, all of which occurs in very close proximity to the printing chamber, leading to a greater potential for exposure to potential airborne hazards.

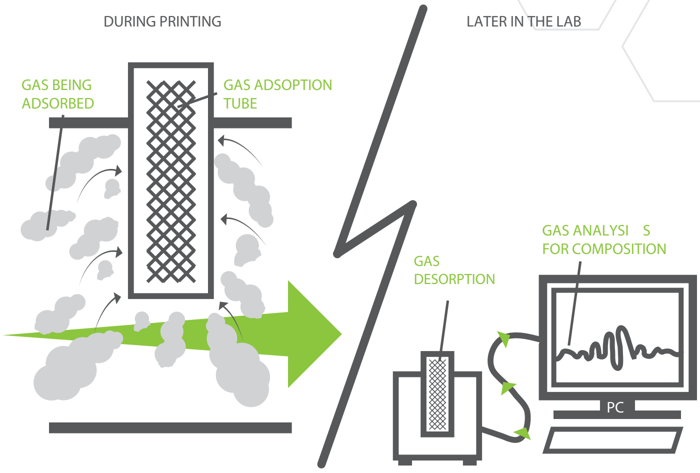
METHODOLOGY

There are proven test methods for investigating airborne emissions. Most test setups involve complicated and expensive equipment and therefore have constrained the amount of 3D printing emissions data which has been created and further, made available to the public. Below is a brief list of equipment / methods for compiling the data presented within this paper:

- Number of particles derived by using a particle counter (1).
- Size of particle derived by using a particle size analyser (PSA).



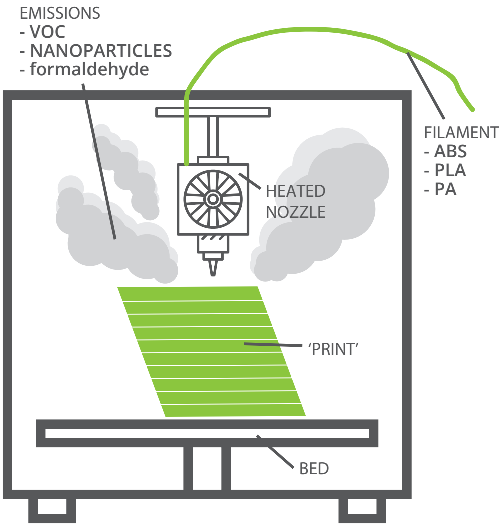
- Gas composition can be derived by using gas chromatography – gas spectrometry.
- Gas can be captured using gas adsorption / desorption tubes (2).



FUSED FILAMENT FABRICATION (FFF)

FFF creates objects by passing a filament of material through a heated extruder/nozzle. Heating the material makes it more malleable and allows it to bond to itself. The nozzle, the print bed, or both travel through three axes of movement which allows a computer aided design (CAD) file to be turned in to a three-dimensional object.

The heating and then subsequent cooling of the filament causes a breakdown of material which results in a release of both particulate and gases. Using the test methodologies outlined in the previous section, data has been made available which characterises these emissions.



FFF PRINTER

PARTICULATE RELEASE

All emissions reports on 3D printers which have actively measured airborne particulate have found their creation and emittance during printing. Particle emission rates have been found to be 1.4-18.7 mg/hr (Parham Azimi, 2016), 19-21 mg/hr (Executive, 2019), 114-564 mg/hr (A.B. Stefaniak, 2019), 0.2-1.2 mg/hr (Aika Y. Davis, 2019). The typical released particle size is between 10 and 100 nanometers (1 nanometer = 0.000000001 meters) (Figure 1 + Appendix Figure 6, Figure 7, Figure 8, Figure 9, Figure 10).

Several relationships have been found during emissions testing when varying the temperature of the 3D printer nozzle. Figure 2 and Figure 11 show how nozzle temperature dramatically changes the number of particles generated by FFF processes. It has been recorded ***"[W]hen printing with PLA filament, particle emission rates varied from 3.26 x 10^9 to 8.23 x 10^{10} particles.min -1 and average particle sizes varied from 69 nm to 24 nm as the nozzle temperature ranged from 220°C to 240°C"*** (Executive, 2019). This shows how small changes to the print process can make significant changes to the particle emission rates.

It has also been found that increasing the nozzle temperature decreases the average particle size generated by FFF processes (Figure 1). The importance of particle size in relation to exposure and potential health impacts is further examined throughout this paper.

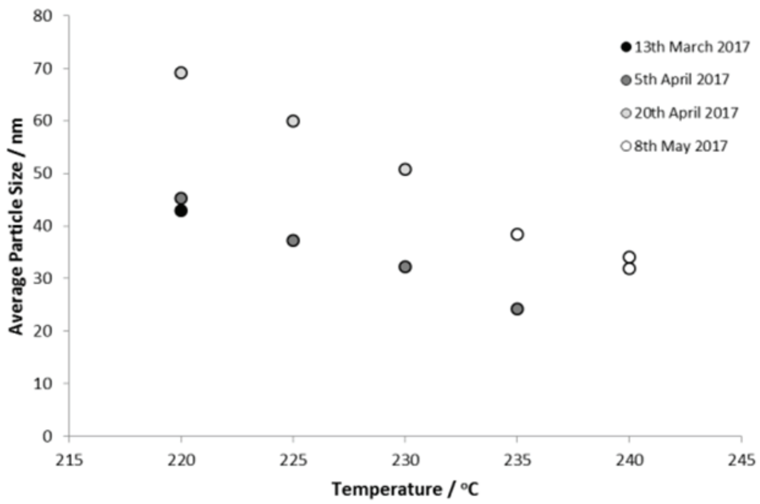


Figure 1 The effect of nozzle temperature on the average particle size using PLA filament with the KORA MIDI; measured using the DISCmini. Emission rates from two repeat tests are plotted for each temperature (three for 220° C) (Executive, 2019)

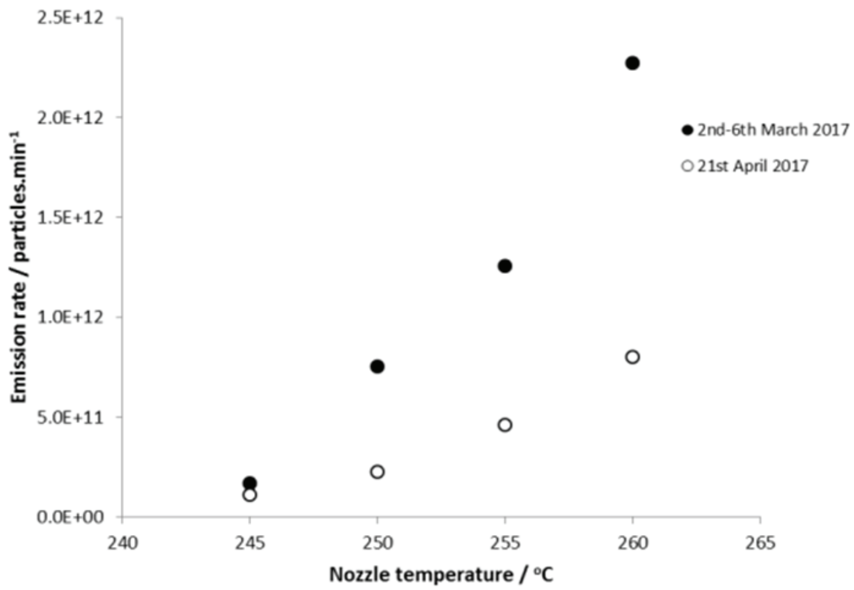


Figure 2 The effect of nozzle temperature on the emission rate using ABS filament with the KORA MIDI (print bed = 78° C); measured using the DISCmini. Data from two repeat tests are plotted for each temperature (Executive, 2019)

GASEOUS RELEASE

Similar to the creation and emittance of particulate, all reports where gases were analysed from FFF printers showed the printing event creating and emitting volatile organic compounds (VOCs) (Appendix Figure 12, Figure 13 and Figure 14). Using composition measurement tools, it was possible to show the variation in emissions from the various filament materials, as seen in Figure 3. For example, ABS filaments commonly give off styrene, acrylonitrile and butadiene, while PLA filaments can give off lactide and organic acids similar to and including lactic acid. This is understandable as these are the building blocks for the chemical structure of these plastics.

Some VOCs have odours, which are detectable by the human nose. The human nose is an incredibly capable gas detector with the ability to identify one part per billion of certain compounds with odours (H.H. Baek, 1999). This is the reason users of AM machines may experience a level of discomfort whilst printing certain materials. Both the subjective experience of the person can differ as well as the mixture of compounds released by the material itself, as the data suggests. For example, as the odour generated by printing with PLA is much lower than with ABS, many perceive the risk to be much lower or even non-existent with PLA. However the data shows there are VOCs being generated for both materials, regardless of whether a human is able to detect with their senses or not.

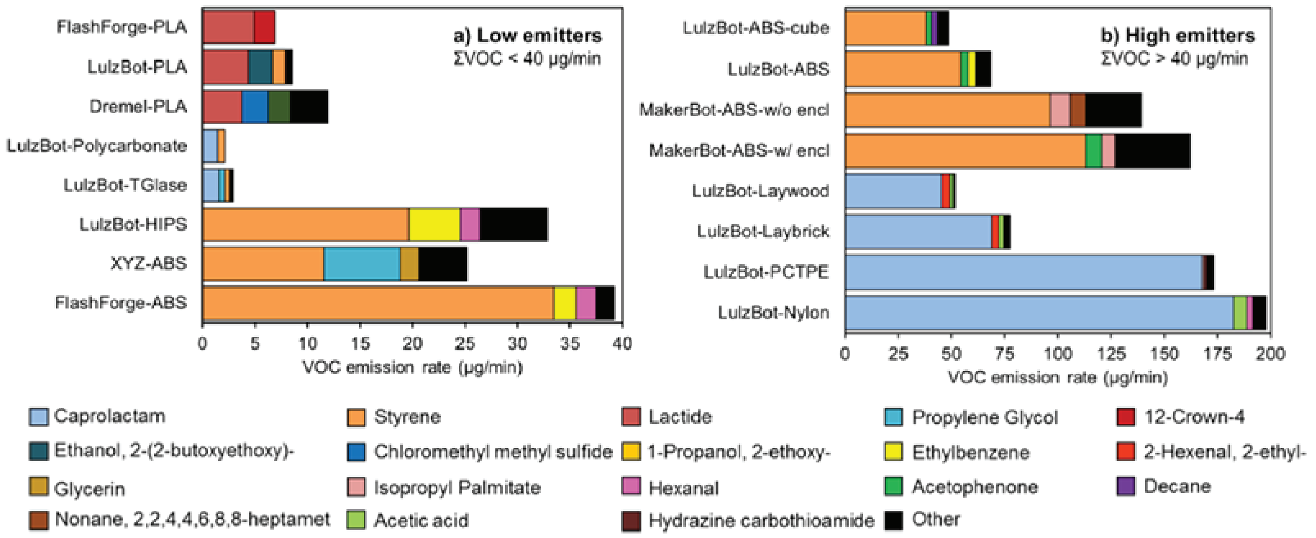


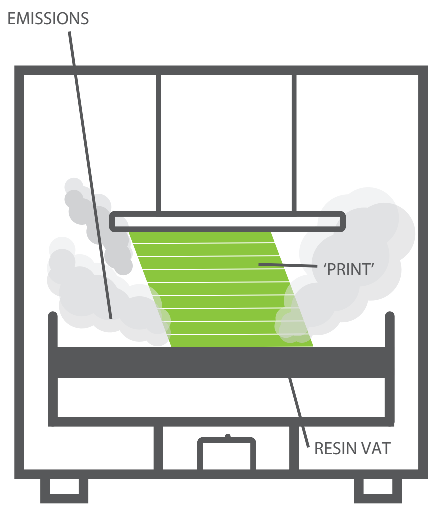
Figure 3 Estimates of emission rates for the top three highest-concentration VOCs as well as sum of the top 10 detectable VOCs (ΣVOC) resulting from operation of 16 3D printer and filament combinations. (Parham Azimi, 2013)

VAT POLYMERISATION

VAT polymerisation processes create objects by photo-reacting a liquid media into a solid. The systems are typically comprised of a light source, a vat of material and some automated adjustment in the Z axis to create height. As light patterns are shown to the media, the material polymerises, and the machine automatically moves onto repeating for the next layer.

The liquid material in its natural state, any heating (a feature on some VAT polymerisation printers) and the photoreaction have been shown to emit airborne matter (A. B. Stefaniak, 2019). The following summarises the particle and VOC emissions well:

"Despite using a bulk liquid resin feedstock, vat polymerization printers released particles and organic vapors during operation at levels that were similar to or exceeded those of other types of AM processes evaluated to date, including material extrusion"



VAT POLYMERISATION

As the printing process converts the resin into solid material not all of this ends up in the finished products. Through this mechanism nanoparticles are generated and these are characterised through data presented in Figure 4.

Printer	Type	#/g printed[A]	# 5.6 to 560 nm/g printed[A]	GM, nm (GSD)[B]	µg TVOC/g printed[A]
Form 1 +	SLA	$2.7 \pm 1.6 \times 10^8$	$1.3 \pm 0.2 \times 10^{10}$	41.3 (1.7)	277.1 ±81.5
Pegasus Touch	SLA	$1.3 \pm 0.3 \times 10^8$	$7.6 \pm 0.9 \times 10^9$	41.1 (1.8)	160.7 ± 47.4
Nobel 1.0A	SLA	$2.8 \pm 2.6 \times 10^8$	$2.1 \pm 0.9 \times 10^{10}$	45.1 (1.6)	321.7 ±228.7
Titan 1	DLP	$9.2 \pm 3.0 \times 10^8$	$4.0 \pm 1.2 \times 10^{10}$	15.3 (1.4)	1280.5 ± 313.3
M-One	DLP	$3.3 \pm 1.5 \times 10^8$	$1.1 \pm 0.3 \times 10^{10}$	28.8 (1.5)	1931.2 ±234.4

[A] Values are arithmetic mean ± standard deviation

[B] Values are geometric mean (GM) and geometric standard deviation (GSD)

Figure 4 Average emission yields and particle sizes during printing for five VAT polymerisation printers (n=5) (A. B. Stefaniak, 2019)

(A. B. Stefaniak, 2019) also characterises particulate emissions stating:

"During printing, particle emission yields (#/g printed) ranged from 1.3 ± 0.3 to 2.8 ± 2.6 × 10^8 (SLA printers) and from 3.3 ± 1.5 to 9.2 ± 3.0 × 10^8 (DLP printers). Yields for number of particles with sizes 5.6 to 560 nm (#/g printed) were 0.8 ± 0.1 to 2.1 ± 0.9 × 10^{10} and from 1.1 ± 0.3 to 4.0 ± 1.2 × 10^{10} for SLA and DLP printers, respectively"

POST PROCESSING

One part of 3D printing that is often overlooked is the post processing. This might include activities such as sanding (that generates particulate); gluing (that generates cyanoacrylates); and solvent-based finishing (which can release VOCs such as acetone). Though quantitative data on AM post processing has not been made public, the physics and mechanisms for emission release are understood and accepted across other industries, such as construction, subtractive manufacturing and the creative industries, with the legislation in those industries protecting those that work in them from the hazards present.

WHAT IS HARMUL IN 3D EMISSIONS?

Understanding the health hazards associated with the air you are breathing is very important. When assessing the health effects of 3D printing processes, it is useful to divide these into gases (usually in the form of VOCs) and particles. However, the potential compounding effects of particles and gases should not be ignored.

Particle size is very important as it affects where in the respiratory system the particle is deposited, as show in Figure 15 (Appendix). In general, the smaller the particle, the further into the respiratory system it is able to penetrate and, therefore, the more potential harm it can do. There is data available which categorises where particles from AM processes will be deposited in which area of the respiratory system (Figure 16, Appendix). Much of the research in this area focuses on micron sized particles however, it is smaller nano-sized particles that are typically generated by 3D processes. This small size, has the potential to allow particulate to be inhaled and potentially move through the body. (Ostiguy C, 2008).

The interaction of gases with the respiratory system must also be considered. The human lungs have roughly the same surface area as a tennis court (Association, 2017). This gives a large potential exposure route to particles. Some chemicals can also be adsorbed through the skin (CDC, n.d.). This includes styrene ((ATSDR), 2011) which is a common emission from ABS printing. Because of the existence of potential routes of exposure, it is important for users to understand what substances they are using and potentially being exposed to along with what adverse health effects those substances may have.

WHAT RESTRICTIONS ARE IN PLACE?

Each country has its own set of regulations used to protect workers from harmful exposure. However, they tend to follow similar structures. Firstly, the governing body will make it the responsibility of the employer to look after people on their site. For example, in the UK, this is covered by the 1974 Health and Safety at Work Act:

"It shall be the duty of every employer to ensure, so far as is reasonably practicable, the health, safety and welfare at work of all his employees".

Then the governing body establishes Occupational Exposure Limits (OELs), which are maximum concentrations of different chemicals that employees can be exposed to. These are known by different names across the world, for example Workplace Exposure Limits (WELs) in the UK; Permissible Exposure Limits (PELs) or Threshold Limit Values (TLVs) in the USA; and Maximum Allowable Concentration / Maximale Arbeitsplatzkonzentrationen (MAK) in Germany. For most chemicals, the OELs will be the same or similar in different countries.

In many countries it is also a legal expectation that employers not only meet the OELs, but reduce exposure concentrations below the OEL as far as reasonably practicable.

This structure is good for helping protect people but it doesn't address one of the key concerns from 3D printing: nanoparticles. As cited earlier, nanoparticles present a higher risk to operators than regular respirable particles, due to how far in to the human body they can penetrate. There are some indications that this may be changing:

2012

Dutch SER's Working Conditions Committee adopted its provisional nano reference values (see Figure 17). While this isn't regulation, it established the maximum number of particles per centimetre cubed that workers could be exposed to during an eight hour working day and has been referenced in risk assessments of 3D printing. 3D printing processes would typically fall into Class 3 meaning that operators should not be exposed to 40,000 particles/cm^3. Figure 18 shows this nano reference value applied to particle concentrations measured by (Executive, 2019).

2019

UL 2904 Standard Method for Testing and Assessing Particle and Chemical Emissions from 3D Printers was established. 3D printer manufacturers would have to be below maximum nanoparticle emission rates ($3x10^{11}$ particle per hour and $2x10^{10}$ particles per gram of feedstock) to achieve this standard.

2019

UK Health and Safety Executive (HSE) released RR1146 - Measuring and controlling emissions from polymer filament desktop 3D printers, which highlights the emissions of nanoparticles from 3D printing processes.

2020

NanoHarmony project launched. This three-year project brings together 14 expert partners from 10 European Countries and will work alongside OECD and ECHA in accelerating the development of priority Test guidelines and Guidance Documents for nanomaterials.

2021

American Conference of Governmental Industrial Hygienists (ACGIH) established threshold limit values for ultrafine particles (nanoparticles) for titanium dioxide. The 'regular' TLV is 15 mg/m^3 while the nanoparticle TLV is fifty times smaller at 0.3 mg/m^3. While titanium dioxide is not a nanoparticle commonly emitted by 3D printing processes this shows how much more harmful the ACGIH considers nanoparticles to be.

These changes show how the understanding of the health implications of nanoparticles is developing and where legislation might be heading.

Another shortfall of these regulations is that, due to the wide variety of chemicals that can be generated by 3D printing chemicals, not all chemicals will have an OEL. This does not mean that they are not harmful or that the regulations do not require them to be controlled, but users don't know what levels are deemed safe. This is where standards like UL2904 are very helpful as they give maximum emission rates for total VOCs, which means that chemicals without OELs can be covered by this.

WHAT MITIGATION STRATEGIES ARE OUT THERE?

A widely accepted risk mitigation system, promoted by numerous safety organisations, is the hierarchy of hazard controls. This can be used to control any hazard, whether it is trip hazard at work, radiation, stress or chemical exposure from a 3D printing process. The system promotes various risk mitigation methods in order of decreasing effectiveness, as shown in Figure 5 Hierarchy of Controls ((CDC), 2015) ((CDC), 2015)):

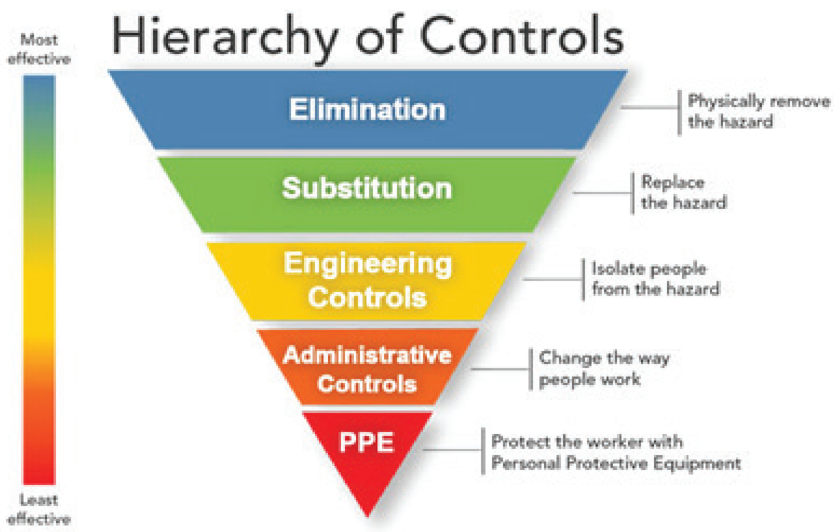


Figure 5 Hierarchy of Controls ((CDC), 2015)

It is in the best interest of the user to attempt to control a hazard using the most effective method possible and, in addition, multiple control methods below that. However, due to 3D printing's value proposition, **eliminating** the technology from use is not possible. Additionally, the benefits the technology brings over other manufacturing processes means **substitution** for another technology is also not a viable alternative. It might be possible to substitute a more harmful printing material for a less harmful one but, from the data shown in the previous sections, even less harmful materials present a hazard.

The next most effective protection against the airborne hazards is to use **engineering controls**. Solutions in this instance are technologies such as fixed ventilation systems (vent to air) and the often lower-cost, more portable alternative: direct extraction (also referred to as local exhaust ventilation (LEV)). Both examples of engineering controls need to complete two main functions: firstly, to capture the particulate, and secondly to filter it. Enclosing the process would also come under this control method. Enclosures can go a long way to separate operators from the particulate, but most will not completely contain it and the particulate may be released at the end of the build when the operator retrieves the product. However, using enclosures in conjunction with extractors, maximises the benefit of both.

In either scenario it is best practice to capture any particulate and fume at the source having the point of entry to any extraction system as close to the point of emission release as physically possible. General room ventilation and heating, ventilation, and air conditioning (HVAC) systems are not as effective at removing the hazard as often people are in between the source and the capture device / filtration system. This means, regardless of the number of air changes per hour, any airborne contaminants produced are potentially passing through the breathing zone of users before being captured.

Administrative controls and **Personal Protective Equipment** (PPE) are the lowest forms of control but often the first ones people think of. The reason they are so low on the hierarchy is they don't actually control the hazard; they just limit individual's (rather than group's) exposure. These can be useful when combined with more effective forms of control but if they're the only control method employed a business should re-evaluate their process.

BOFA believes the level of protection offered against the risks associated with 3D printing is best provided through the use of a specialist direct extraction (LEV) system. BOFA offer a comprehensive range of solutions for all AM processes and applications, with the ability to customise and produce bespoke solutions designed specifically for our customers.

HOW THINGS ARE CHANGING

There are many trends in the industry which may impact the emission release of 3D printers. Two of the most obvious are the drive to increase productivity and efforts to increase the diversity of material which can be printed. Any productivity gain is directly proportional to the amount of material printed, which in turn is directly proportional to the amounts of emissions being produced. Considering work areas are not getting any bigger in parallel this would mean concentrations of emissions will increase and the need to effectively manage those emissions will increase as well.

Additionally, as presented in this document, temperature is directly proportional to the volume of emissions and therefore to the potential exposure to such emissions. In general, the hotter the process gets to support a greater variety of materials, the more airborne contaminants are present which then can lead to more potential exposure.

Greater adoption and maturity are likely to bring greater focus on making sure technology is used safely. By its very nature, FFF and VAT polymerisation processes will create by-products.

BOFA CONTINUE TO WORK CLOSELY WITH PRINTER AND MATERIAL MANUFACTURERS TO ENSURE THEIR PRODUCT PORTFOLIO IS READY TO ADDRESS EMISSIONS CONCERNS. GET IN TOUCH TODAY TO FIND OUT MORE, BUY OUR PRODUCTS OR WORK WITH US TO DESIGN AND PRODUCE FUTURE INNOVATONS.

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DATA APPENDIX

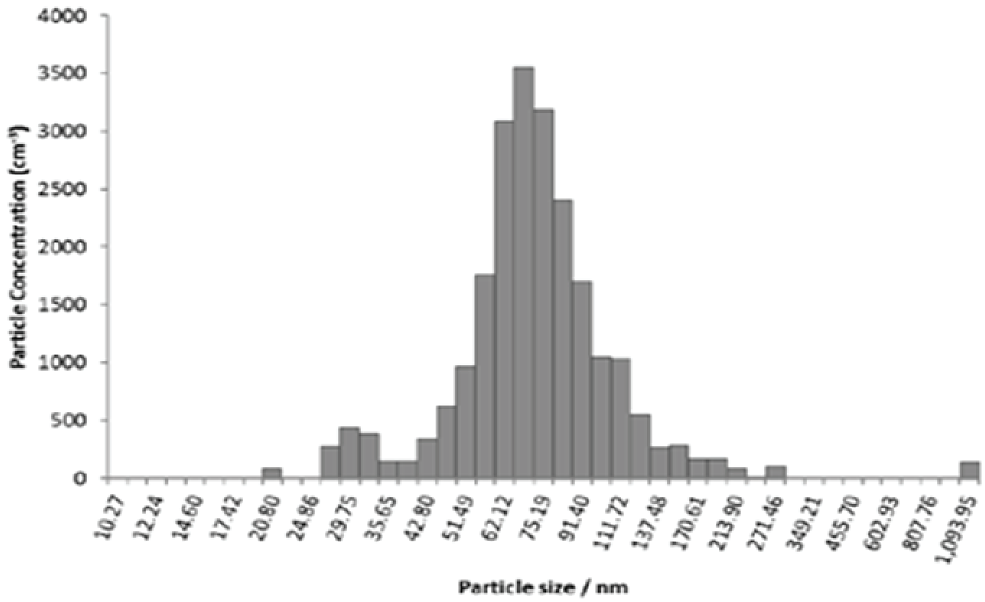

Figure 6 Particle size distribution measured with the GRIMM SMPS during a print with PLA filament on the KORA MIDI (nozzle = 220°C and print bed = 50°C) (Executive, 2019)

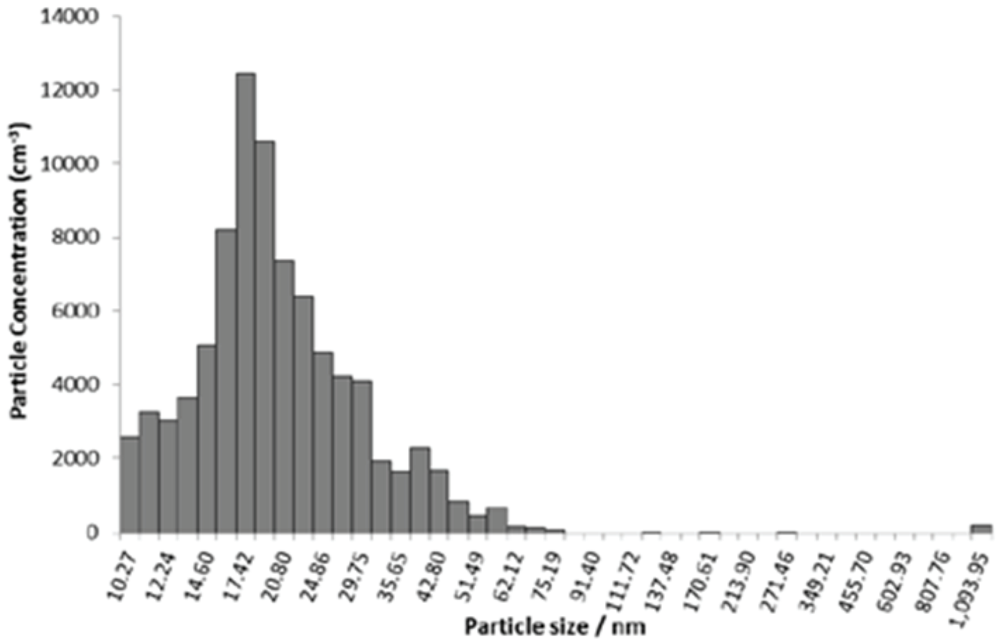

Figure 7 Particle size distribution measured with the GRIMM SMPS during a print with PLA filament on the Makerbot Replicator 2 (nozzle = 230°C and print bed = ambient temperature) (Executive, 2019)

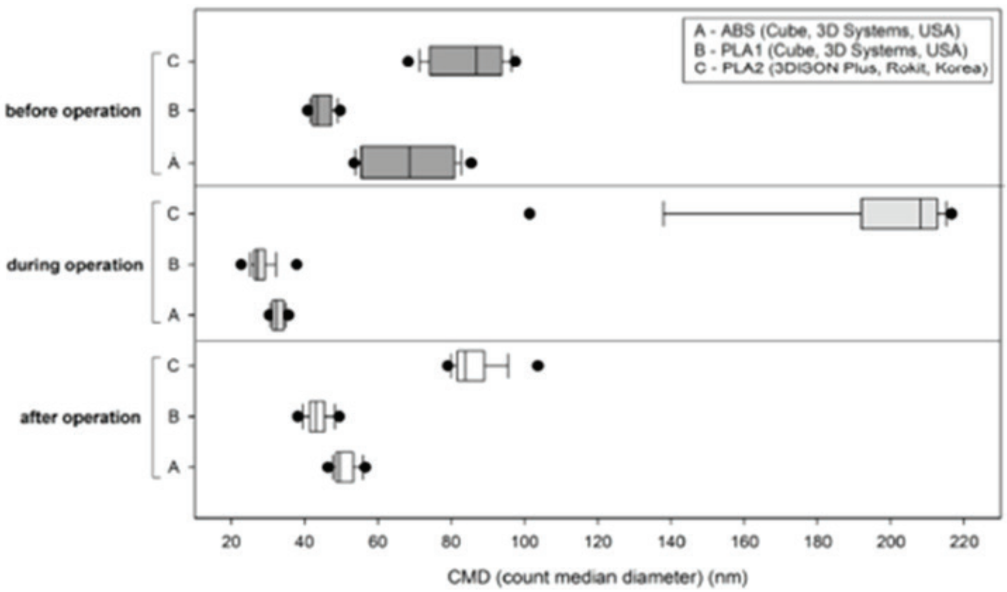

Figure 8 The number concentrations according to the count median diameter (CMD) measured by SMPS. Box plots indicate the median (line within box), upper quartile and lower quartile (top and bottom part of the box, respectively), the maximum excluding outliers and the minimum excluding outliers (upper and lower bars on whiskers, respectively), and outliers (black circles). (Emissions of Nanoparticles and Gaseous Material from 3D Printer Operation, September 2015, Environmental Science & Technology 49(20), DOI:10.1021/acs.est.5b02805)

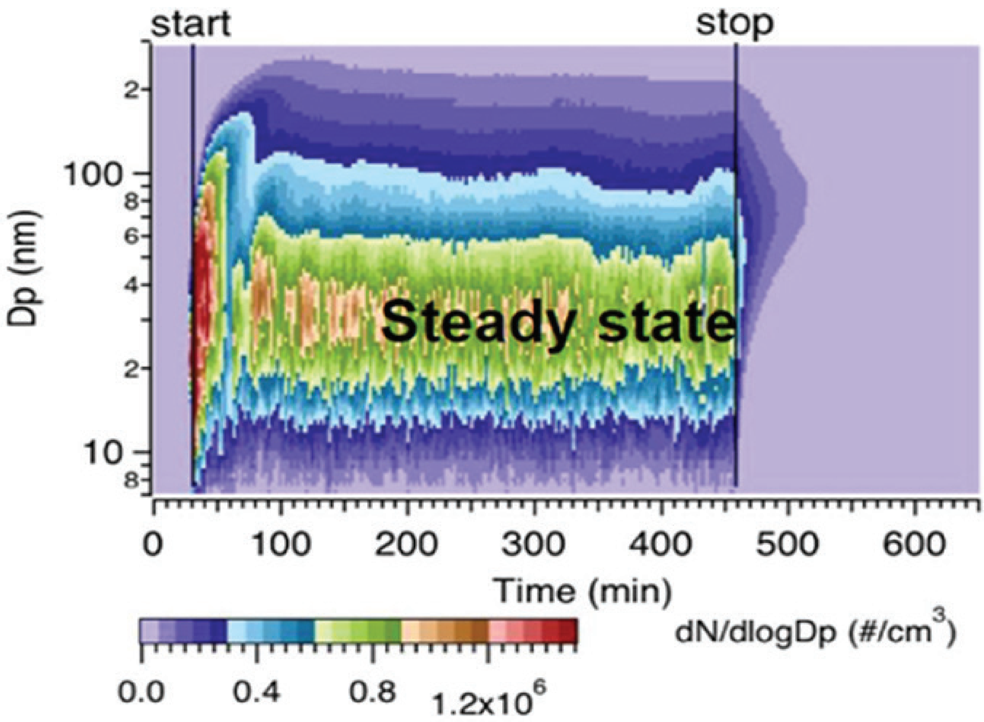

Figure 9 Particle size distribution from an ABS filament printer (Underwriters Laboratories, EMISSIONS AND HEALTH HAZARDS FROM CONSUMER LEVEL 3D PRINTERS, "Quantifying Exposure to Engineered Nanomaterials" Workshop, Oct. 9-10, 2018)

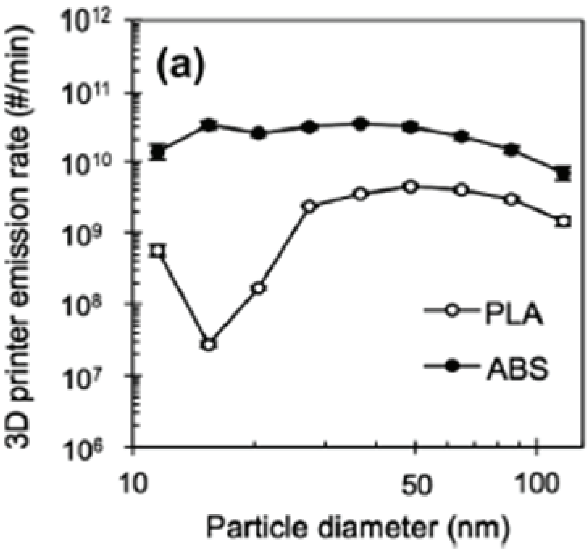

Figure 10 19 Individual UFP emission rates from 3D printers utilizing two types of thermoplastic feedstocks (Ultrafine particle emissions from desktop 3D printers, Brent Stephens, Parham Azimi, Zeineb El Orch, Tiffanie Ramos, Atmospheric Environment 79 (2013) 334

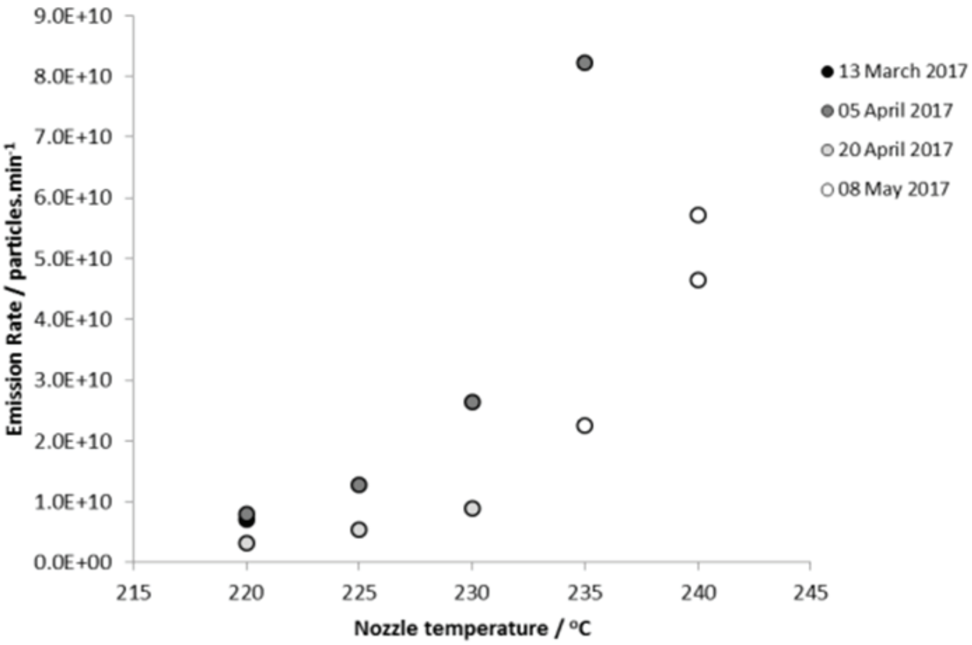

Figure 11 The effect of nozzle temperature on the emission rate using PLA filament with the KORA MIDI; measured using the DISCmini. Two emission rates are plotted for each temperature from repeat tests (three for 220° C) (Executive, 2019)

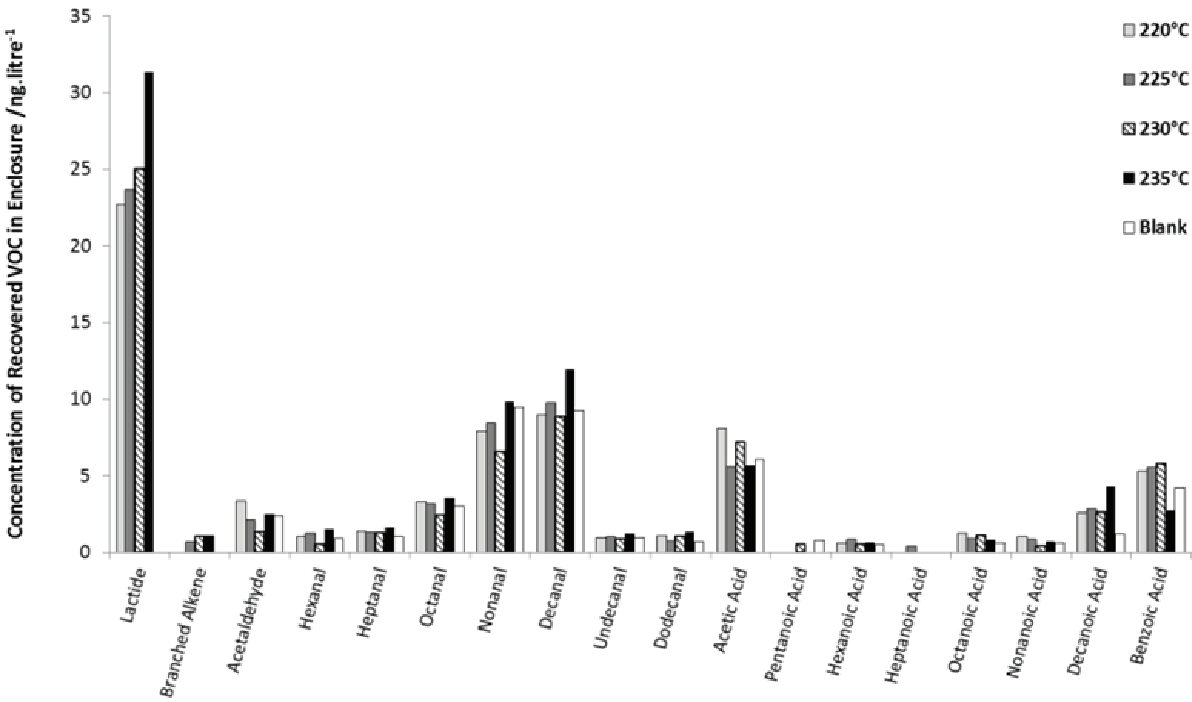

Figure 12 Recovered VOC species from a sampling tube at the nozzle of the KORA MIDI whilst printing with PLA inside an enclosed box across a range of nozzle temperatures 200°C – 235°C (Executive, 2019)

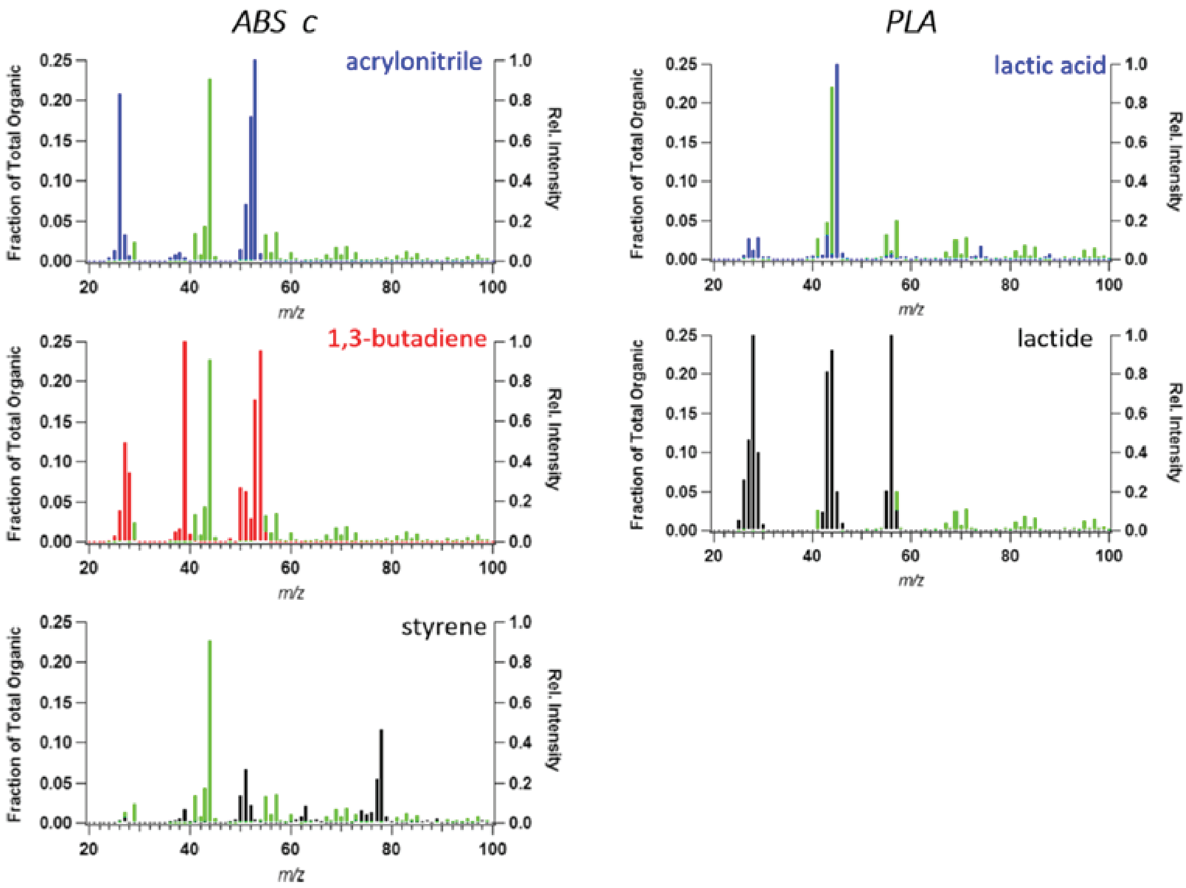

Figure 13 Online chemical composition measurements (with an ACSM) of particles emitted from filament ABS c and PLA. Particle mass spectra are shown in green. Reference spectra of monomers corresponding to the raw filament materials for ABS (acrylonitrile, blue; 1,3-butadiene, red; styrene, black) and PLA (lactic acid, blue; lactide, black) are included for comparison. (Qian Zhang, n.d.)

	ABS				PLA			
VOC	Natural	Blue	Red	Black	True red	Army green	Ocean blue	Trans blue
Acetaldehyde	16.3 ± 10.1	13.7 ± 8.5	7.7 ± 0.4	11.1 ± 2.2	3.6 ± 1.4	5.5 ± 3.7	5.0 ± 2.0	5.0 ± 0.6
Ethanol	57.3 ± 32.4	67.2	39.9	63.1	103.3 ± 5.6	85.0 ± 79.1	55.5 ± 22.1	73.0 ± 77.1
Acetonitrile	0.6			2.7	5.4 ± 1.9	0.4	0.4 ± 0.2	1.0 ± 1.3
Acetone	15.0 ± 7.9	62.4 ± 12.0	31.5	45.3 ± 2.3	27.0 ± 18.7	31.8 ± 1.0	7.2 ± 2.7	3.5 ± 0.9
Isopropyl alc.	87.2 ± 83.8	47.7	108.1	213.0	552.3 ± 66.9	1582.8	278.3 ± 3.4	99.4 ± 44.6
n-Hexane		1.8 ± 1.2	0.8	3.1	0.2 ± 0.0	1.3	0.3	1.9 ± 2.0
Chloroform		1.4	0.4	1.2	1.0	0.3	0.6	0.7 ± 0.5
Benzene	0.2	1.5						1.8
Toluene		1.4 ± 1.5				1.9	1.1	
Ethylbenzene	4.7	7.3 ± 1.0	6.6 ± 0.6					
m,p-Xylene	0.2	3.1 ± 2.1	3.0	1.8				
Styrene	252.1 ± 128.7	212.1 ± 9.9	237.1 ± 62.9	100.5 ± 11.7				
o-Xylene		1.6 ± 0.0		1.9				
D-Limonene								

Note. Empty cell = compound not detected or present at level less than background (pre-operating phase), ABS = acrylonitrile butadiene styrene, PLA = polylactic acid.

Figure 14 Average±standard deviation of background-corrected concentrations of individual VOCs measured by whole-air sampling with canisters during 3-D printing (μg m-3). (Aleksandr B. Stefaniak, 2017)

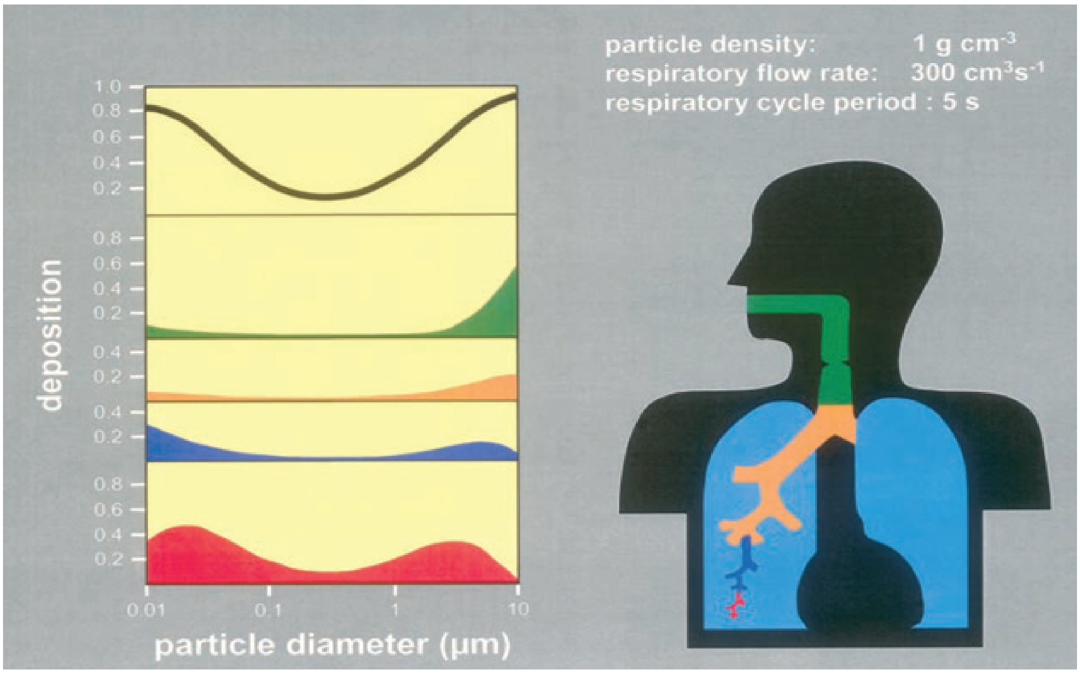

Figure 15 Total and regional deposition of unit-density spheres (Heyder, 2004)

Printer	Type	Head	Tracheobronchial	Pulmonary
Form 1 +	SLA	0.0312	0.0926	0.1704
Pegasus Touch	SLA	0.0282	0.0866	0.1509
Nobel 1.0A	SLA	0.0330	0.0953	0.1804
Titan 1	DLP	0.0684	0.2115	0.3757
M-One	DLP	0.0383	0.1304	0.2744

Figure 16 Regional lung deposition fractions for particles emitted by vat polymerization printers during operation. (A. B. Stefaniak, 2019)

Table 1: NRVs for four hazard bands for MNMs; SWCNT = SWCNT = single-wall carbon nanotubes, MWCNT = multi-walled carbon nanotubes.

Class	Description	Density in kg/m^3	NRV (8-hour TWA)	Examples
1	Rigid, biopersistent nanofibres for which asbestos-like effects cannot be ruled out	-	0.1 fibres/cm^3 (= 10,000 fibres/m^3)	SWCNT, MWCNT or metal oxide fibres for which the manufacturer cannot rule out asbestos-like effects.
2	Biopersistent granular nanomaterials in the range of 1 and 100 nm	> 6,000	20,000 particles/cm^3	Ag, Au, CeO_2, CoO, Fe, Fe_xO_y, La, Pb, Sb_2O_5, SnO_2,
3	Biopersistent granular and fibrous nanomaterials in the range of 1 and 100 nm	< 6,000	40,000 particles/cm^3	Al_2O_3, SiO_2, TiN, TiO_2, ZnO, nanoclay, carbon black, C_{60}, dendrimers, polystyrene Nanofibres for which asbestos-like effects have been explicitly ruled out
4	Non-biopersistent granular nanomaterials in the range of 1 and 100 nm	-	Normal exposure limit	Examples: fats, table salt (= NaCl)
NB:	For short peak exposures: $NRV_{15\text{-min TWA}} = 2 \times NRV_{8\text{-hour-TWA}}$			

Figure 17 Nano Reference Values in the Netherlands (B. Hendrikx, 2013)

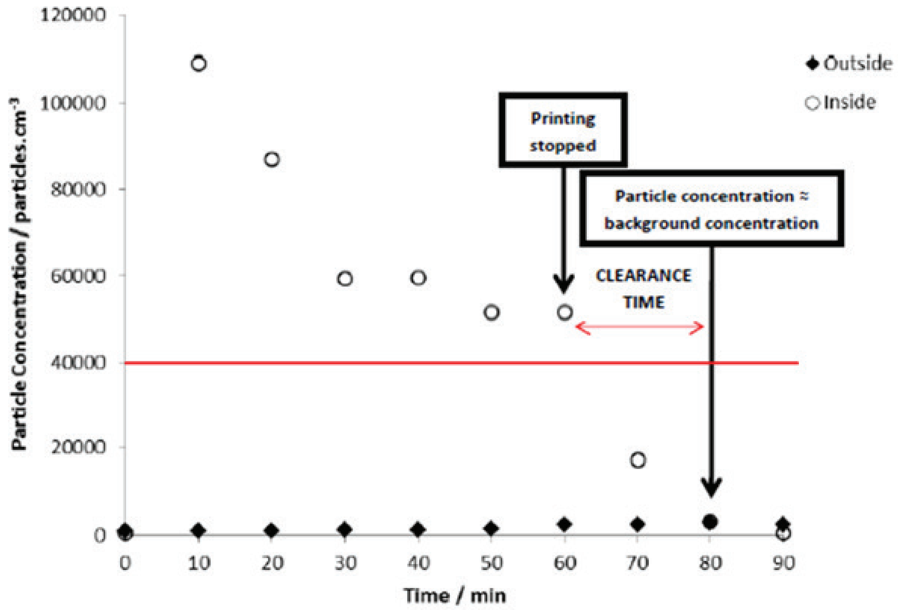

Figure 18 Particle concentration measured with two pTrak instruments inside and outside the enclosing hood as the KORA MIDI printed with PLA filament (nozzle = 220ºC and print bed = 50ºC) (Executive, 2019). Red line indicates nano reference value established by (B. Hendrikx, 2013)

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