Ongoing research @ NIOSH

- Laboratory investigations of emissions
  - Characterization
  - Rates
  - Factors

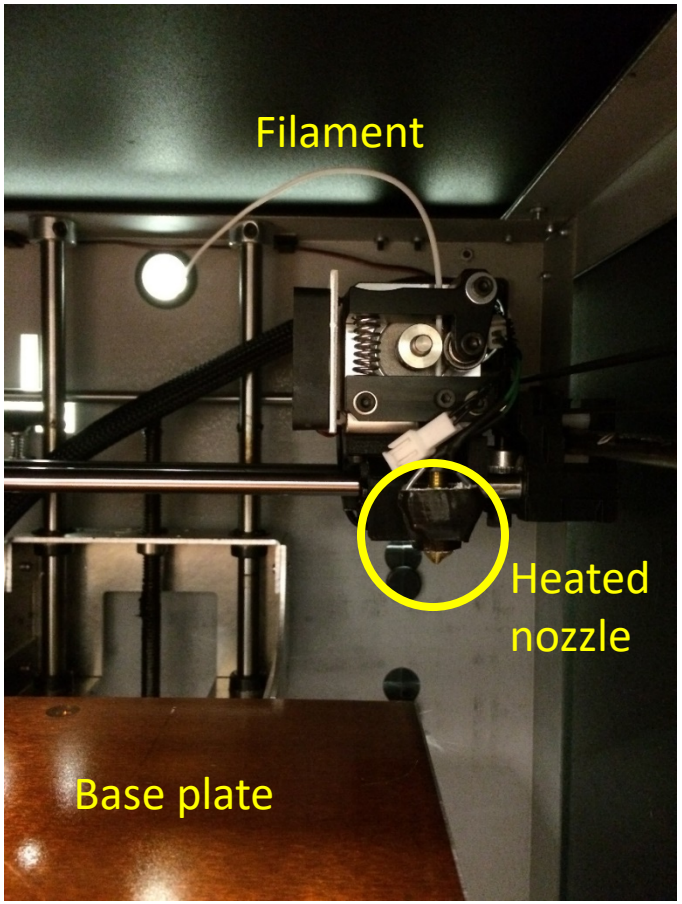
- Commercially available printers
  - Cost ~ $500 to 2500 dollars
  - “desktop” scale devices

Laboratory investigations

- Material extrusion printers
  - Fused deposition modeling (FDM™)

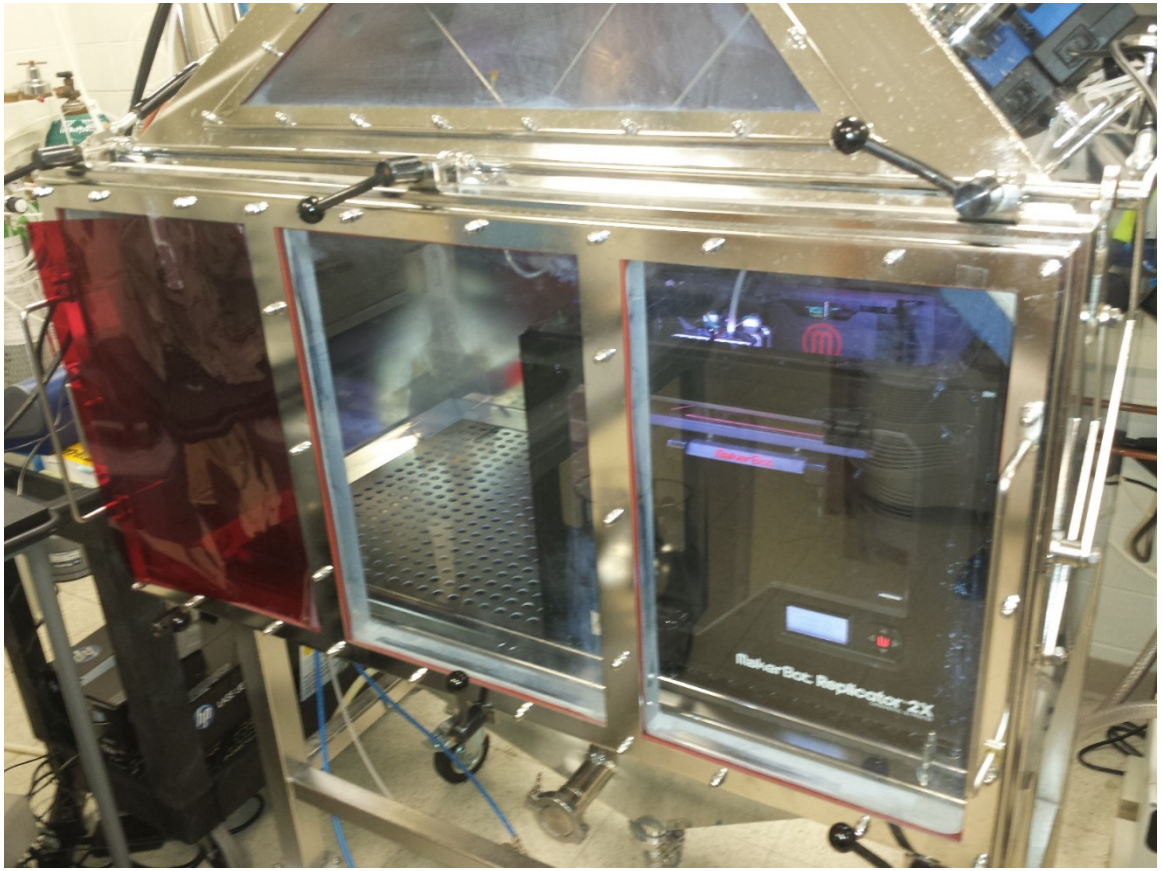
Filament

Acrylonitrile butadiene styrene (ABS)
Poly lactic acid (PLA)
Polycarbonate (PC)

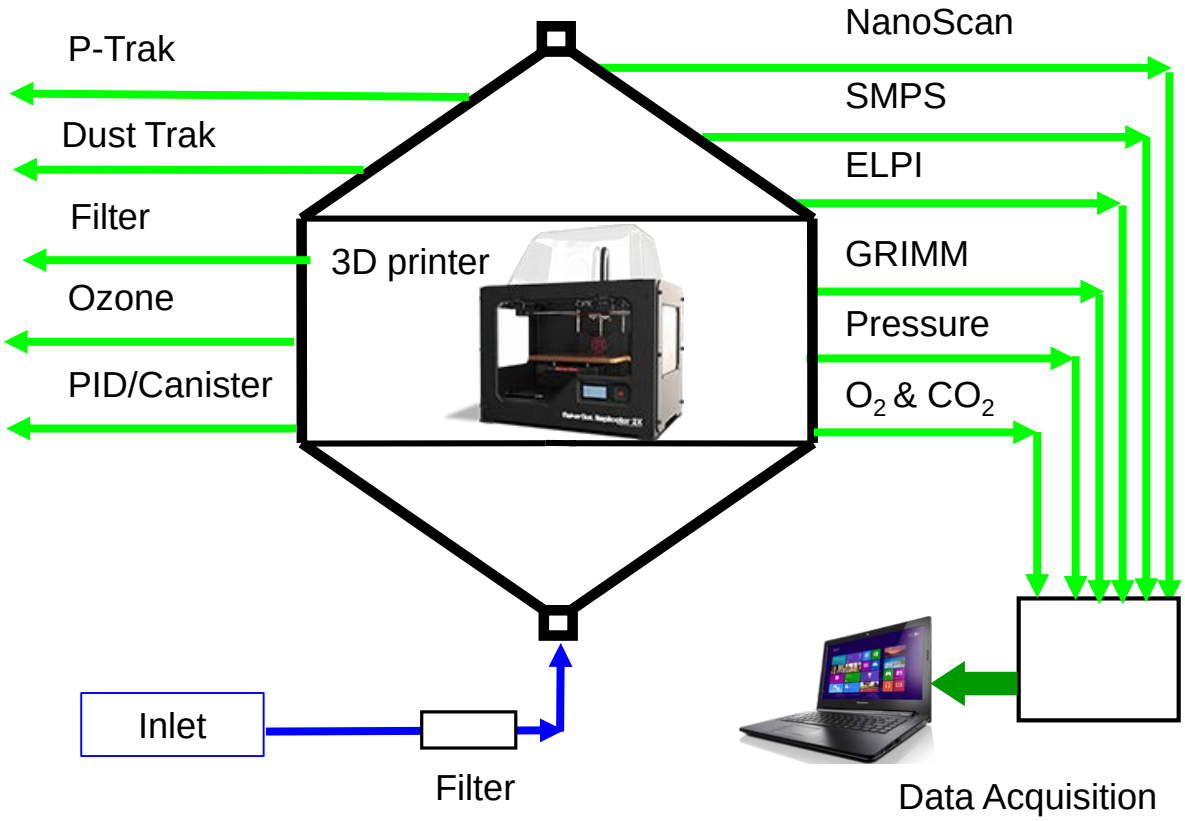


Laboratory investigations

- Performed in chamber
  - Controlled environment (temperature, RH)
  - Clean air (filtered)



Emissions characterization



Particle measurement

- Real-time
  - Number concentration from 0.02 to 1 µm
  - PM_{10} mass concentration
  - Surface area concentration
  - Size distribution from 0.01 to 0.66 µm
  - Size distribution from 0.3 to >20 µm

- Time integrated
  - Track -etched filter
    - Scanning electron microscopy-energy dispersive x-ray detector (SEM-EDX)

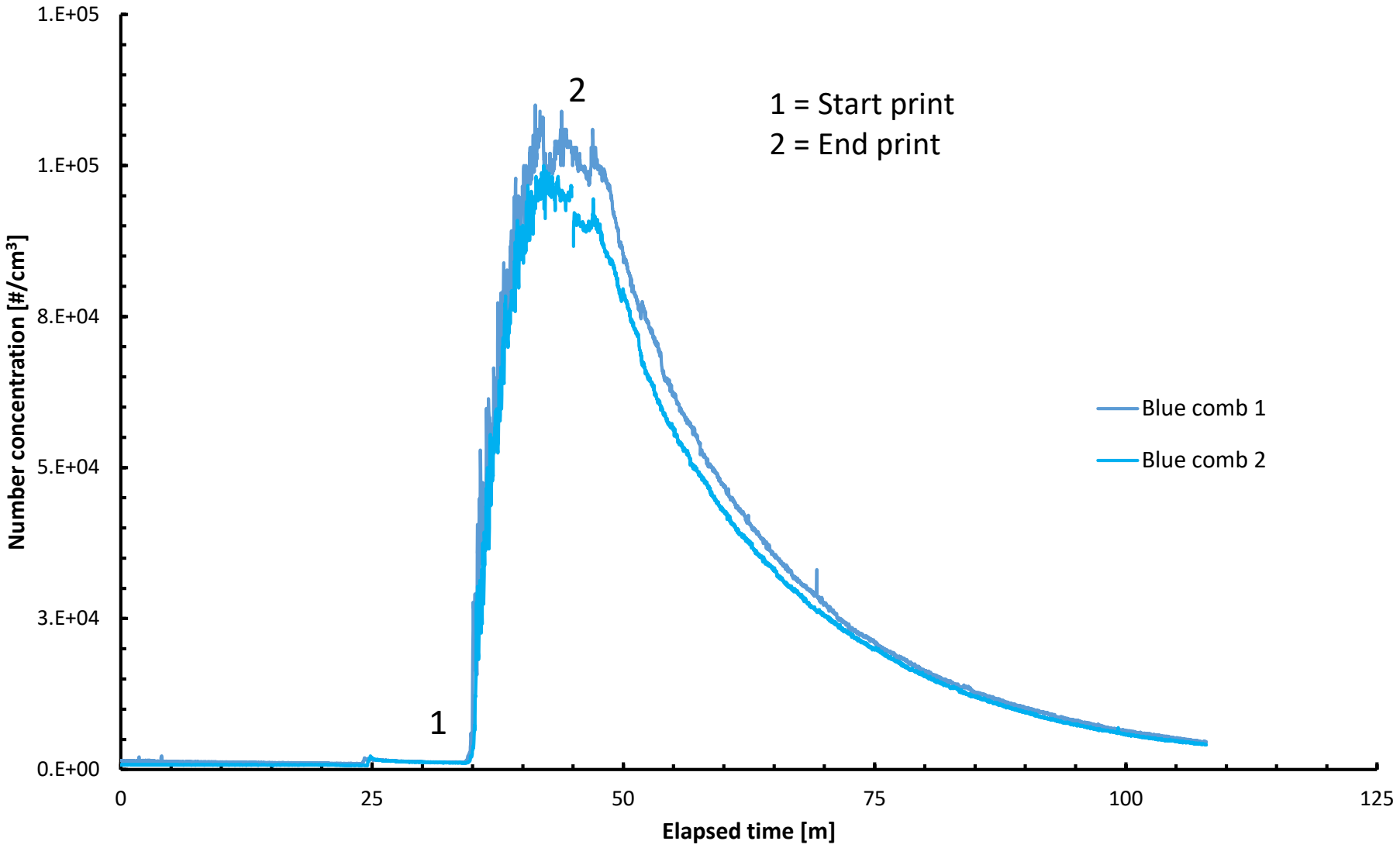
Vapor and gas measurement

- Real-time
  - Ozone sensor
  - TVOC concentration

- Time integrated
  - 6 L Silonite®-coated canisters: individual VOCs
    - Gas chromatography-mass spectrometry (GC-MS)

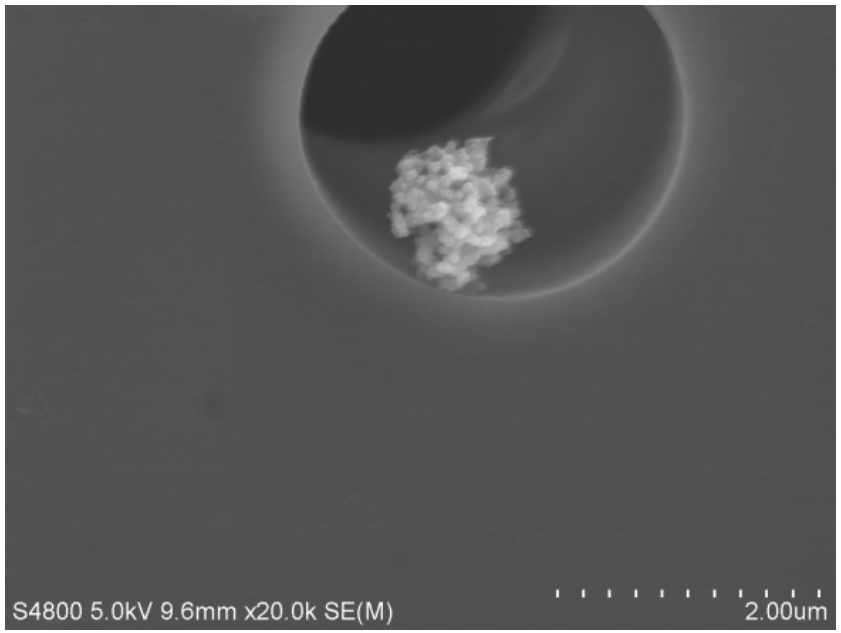
Particle emissions profile

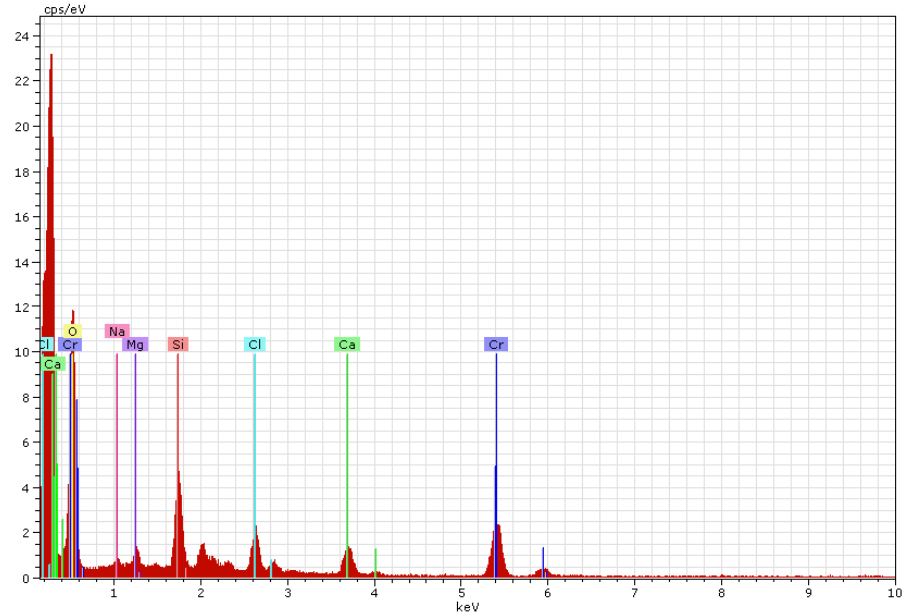
- Real-time number concentration



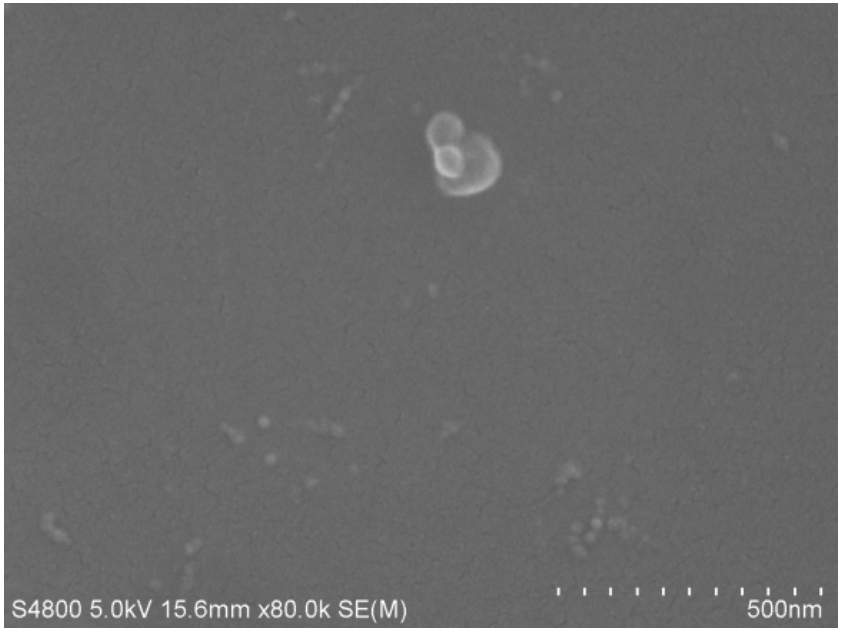
Particle emissions chemistry

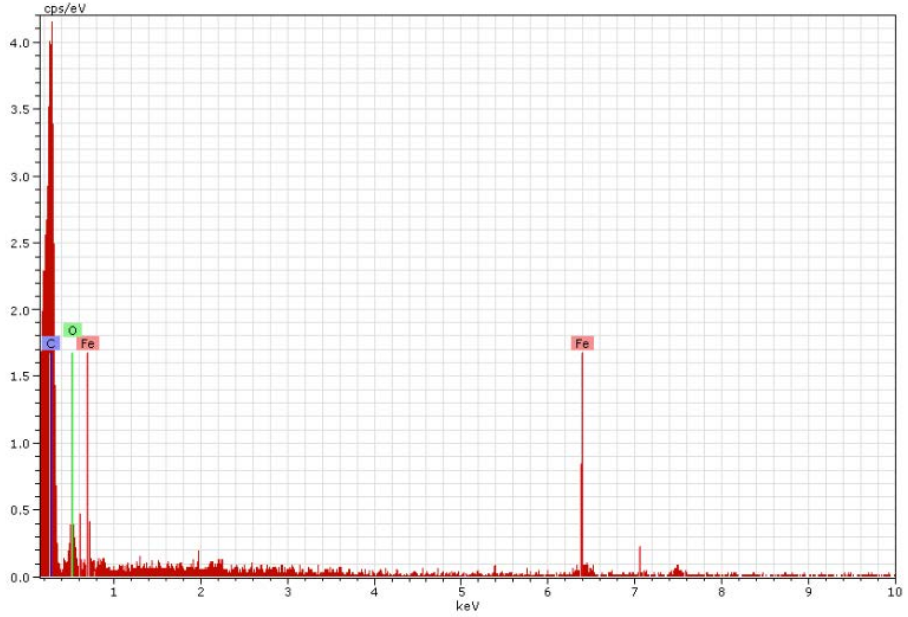
ABS - blue





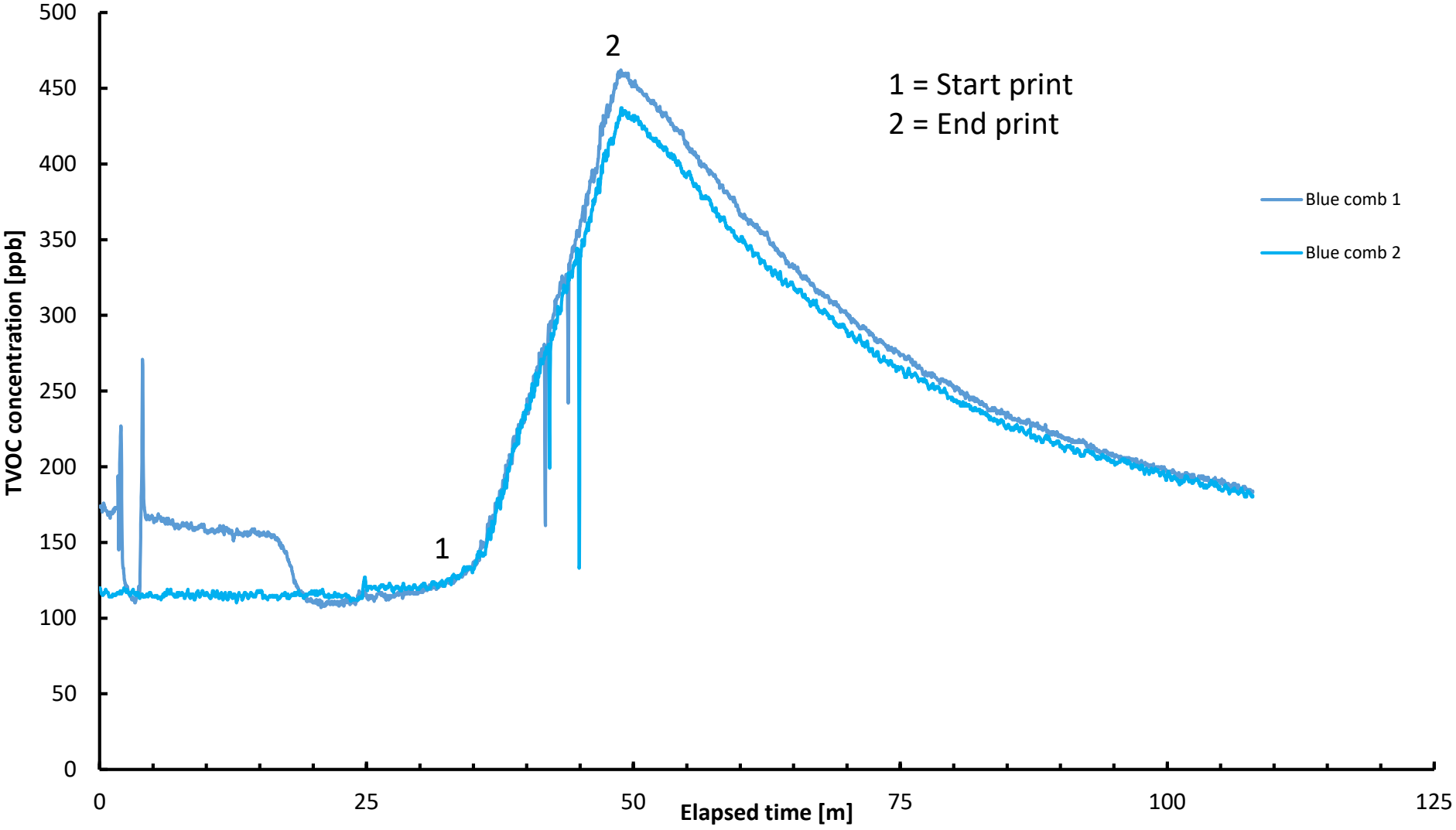
PLA – ocean blue





Vapor emissions profile

- Real-time TVOC concentration



Vapor emissions chemistry

Table 3. Average ± standard deviation of background-corrected concentrations of individual VOCs measured by whole-air sampling with canisters during 3-D printing (μg m^{-3}).

	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.

Stefaniak et al. J Occup Environ Hyg. (2017)

Emission rates

- Real-time particle number (#/min)

Table 5. Average geometric mean (GM) particle size and average ± standard deviation particle emission rates (PER) for 3-D and laser printers.

Printer	Consumable	Print job	Avg. GM[a] (nm)	SMPS (# < 0.66 µm min^{-1})
HP2055dn	Monochrome toner	80 pages @ 5%	39.6	$7.1 \pm 0.7 \times 10^{10}$
HP2600	Monochrome toner	80 pages @ 5%	168.3	9.8×10^{7}
3-D[b]	ABS natural	3 combs	53.7	$1.6 \pm 0.0 \times 10^{10}$
	ABS blue	2 combs	63.1	$7.5 \pm 1.0 \times 10^{9}$
	ABS red	2 combs	49.9	$1.4 \pm 0.3 \times 10^{10}$
	ABS black	2 combs	45.3	$1.0 \pm 0.2 \times 10^{10}$
	PLA true red	4 combs	36.4	$1.3 \pm 0.5 \times 10^{10}$
	PLA army green	4 combs	36.1	$1.3 \pm 0.2 \times 10^{10}$
	PLA ocean blue	4 combs	36.5	$1.1 \pm 0.7 \times 10^{10}$
	PLA transparent blue	4 combs	37.7	$1.6 \pm 0.2 \times 10^{10}$

[a]Mobility diameter from electrical low-pressure impactor (ELPI) measurements.
[b]Scanning mobility particle sizer (SMPS) data from Yi et al.,[19] ABS = acrylonitrile butadiene styrene, PLA = polylactic acid.

Stefaniak et al. J Occup Environ Hyg. (2017)

Emission rates

- Real-time TVOC (µg/hr)

Table 2. Average ± standard deviation of TVOC SER_u values for 3-D and laser printers.

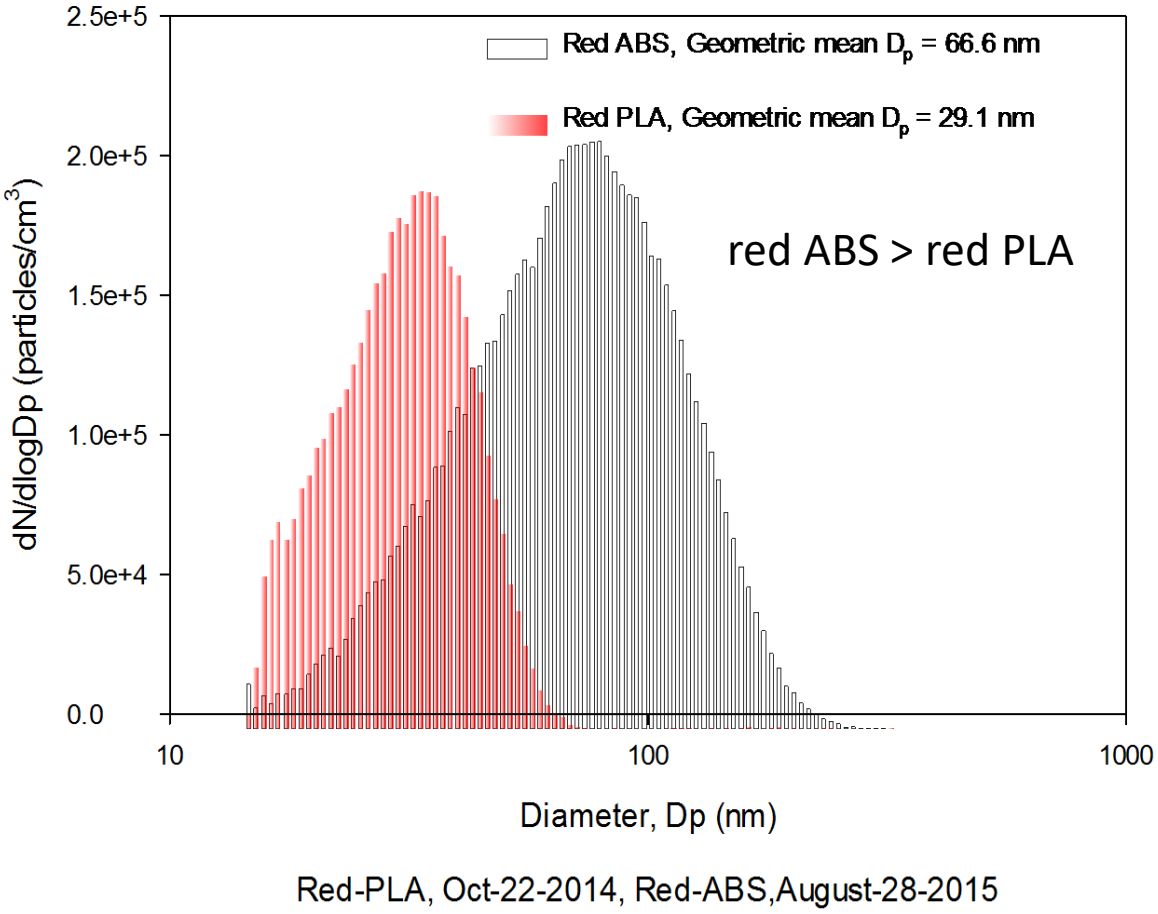
Printer	Thermoplastic	Replicates	Cover	SER_u ($\mu g\ h^{-1}$)
3-D	ABS natural	2 combs	On	3552 ± 549
3-D	ABS natural	1 comb	Off	3430
3-D	ABS natural	1 comb [malfunction]	Off	6454
3-D	ABS blue	2 combs	On	2385 ± 82
3-D	ABS red	2 combs	On	2383 ± 357
3-D	ABS black	2 combs	On	1085 ± 217
3-D	PLA ocean blue	2 combs	On	ND
3-D	PLA transparent blue	2 combs	On	131 ± 37
3-D	PLA true red	2 combs	On	ND – 49
3-D	PLA army green	2 combs	On	ND – 51
HP2055dn	Monochrome toner	80 pages @ 5%	N/A	5782
HP2600	Monochrome toner	80 pages @ 5%	N/A	7735

Note. N/A = not applicable for laser printers, ND = not detected using real-time TVOC instrument, ABS = acrylonitrile butadiene styrene, PLA = poly-lactic acid.

Stefaniak et al. J Occup Environ Hyg. (2017)

Factors influencing emissions

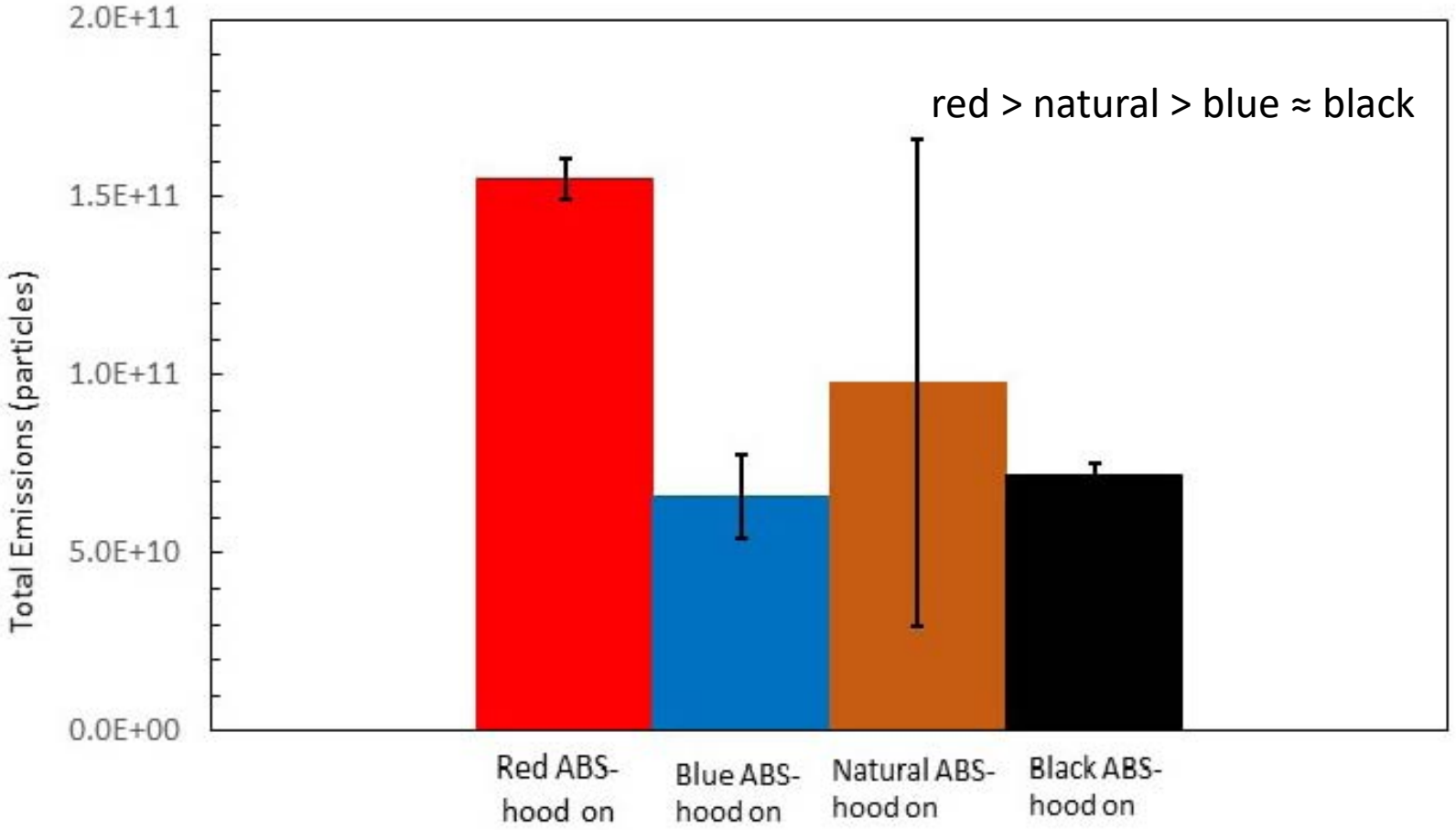
- Filament type – particle size



Yi et al. J Toxicol Environ Health. Part A (2016)

Factors influencing emissions

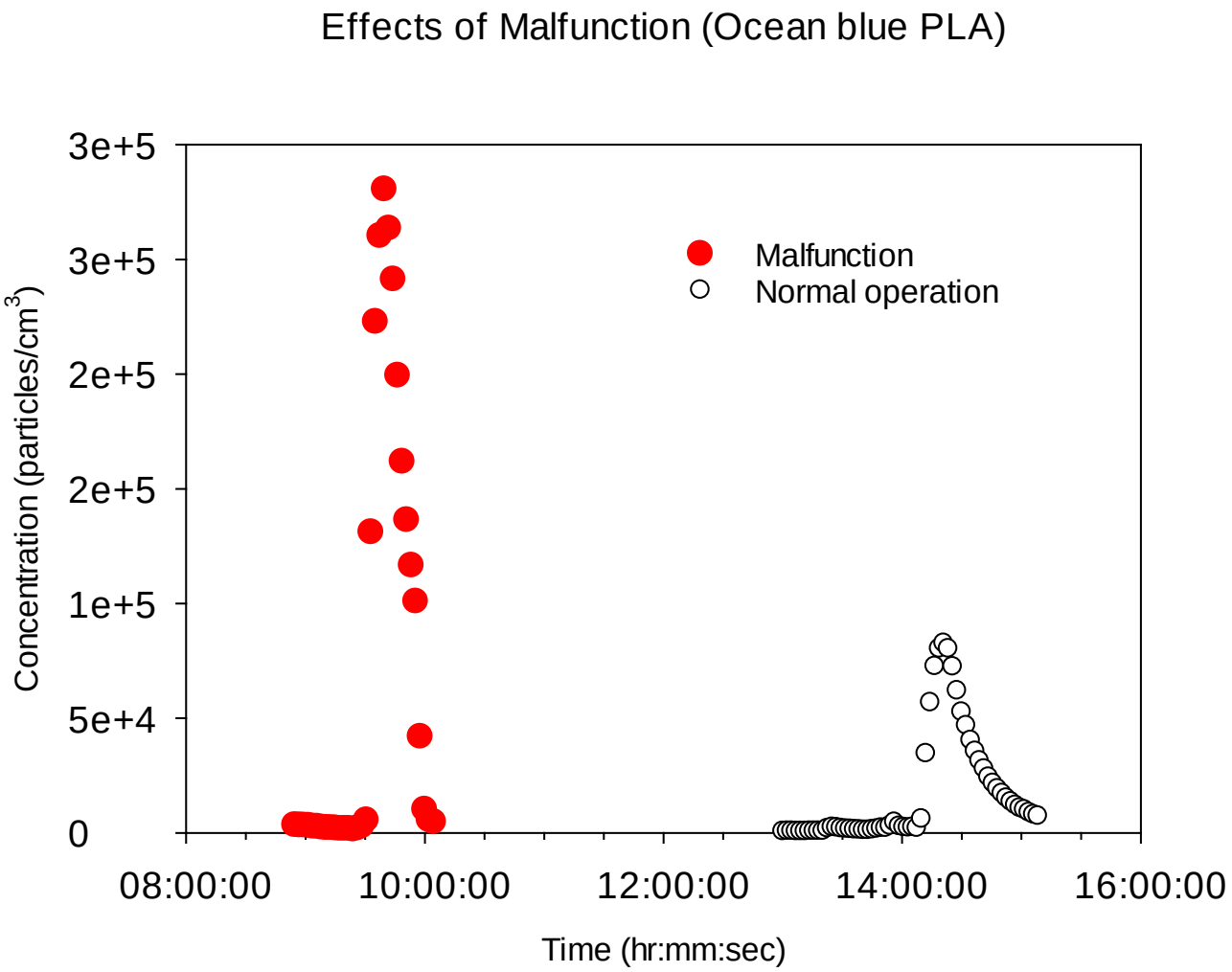
- Filament color – particle number



Yi et al. J Toxicol Environ Health. Part A (2016)

Factors influencing emissions

- Print failure – particle number



Yi et al. J Toxicol Environ Health. Part A (2016)