

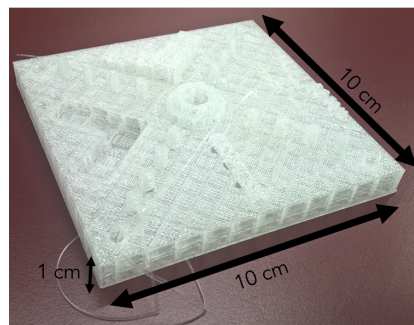


## Emissions Report: Ultrafine particles (UFPs) and volatile organic compounds (VOCs) from desktop 3D printers and filaments

**Filament:** NinjaFlex Semi-Transparent

**Printer:** LulzBot Mini

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**Figure 1.** Printed standardized test part from NIST used for emissions testing

### Summary:

The goal of this work is to experimentally characterize the emissions of ultrafine particles (UFPs, or particles  $<100$  nm) and speciated volatile organic compounds (VOCs) when printing a standardized test part with a desktop 3D printer and polymer filament following manufacturer recommended settings.

### Methods:

We conducted controlled environmental chamber testing following methods described in Azimi et al. (2016) *Environ Sci Technol* 50(3):1260-1268. All measurements were conducted inside a well-mixed  $3.6 \text{ m}^3$  stainless steel chamber. The 3D printer bed was prepared for printing before sealing the chamber by applying small amounts of adhesive from glue sticks following manufacturer recommendations. We printed a  $10 \times 10 \times 1$  cm standardized sample from the National Institute of Standards and Technology (NIST), as shown in Figure 1.

### Results:

#### UFP emissions

Figure 2a shows time-varying total UFP concentrations resulting from the single print test and Figure 2b shows estimates of time-varying total UFP emission rates. The left guideline in Figure 2a shows the moment that the printer began warming up prior to printing, which we considered part of the printing emissions period. The second guideline shows the moment that the printer stopped printing. The data smoothing method (SM) that was used and the corresponding coefficient of determination ( $\text{SM-R}^2$ ) are shown in Figure 2a. The error bars in Figure 2b show an estimated  $\sim 45\%$  uncertainty in the UFP emission rate estimates. The solid line and the upper and lower dashed lines in Figure 2b demonstrate the median and interquartile range of the estimated UFP emission rates. The number of negative estimated emissions (NNEE) is also provided in Figure 2b.

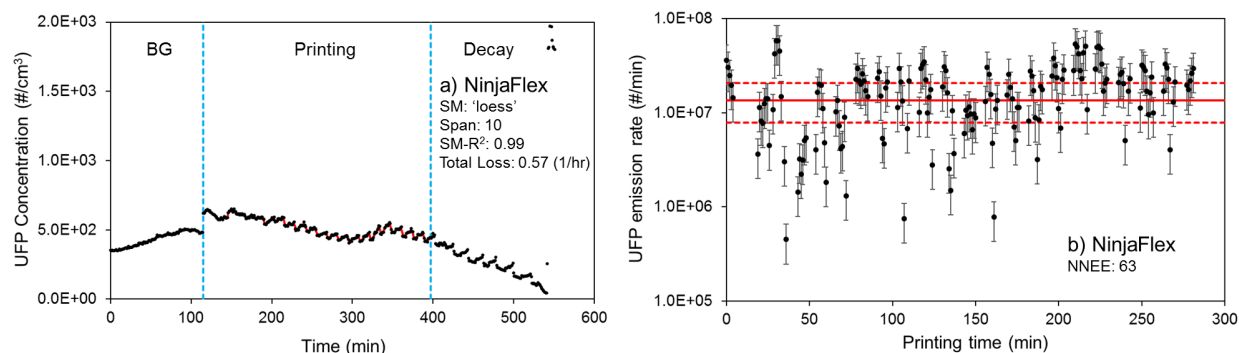
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**Figure 2.** a) Time-varying UFP concentrations inside the chamber during background, printing, and decay time periods, and b) estimates of time-varying UFP emission rates during the printing period

Table 1 summarizes the estimated UFP emission rate results. The UFP concentration in the chamber increased only slightly once printing began. The UFP emission rate during the printing period was approximately constant and low relative to prior tests (e.g., a median UFP emission rate of  $\sim 1.4 \times 10^7$  #/min compared to an average of  $\sim 2 \times 10^{10}$  #/min from 15 printer and filament combinations reported in Azimi et al. 2016).

**Table 1.** Summary of total UFP emission rate results

Average ( $\pm$ SD) (/min)	Median (/min)	Max (/min)	Min (/min)	Total UFPs emitted (#)	Emission per mass of filament (/g)	Printing duration (mins)	Printing temperature ( $^{\circ}$ C)	
							Nozzle	Bed
$1.5 \times 10^7$ ( $\pm 1.0 \times 10^7$ )	$1.4 \times 10^7$	$5.2 \times 10^7$	$6.8 \times 10^5$	$3.6 \times 10^9$	$9.7 \times 10^7$	283	227	50

## Speciated VOC emissions

Table 2 summarizes estimates of individual speciated VOC and  $\Sigma$ VOC emission rates (i.e., the sum of the emission rates of the top 5 speciated VOCs with the highest individual emission rates). The results from Table 2 demonstrate that "1,6-Dioxacyclododecane-7,12-dione"; "cyclohexane, (1,3-dimethylbutyl)"; and "styrene" have the highest individual VOC emission rates from the tested filament, but that  $\Sigma$ VOC emissions from this filament and printer combination (7.1  $\mu$ g/min) were low relative to an average of  $\sim 67$   $\mu$ g/min from 15 printer and filament combinations reported in Azimi et al. (2016). The uncertainty in individual VOC emission rates is estimated to be  $\sim 36\%$ .

**Table 2.** Summary of top-five individual speciated VOC emission rates

Compound	1,6-Dioxacyclododecane-7,12-dione	Cyclohexane, (1,3-dimethylbutyl)	Styrene	Nonanal	Hexanal	$\Sigma$ VOC
E ( $\mu$ g/min)	3.7	1.5	1.5	0.2	0.2	7.1