Ultimaker white paper

3D printer emissions and indoor air quality

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Introduction

Today's fused filament fabrication (FFF) 3D printers are more popular and more accessible than ever. No longer a novelty, they are used as an everyday tool to accelerate innovation in studios, workshops, labs, and schools worldwide.

But their increased popularity has triggered an increased concern:

How does the process of melting and depositing thermoplastics affect indoor air quality?

As the global scientific community conducted deeper research into this question, their findings made us aware that in some situations FFF 3D printing could have a negative effect on air quality.

At Ultimaker, product safety is one of our highest priorities. We therefore took these findings seriously and carefully investigated the question.

We share our results below. You will find details and data about particle emissions, plus how the Ultimaker S5 Air Manager works to reduce them.

But for now – to dispel any concerns straightaway – it's worth stating that if you 3D print under the recommended conditions, using any Ultimaker 3D printer with any Ultimaker material is safe.[1]

The launch of the Ultimaker S5 Air Manager shouldn't lead you to question that fact.

Instead, its introduction offers users a highly effective and integrated air filtration solution – one that accommodates the desire to 3D print with more confidence using multiple printers, a wider range of materials, or with more flexibility in 3D printing setup. And while we're satisfied with its standalone performance, the Ultimaker S5 Air Manager can and should be used in addition to other best practices for safe 3D printing (like good ventilation, using a dedicated printer room, etc.).

[1] Recommended conditions are to use a single 3D printer in a room of 30.6 m^3 with an air exchange rate of 1.8 hr^{-1}

Setting the standard for emissions testing

Until recently, there was no standardized process for testing a 3D printer's exhaust air.

Then in February 2019, UL Chemical published their '2904 standard' for testing particles emitted from 3D printers. This was drawn up based on input from an international body of 34 government representatives, environmental groups, chemical companies, and 3D printer manufacturers – including Ultimaker. The standard describes how to measure emissions and which parameters to determine. In addition, it sets 'pass' and 'fail' criteria for ultrafine particles (UFPs) and for some volatile organic compounds (VOCs).

With this new standard, we commissioned independent researchers to test our most powerful 3D printer, the Ultimaker S5, using Ultimaker materials. This means that the results we'll share below are all backed up by 100% impartial data – rather than guesswork.

But first, let's cover a few terms that we'll use in this document.

5 useful definitions

Safe threshold limit values

The key to stating whether 3D printing may be harmful to your health depends on safe threshold limit values (TLVs).

A safe TLV is the maximum acceptable concentration of a chemical substance in a specific setting (for example, in indoor air). They exist to protect us from adverse health effects caused by (over-) exposure. That's because in small quantities (i.e. below the TLV), substances do not express their toxic potential and might even be an essential nutrient at low concentrations (e.g. kitchen salt, minerals, vitamins). Or our body can cope with them in a different way because it can neutralize them – like alcohol from overripe fruits is broken down by our liver. For non-soluble particles, something similar applies, because we have a clearing mechanism for them (e.g. we cough if we inhale particles from the air).

But what if your exposure to a substance or particles goes above its TLV? Then your body cannot get rid of it, which in case of inhalation of non-soluble particles is called 'lung overload'.[2]

[2] *For more on 'lung overload', there are several scientific articles, e.g. by Oberdürster et al.*

Because of their small size, ultrafine particles and other nanomaterials also have a 'nano reference value'. Among others, the Dutch National Institute for Public Health and the Environment (RIVM) have published scientific articles for four categories of nanomaterials. Although research is still ongoing, the limit values are considered to offer good protection when maintained.

But when any new findings are available, we will take them into account when stating the safe-use conditions for Ultimaker 3D printers.

Hazard vs. risk

'Hazardous' means 'having the potential to do harm'. But to actually cause harm, certain conditions need to be met. 'Risk' means the probability that harm is actually caused and to what extent.

For example, a tiger is by definition a 'hazardous' animal. Encounter one in the wild and it's likely it will harm you. Then again, there is a low risk of accidentally finding one because of their low population density.

Substances and particles labelled as 'hazardous' are no different: here 'hazard' refers to the type and severity of harm that can be done, like causing irritation or sensibilization or even cancer or death, depending on the nature of the toxin.

In general, high concentrations increase risk (the probability of harm), but not the hazard (e.g. irritation or acute toxicity). Some substances, like cyanide, can cause health problems even at relative low exposure levels. Others require much higher levels to pose a health risk. Below that level they are not risky, and in small quantities, some can be an essential part of your diet – like kitchen salt.

Keeping concentrations of hazardous substances and particles below their TLV, the use of protection measures (air extraction, gloves, masks), or limiting the duration of exposure all help to reduce risk to acceptable levels.

Ultrafine particles

Less than 100 nanometers (0.1 micron) in diameter, ultrafine particles (UFPs) cannot be seen without an electron microscope. They come from natural sources (like ocean spray or citrus fruit peel), as well as man-made (e.g. photocopiers and – as we'll see – 3D printers). Too much exposure to airborne UFPs becomes a health concern because they are small enough to inhale into the lungs and possibly transfer to the bloodstream. Ultimaker uses nano reference values (among others) as proposed by the Dutch RIVM to determine whether a significant risk is to be expected. For current Ultimaker materials, a nano reference value of 40,000 particles per cubic centimeter (p/cm^3) is relevant. Below this concentration a health risk is very unlikely.[3]

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[3] This nano reference value approach was originally raised by the German IFA (Institute for Occupational Safety and Health of the German Social Accident Insurance). After extensive comparative research, the Dutch RIVM confirmed this to be best practice for non-specific UFPs grouped by a specific density. For UFPs of one specific substance, other limit values may apply. If so, these will be taken into account by Ultimaker

Using an Ultimaker S5 Air Manager gives you the flexibility to 3D print with different setups in more locations

Volatile organic compounds

Volatile organic compounds (VOCs) are natural or synthetic airborne chemicals with a vapor pressure above 0.1 kPa at 20 °C. While they are often detectable as smells or odors, scientific detection takes place by sampling air around a printer under controlled conditions and then analyzing the samples.[4] Some VOCs are hazardous. But depending on the molecular structure of the VOC, its safe TLV concentration can range from a few micrograms to several milligrams per cubic meter.

Air exchange rate

Also known as 'air changes per hour', an air exchange rate is a measure of the volume of air added or removed from a room, divided by the volume of that room. A baseline air exchange rate of 1 means that 63.2% of the air in the room changed in the last hour. The higher the value, the better the room's air quality.[5]

Now let's tackle the big question...

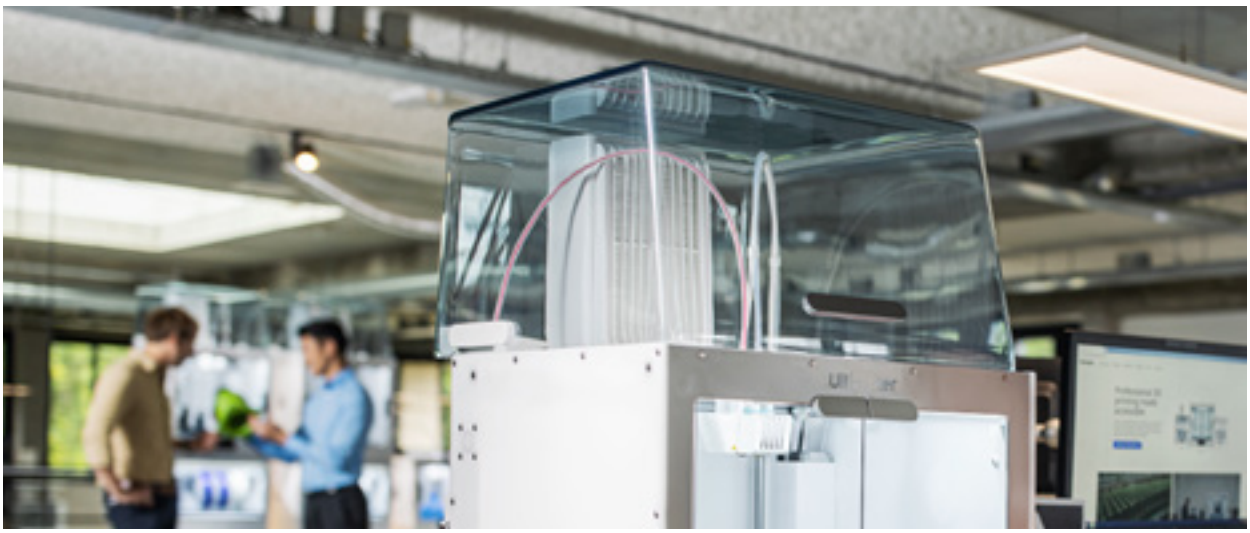
[4] *For example, see the test protocol in UL-2904 for more details*

[5] *Provided that the room's air is mixed constantly and homogeneously, and that the air coming into the room is clean*

Does desktop 3D printing have a negative impact on air quality?

Sadly, we can't give you a definitive yes or no for your specific situation. That's because there are too many factors to take into account. And your answer will depend on your 3D printing setup and throughput.

What we can do is provide a list of these factors and offer some recommendations that are in line with safety standards endorsed by the 3D printing industry.



Long-term exposure to UFPs below a concentration of 40,000 p/cm^3 is widely considered to be safe

7 factors that affect indoor air quality when 3D printing

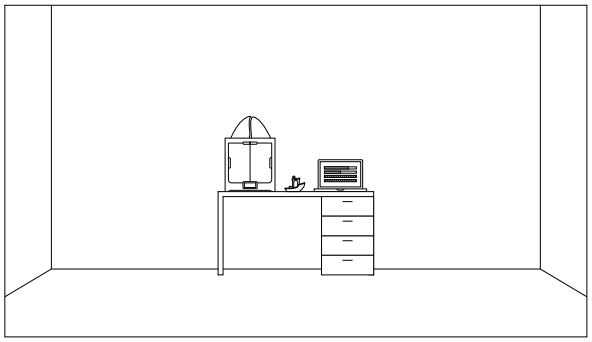
- The room's dimensional volume
- The room's air exchange rate
- How many 3D printers are in use at the same time
- What material(s) you're printing
- How long you're printing for
- How close you sit to the 3D printer(s)
- Whether there are other emission sources in the room

These factors are all important because the more concentrated UFPs are in an indoor space, the more potential they have to affect air quality.

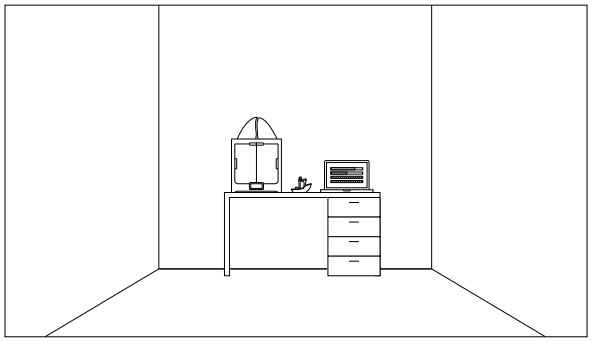
As already mentioned, for UFPs emitted when 3D printing current Ultimaker materials, concentrations below the relevant nano reference value of 40,000 particles per cubic centimeter (p/cm^3) are considered safe.

4 example scenarios

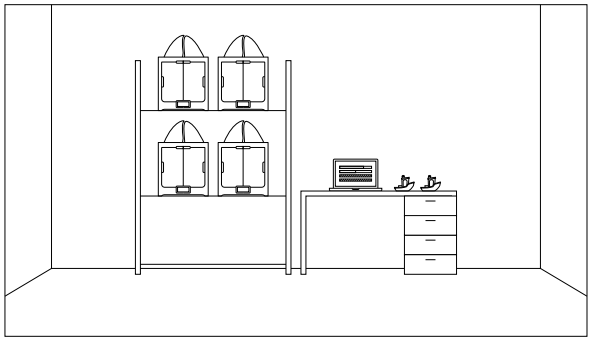
Without gravimetric testing equipment, it’s impossible to measure particle concentration levels. So, here are four common 3D printing scenarios to demonstrate how these factors change the air’s concentration of UFPs:



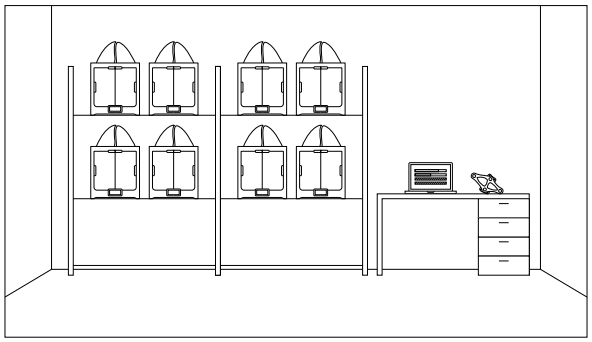
One 3D printer in a large room, occasionally printing parts in PLA
Low UFP concentration



One 3D printer in a small room, frequently printing parts in PLA
Medium UFP concentration



Multiple 3D printers in a large room, frequently printing parts in PLA
Medium UFP concentration



Multiple 3D printers in a large room, frequently printing parts in engineering materials
High UFP concentration

What UFPs are emitted when 3D printing Ultimaker materials?

Ultimaker materials take advantage of tested, predefined print settings in Ultimaker Cura. This material portfolio provides our customers with excellent flexibility to choose different material properties for their 3D printing applications.

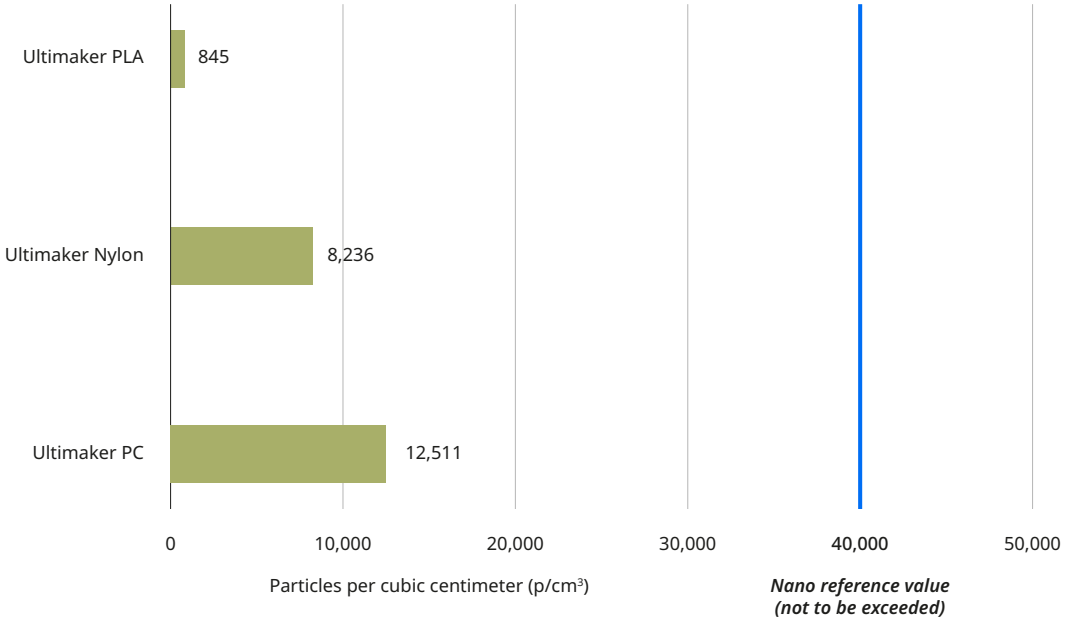
Our build materials currently include Ultimaker PLA, Tough PLA, ABS, Nylon, CPE, CPE+, PC, PP, and TPU 95A. And these can be dual extruded with water-soluble PVA or easy-to-remove Breakaway support materials for increased design freedom.

But which of these polymers emit UFPs when heated and extruded?

The simple answer is: they all do. But digging deeper reveals that some materials emit more UFPs than others.

For example, when testing in the same controlled conditions on the same Ultimaker S5, independent researchers found that Ultimaker PLA (polylactic acid) emitted the lowest concentration of UFPs. While, Ultimaker PC (polycarbonate) – with its higher melting temperature and higher-strength mechanical properties – emitted an increased UFP concentration.

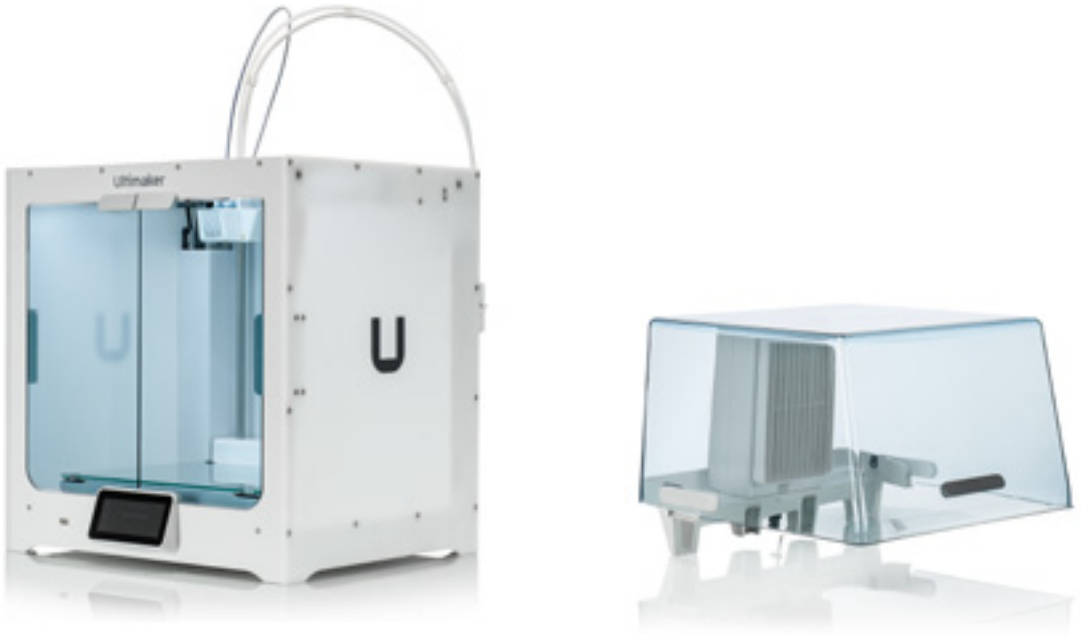
Average UFP concentration of three Ultimaker materials (without Ultimaker S5 Air Manager)*



** Calculated based on the particle emission rate determined from independent test laboratory measurements and assuming a typical office room of 30.6 m^3 with an air exchange rate of 1.8 hr^{-1}*

If those results are lower than you expected, perhaps now you can understand why it's so tricky to say whether 3D printing has a negative impact on your specific air quality. A single Ultimaker S5, printing Ultimaker PC in a typical office room, with a typical air exchange rate emits less than half the safe TLV for UFPs.

But not everyone 3D prints with one machine in the same conditions or with the same materials. And it's for this reason that we created the Ultimaker S5 Air Manager.



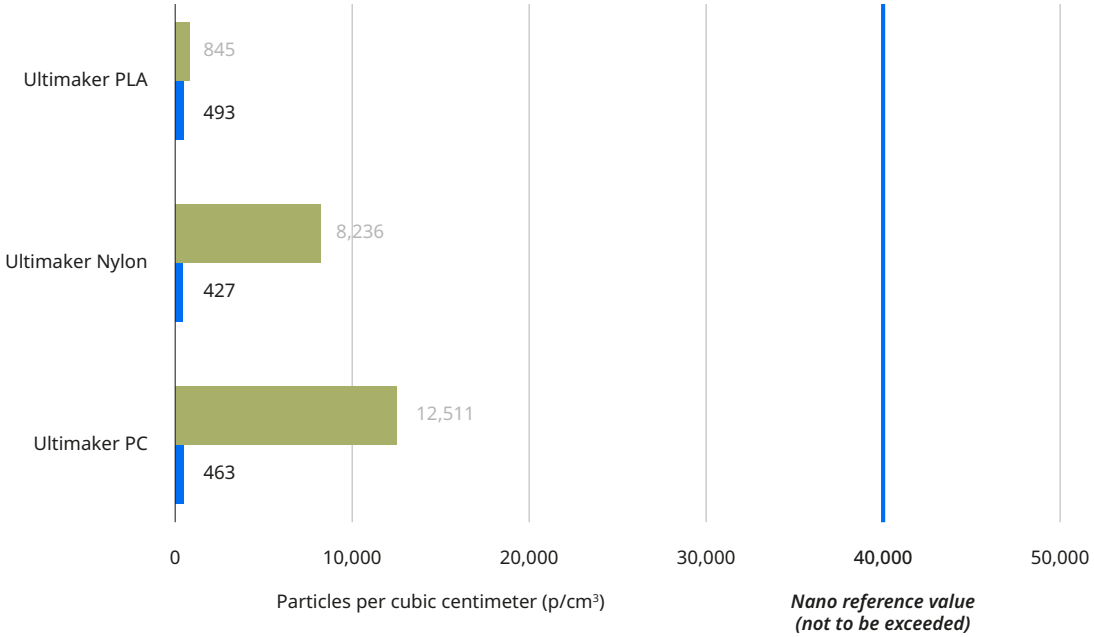
The Ultimaker S5 and its Air Manager integrate seamlessly and can be installed without using tools

How effective is the Ultimaker S5 Air Manager in removing UFPs?

To maintain a proper scientific process, we conducted the same test, with the same printer, printing the same part, in the same conditions. But this time with the Ultimaker S5 Air Manager installed.

Here are the results:

Average UFP concentration of three Ultimaker materials (with Ultimaker S5 Air Manager)*



** Calculated based on the particle emission rate determined from third-party measurements and assuming a typical office room of 30.6 m^3 with an air exchange rate of 1.8 hr^{-1}*

With the Ultimaker S5 Air Manager installed, UFP concentrations when printing Ultimaker materials are significantly reduced to a stable value of around 400 to 500 particles per cm^3. And in the case of Ultimaker PC, that difference is 95%.

But how do these results compare to the UFP concentrations in the air we breathe every day?

Multiple studies show that background UFP concentrations in different locations vary greatly. From 2,600 p/cm^3 in a clean environment, to 4,800 p/cm^3 in a rural setting, and over 10,000 p/cm^3 in urban areas.[6]

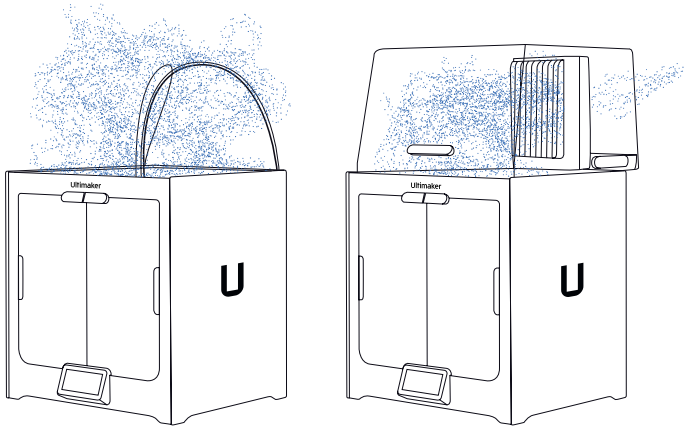
[6] *Slezakova, Morais, and do Carmo Pereira: 'Atmospheric Nanoparticles and Their Impacts on Public Health'. 2013*

While the graphs above do not include background UFP concentrations, it is clear that the Ultimaker S5 Air Manager dramatically reduces exhaust particle emissions. By normalizing the air quality, this effective solution can give you greater peace of mind when printing with Ultimaker materials.

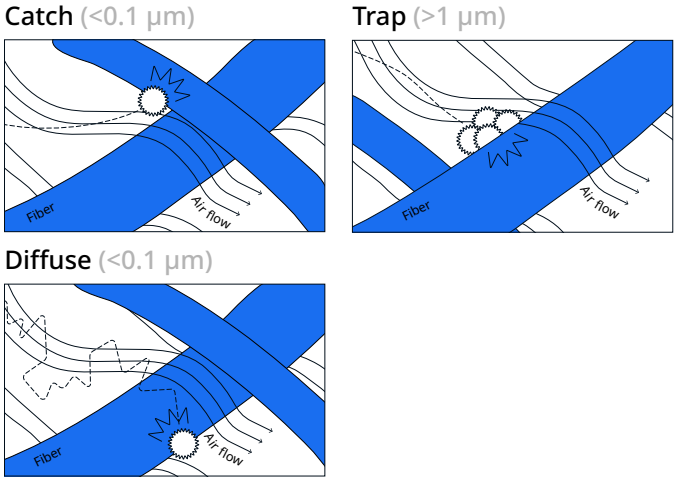
Overall, because of the tests performed, we can confidently claim that the Ultimaker S5 Air Manager removes 'up to 95% of UFPs'. And while we would like to give a constant percentage, the filter's efficiency is dependent on the nature, size, and concentration of the particles – not because the data does not support a 95% efficiency level.

How does the Ultimaker S5 Air Manager achieve this?

The Air Manager works because its quiet, multi-speed fan sucks air from the enclosed build chamber, creating an inside-out airflow. This means that almost all air leaving the Ultimaker S5 passes through the filter.



Its replaceable EPA filter is also positioned at the top of the chamber for maximum efficiency. And its large size means more filter surface area to catch, trap, or diffuse particles emitted during 3D printing.



It would have been easy to manufacture a top enclosure with an extractor fan and call it a day. But the Ultimaker Process Team's vision was always that the Ultimaker S5 Air Manager would provide a deeply integrated and automated solution to give users greater peace of mind when 3D printing with more materials.

This integration means that:

- The Air Manager is recognized by and connects directly to the Ultimaker S5
- The fan changes speed to achieve the desired build volume temperature, while maintaining optimal filtering efficiency
- The filter's use and remaining lifetime is tracked to notify you when it needs to be replaced

And because the Air Manager fully encloses the Ultimaker S5 build chamber, users have more freedom to set up 3D printers in more locations – including where unwanted airflows would affect print quality. Plus, by providing a physical barrier that stops anyone touching hot or moving parts, workplace safety is increased.

Why not use a HEPA filter?

Good question. It's true that HEPA filters have a higher efficiency rating than EPA (at 99.99%). But after testing the options, developers of the Ultimaker S5 Air Manager chose not to use this filter type.

Why? For the same reasons they chose not to use the even more efficient ULPA filter – which has an efficiency rating of 99.999%:

- **The EPA filter already removes a high percentage of UFPs**
  Our results show UFP concentration levels stay far below their nano reference value limit with the EPA filter. This nano reference value has been determined help make risk-based decisions – striking a careful balance between the precautionary principle and the ALARA ('As Low As Reasonably Achievable') principle. If UFP concentrations rise above their nano reference value, action is advised.[7]
- **More efficient filters restrict more air**
  This could have a negative impact on the system's overall filtration because exhaust air would be more likely to leak out via other parts of the printer. Lower airflow also affects temperature control, which would have a negative impact on the printing process
- **HEPA filters cost more to replace**
  And we don't want to force our customers to replace a higher-cost filter when evidence suggests it is unnecessary

[7] *For more information on determining nano reference values, see for example, 'Exposure Limits for Nanoparticles'. 2012*

What about third-party materials' UFP emissions?

Ultimaker 3D printers feature an open filament system. And we make working with third-party materials from leading brands easy – thanks to our ever-growing library of predefined print profiles, downloadable via the Ultimaker Cura Marketplace.

Therefore, should you be concerned about air quality when printing with filaments from other leading materials brands?

Rest assured: we're working toward a clear answer. But for now, we can state that we have yet to test a material that does not have its UFP concentration reduced by the addition of an Ultimaker S5 Air Manager.

In the meantime, we're also conducting further research, refining Ultimaker materials settings, and optimizing the Air Manager's firmware. This means the solution will continue to improve in UFP-filtration efficiency and effectiveness for months and years to come.

Enjoy greater peace of mind when printing with an extended range of materials with the Ultimaker S5 Air Manager

What about volatile organic compounds (VOCs)?

While the Air Manager does not filter VOCs, we didn’t forget about them.

The independent research team also performed tests for VOC emissions, while 3D printing with Ultimaker materials. It was found that relatively few VOCs were emitted, both when looking at the sum of all VOCs (TVOC, see table), as well as when looking at individual VOCs compared to their safe threshold limit value. And indeed, not enough to merit a specific VOC-filtering solution. Like with UFPs, Ultimaker will keep monitoring developments and take additional measures when needed.

	Ultimaker PLA	Ultimaker ABS*	Ultimaker Nylon	Ultimaker PC	Maximum TVOC emission rate (UL-2904) in [mg/hr]
TVOC emission rate [mg/hr]	0.32	0.57	0.3	0.15	10.4

** Ultimaker ABS of the 11 materials tested had the highest Total VOC emission rate. Even then the rate stays well below the maximum rate allowed according to UL. (It is also worth noting that the maximum emission rate allowed for office paper printers is 10.4 mg/hr.)*

Conclusion: Should I buy an Ultimaker S5 Air Manager?

As outlined above, your answer depends on your in-house 3D printing setup (number of printers, throughput, ventilation, room size, materials used etc.). It also depends on your level of concern regarding air quality.

At Ultimaker, we're dedicated to being transparent with our users. While it would be easy to exaggerate any potential health impact to encourage you to buy this device, we're not going to.

Your choice whether to buy an Ultimaker S5 Air Manager should remain your choice. This white paper's findings serve only to inform and guide that choice. For example, the independent research data suggest that the Air Manager offers an effective solution when 3D printing:

- In a small room
- In a room with poor ventilation
- With more than one 3D printer
- Large amounts of engineering-grade materials (which tend to emit higher UFP concentrations)

After taking into account all the influencing factors and your level of concern, if you want greater peace of mind when it comes to air quality and UFP emissions when 3D printing, then we recommend the Air Manager as the most effective and integrated air filtration solution for use with the Ultimaker S5.

About Ultimaker

Since 2011, Ultimaker has built an open and easy-to-use solution of 3D printers, software, and materials that enables professional designers and engineers to innovate every day. Today, Ultimaker is the market leader in desktop 3D printing. From offices in the Netherlands, New York, Boston, and Singapore – plus production facilities in Europe and the US – its global team of over 400 employees work together to accelerate the world's transition to digital distribution and local manufacturing.

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