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Emissions from Consumer 3D Printers

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Introduction

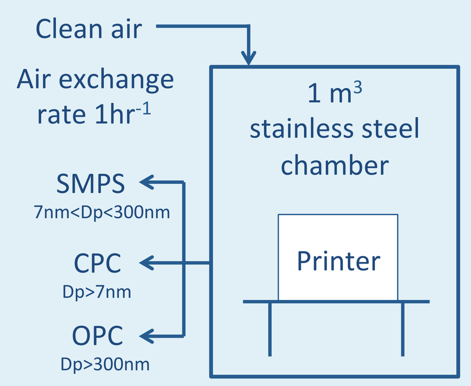
Consumer-level 3D printers are widely used in both public areas and private residences, but little is known on emissions. A previous study observed substantial emissions of ultrafine particles[1], but sensitivities to printing or operating parameters are not well characterized.

Objectives:

- Study emissions and dynamics of particles generated from 3D printers
- Test parameters that influence emissions and characterize emissions by fewest factors

Method

Experimental System



http://ieet.org/index.php/IEET/more/mcgill20121014

Testing Parameters

- Print time, Object mass
- Filament color
- Filament brand
- Printer brand
- Filament material
- Nozzle temperature

Calculation of Particle Emission Rates[2]

- Particle emission rate (PER(t)), s^{-1}

$$PER(t) = V_C\left(\frac{C_P(t) - C_P(t-\Delta t)\exp(-\beta\cdot\Delta t)}{\Delta t\exp(-\beta\cdot\Delta t)}\right)$$

- TP: total particle number emitted, #

$$TP = V_C\left(\frac{\Delta C_P}{t_{stop} - t_{start}} + \beta\cdot C_{av}\right)(t_{stop} - t_{start})$$

$C_p(t)$: particle number concentration, #/cm^3
V_C : test chamber volume, cm^3
Δt : time interval between two successive data points, s
β : particle loss coefficient, s^{-1}
ΔC_p: concentration difference between t_{start} and t_{stop}, #/cm^3
t_{start}: time when emission begins, s
t_{stop}: time when emission stops, s
C_{av}: arithmetic average concentration during emission period, #/cm^3

Aerosol Physics

Printer A, Filament: ABS 1 White

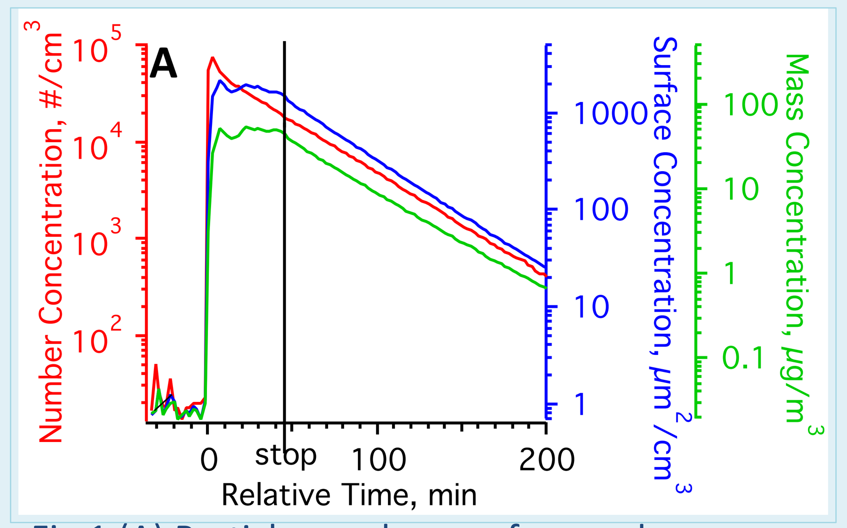


Fig.1 (A) Particle number, surface and mass concentration

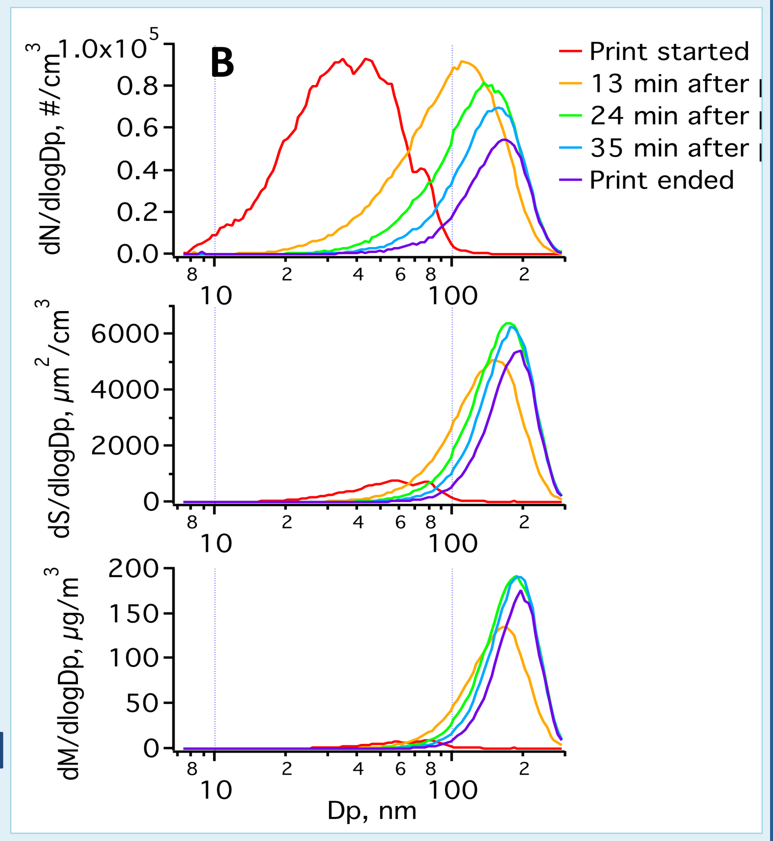


Fig.1 (B) Particle size distribution

Particle concentrations increase when printing started. Particles are generated from vapor nucleation and grow due to condensation and coagulation.

Emissions as a Function of Particle Size

Printer A, Filament: ABS 1 Green

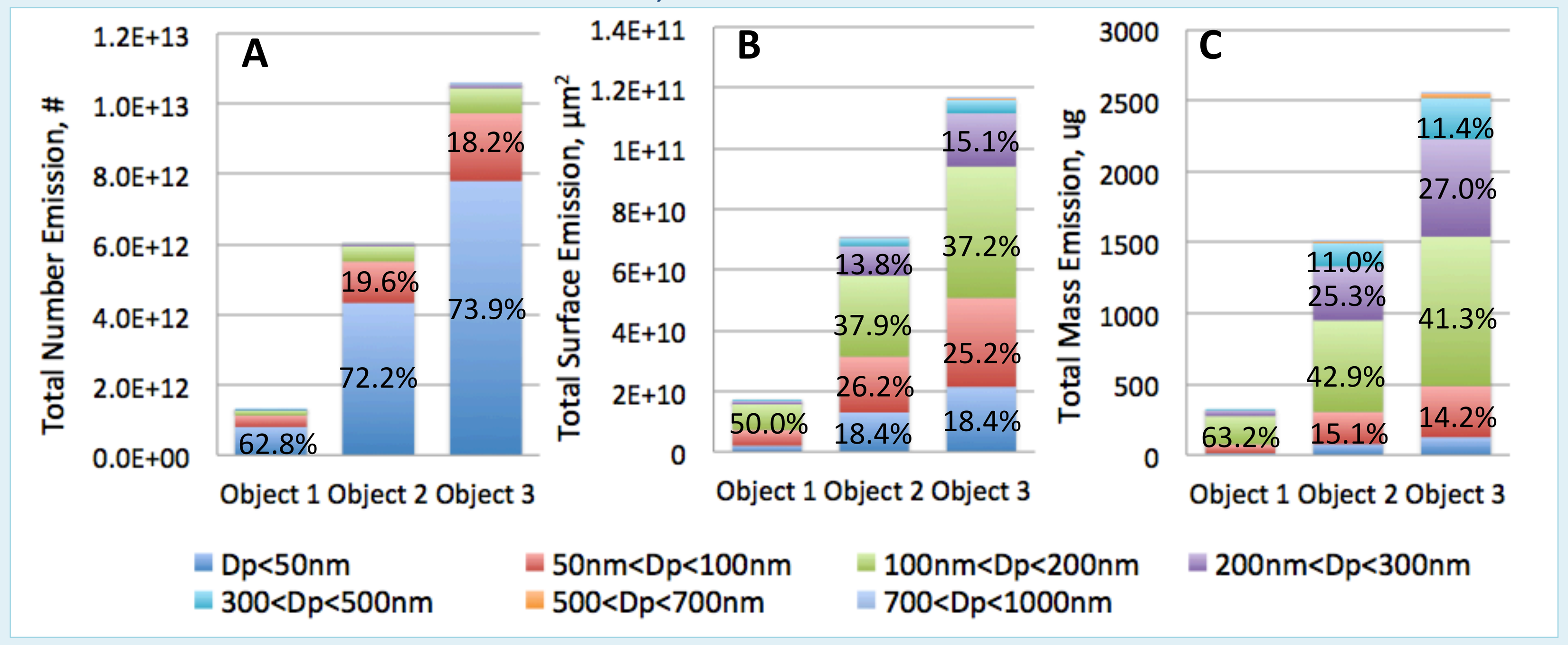


Fig.3 (A) Total particle number, surface area (B) and mass (C) emissions as a function of particle size for three printing objects

Smaller particles (D_p<50nm) dominate number emissions, larger ones (100 to 200nm) dominate emissions of surface area and mass.

Yield=Particles Emitted per Print Time or Object Mass

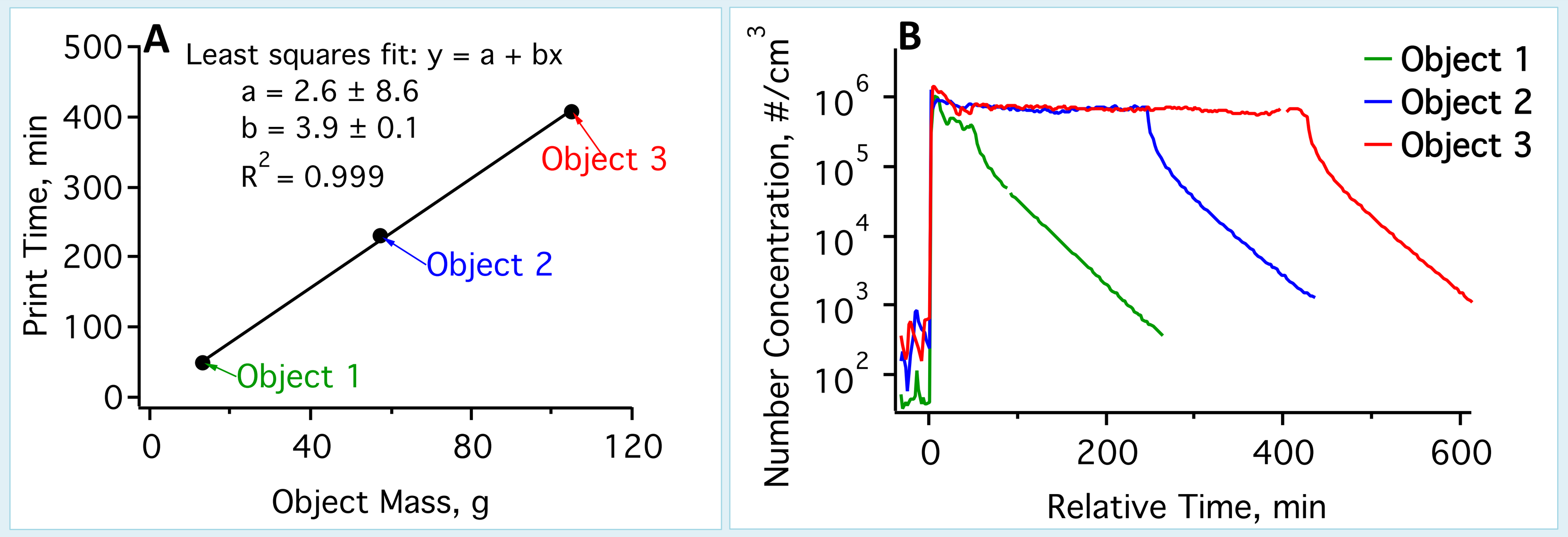


Fig.2 (A) Linear fitting for object mass vs. print time;
(B) Total particle number concentration vs. time series for three printing objects.

Larger mass of object, longer printing time, more particles emitted.

Factors Controlling Particle Emission

Filament Color

Printer A, Filament: ABS 1

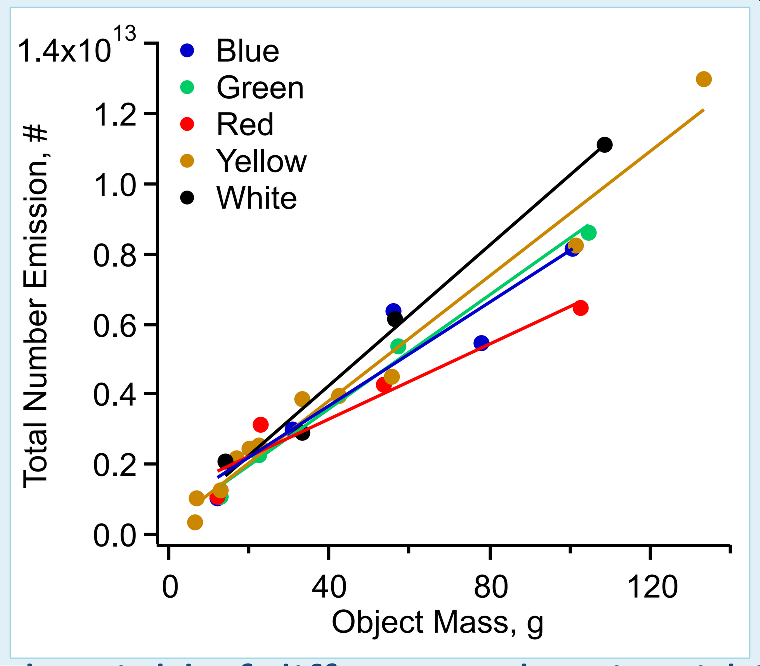


Fig.4 Total particle number emission and least square linear fit for various colors.

Table 1 Number and Mass Yield

Filament Color	Number Yield, x10^{10} #/g	Mass Yield, μg/g
Blue	7.3 ± 1.2	19.7 ± 3.2
Green	8.1 ± 0.5	20.3 ± 0.8
Red	5.3 ± 1.1	13.3 ± 4.7
Yellow	8.8 ± 0.5	24.8 ± 1.1
White	9.9 ± 0.8	30.8 ± 5.7

The yield of different colors is within a range with magnitude of 1x10^{10} # particle/g object. Color is not a significant factor.

Filament Brand

Printer A, Filament: ABS 1 and 2

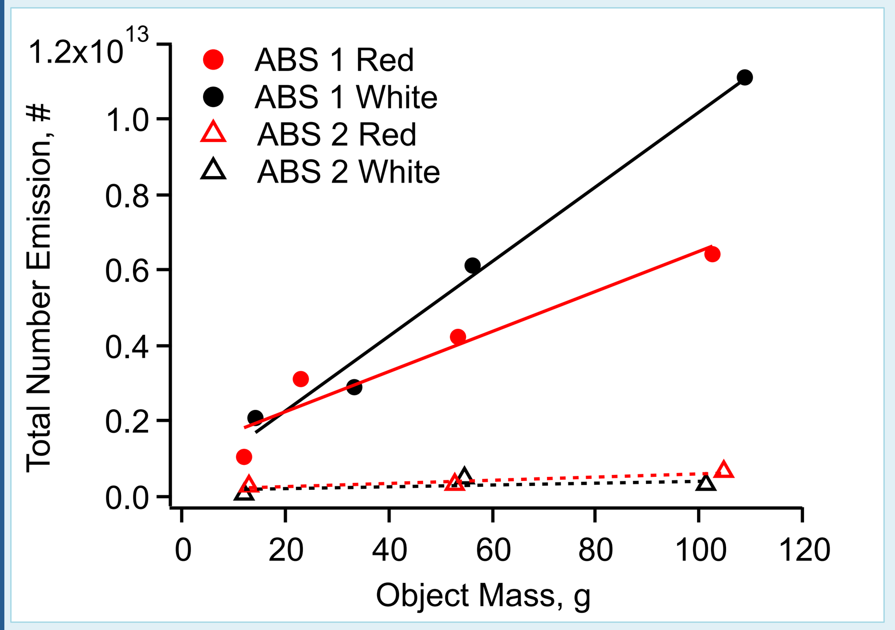


Fig.5 Total particle number emission and linear fit for two filament brands on the same printer

Yield of ABS 2 is 2.6-4.4 x10^9 #/g, order less than ABS 1.

Printer Brand

Printer A and C
Filament: ABS Red and White

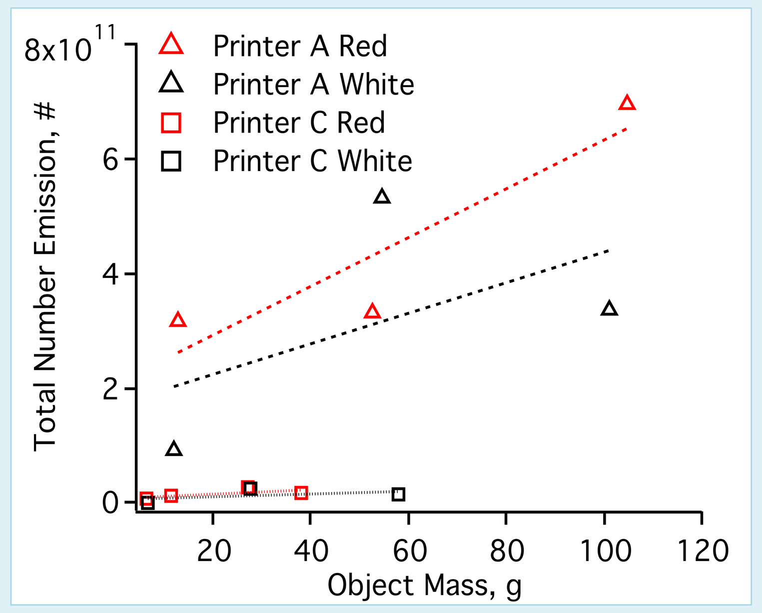


Fig.6 Total particle number emission and linear fit for ABS on two printer brands

Yield of Printer C is 4.3-8.0 x 10^8 #/g, order less than Printer A.

Filament Material

Table 2 Yield for different material

Filament	Number Yield, #/g
ABS 2 White (Printer A)	(2.6 ± 4.2) x 10^9
ABS 2 Red (Printer A)	(4.3 ± 1.9) x 10^9
ABS White (Printer C)	(0.8 ± 1.2) x 10^9
ABS Red (Printer C)	(4.3 ± 2.9) x 10^8
PLA White (Printer C)	(6.2 ± 2.6) x 10^7
PLA Red (Printer C)	1.1 x 10^9
PLA White (Printer B)	(8.1 ± 0.5) x 10^7
PLA Red (Printer B)	6.7 x 10^8
Nylon White (Printer A)	(2.2 ± 15.1) x 10^8

Preliminary results show ABS filament emits more particles than PLA and nylon material.

Nozzle Temperature

Printer A, Filament: ABS

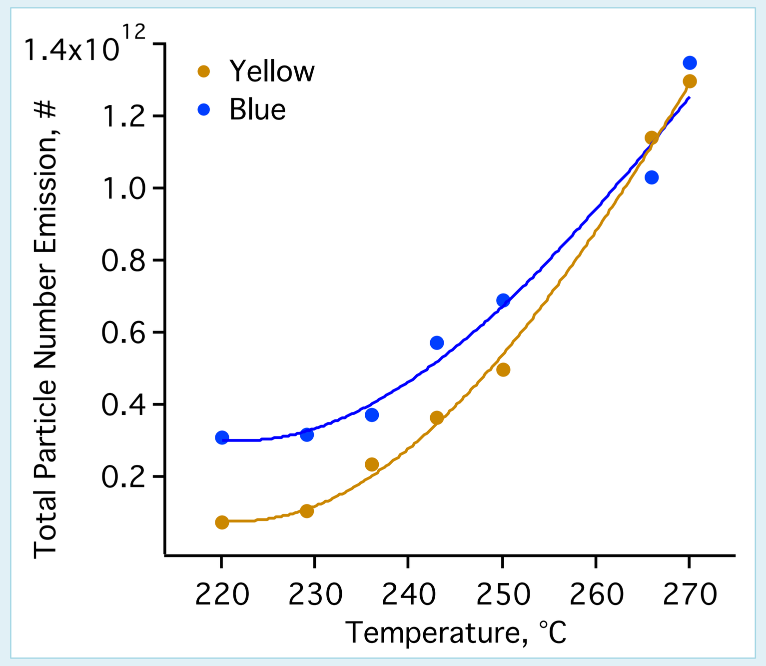


Fig.7 Emissions vs. nozzle temperature

Exponential relationship between nozzle temperature and total particle number emission.

Conclusions

- Commercial 3D printer particle emission mass yields reach ~ 20 ppm
- Particle emissions as function of factors:
  - Filament color (small effect)
  - Filament brand (ABS 1>ABS 2)
  - Printer brand (Printer A>C)
  - Filament material (ABS>PLA~nylon)
  - Nozzle Temp. (emissions increase exp.)
- Other work:
  - Emissions of VOC
  - Composition of particles
  - Toxicity
  - Development of testing standards

Acknowledgement
Funding is provided by UL Inc.

Reference

1. Brent S., et al. Atmospheric Environment. **2013**. 79, 334
2. Blue Angel Ecolabel. Test method. **2012**