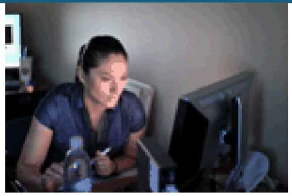
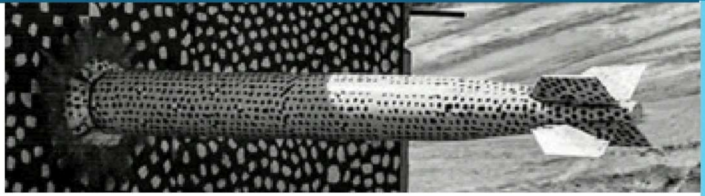
SAND2020-8077C

Aerosol jet printing: From fundamentals to graded multimaterial patterning





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LOPEC Scientific Conference

26 March, 2020

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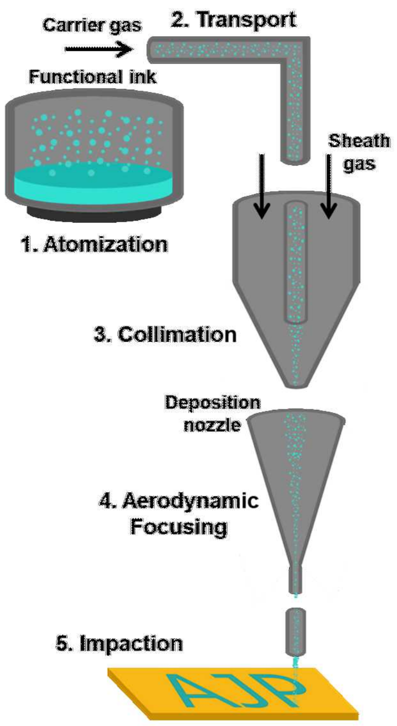
Outline

Aerosol jet printing background/motivation

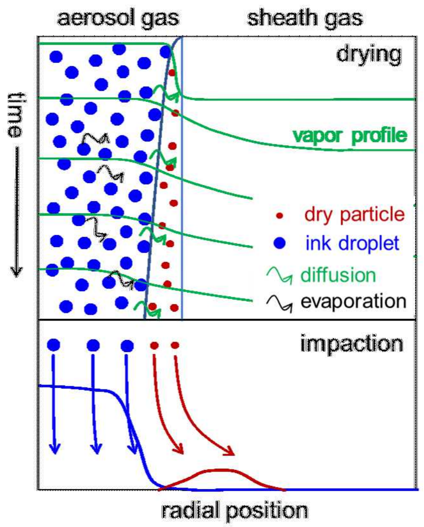
Aerosol physics

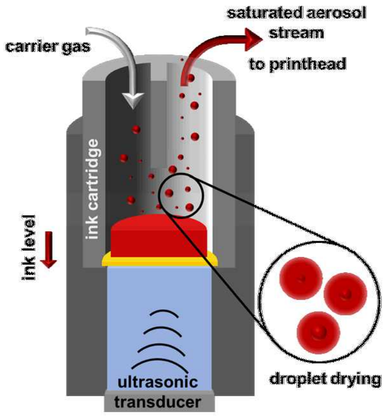
- General principles
- Baseline understanding
- Limitations



Mass transfer effects

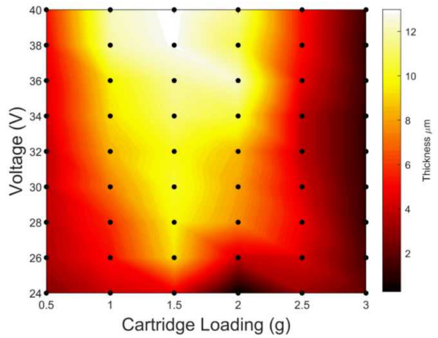
- Conceptual framework
- Ink formulation
- Printhead design

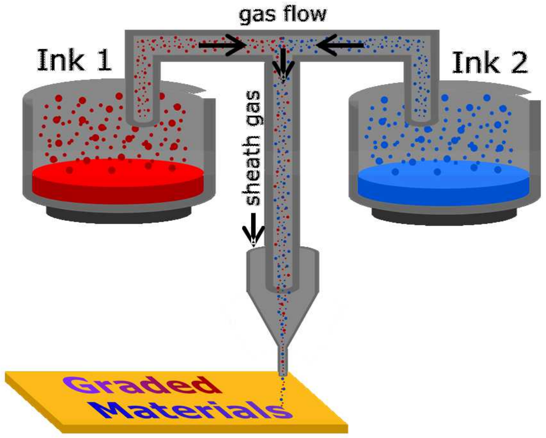




Process drift

- Understanding drift
- Passive strategies
- Closed-loop control



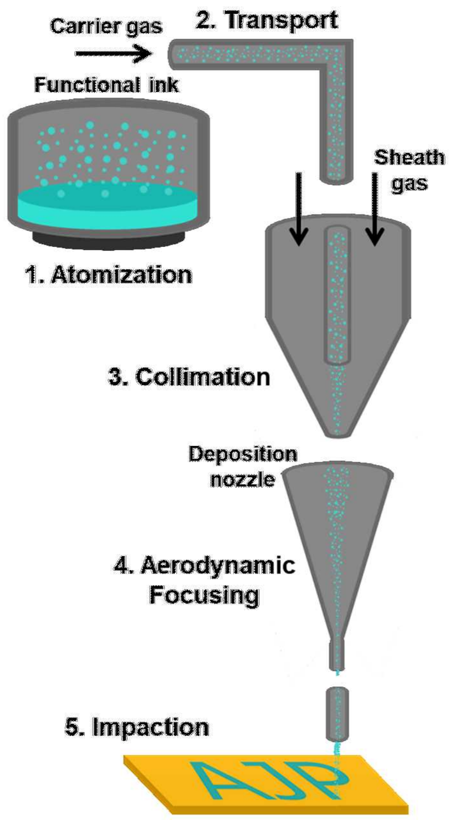


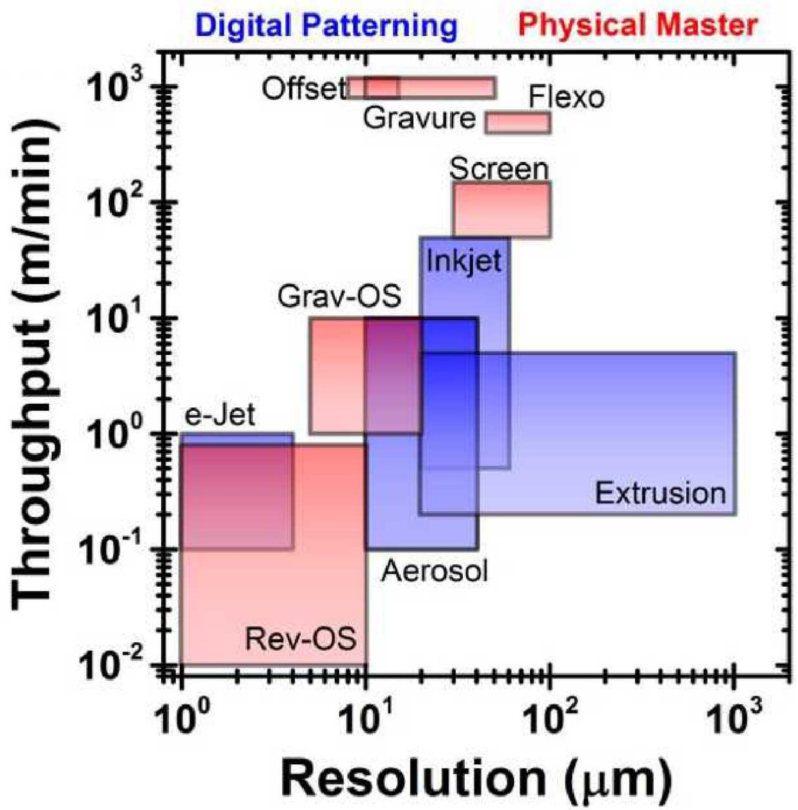
Multimaterial printing

- Proof-of-concept
- Graded functionality
- Application potential

Background and motivation for aerosol jet printing

Aerosol jet printing (AJP) uses focused deposition of micron-scale ink droplets suspended in a carrier gas flow

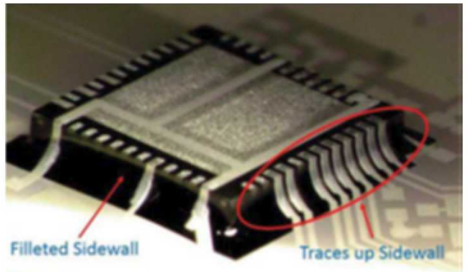




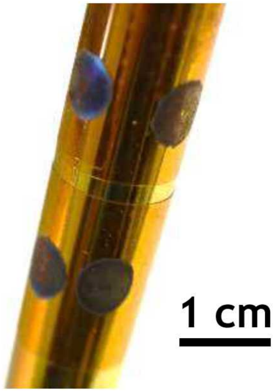
AJP is a versatile technology for prototyping functional devices

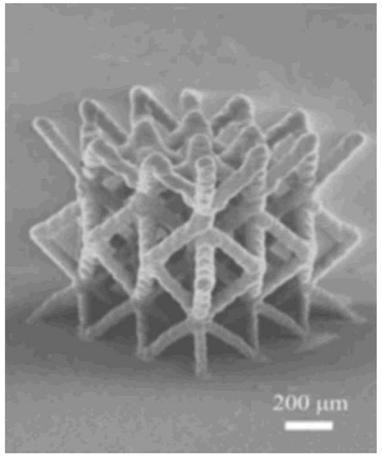
Benefits:
- Digital
- Non-contact
- High-resolution
- Versatile

Limitations:
- Process drift
- Low throughput



https://www.draper.com/news





Saleh, H., et al. *Sci. Adv.* (**2017**) 3, e1601986.

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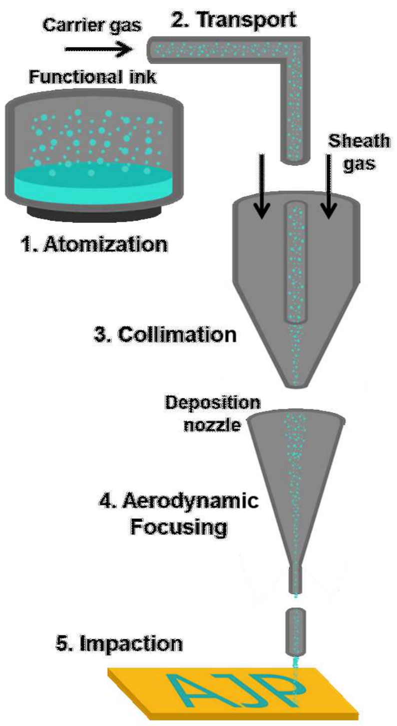

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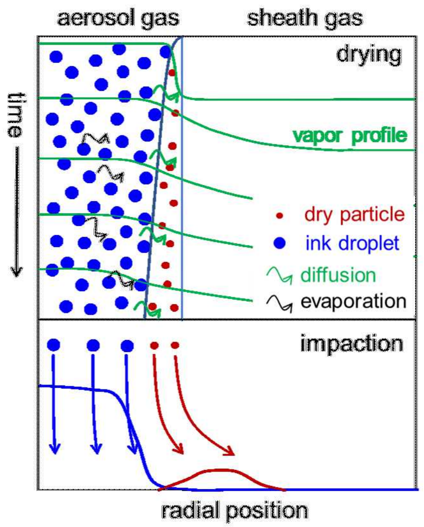

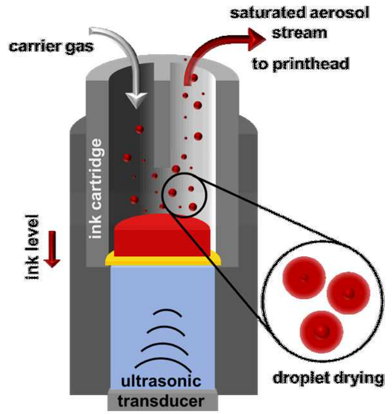

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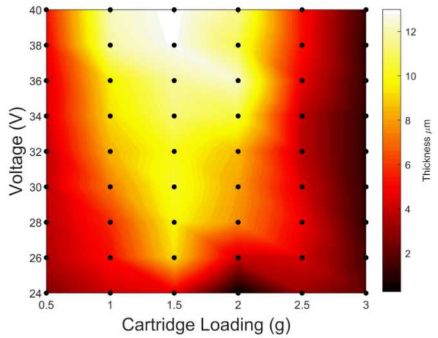

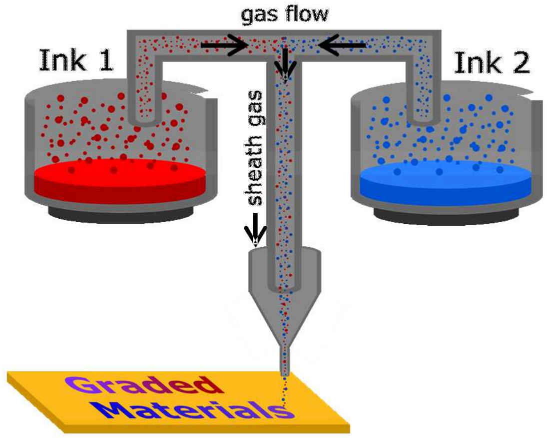

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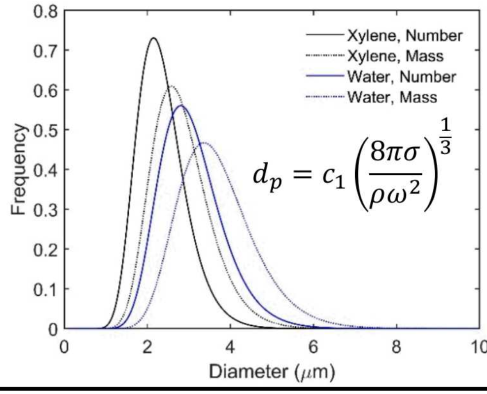
Insight from aerosol physics

Analytical models of the five physical processes can provide insight when coupled

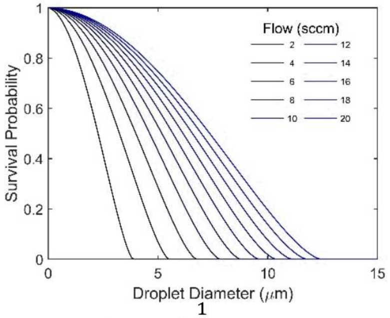
1. Atomization



$$d_p = c_1 \left(\frac{8\pi\sigma}{\rho\omega^2}\right)^{\frac{1}{3}}$$

2. Transport

$$F = \frac{2}{\pi}(\alpha\beta + \sin^{-1}\beta - 2\alpha^3\beta)$$

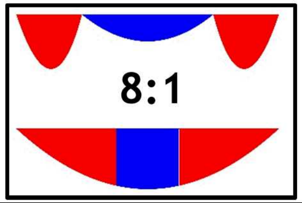


$$where\ \alpha = \left(\frac{3Lu_{TS}}{8u_aR}\right)^{\frac{1}{3}}; \qquad \beta = \sqrt{1-\alpha^2};$$

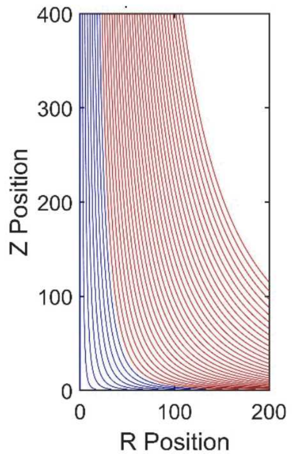
3. Collimation

$$f_a = \int_0^{2\pi} d\theta \int_0^{R_a} r dr \left[2u_a\left(1 - \frac{r^2}{R^2}\right)\right] = \pi u_a R_a^2 \left[2 - \frac{R_a^2}{R^2}\right]$$

$$x_c = \sqrt{1 - \sqrt{\frac{FR}{1+FR}}}$$



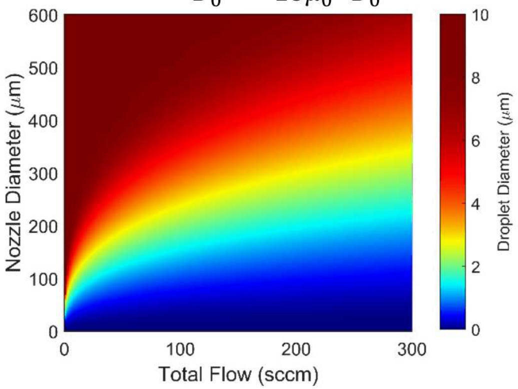
5. Impaction



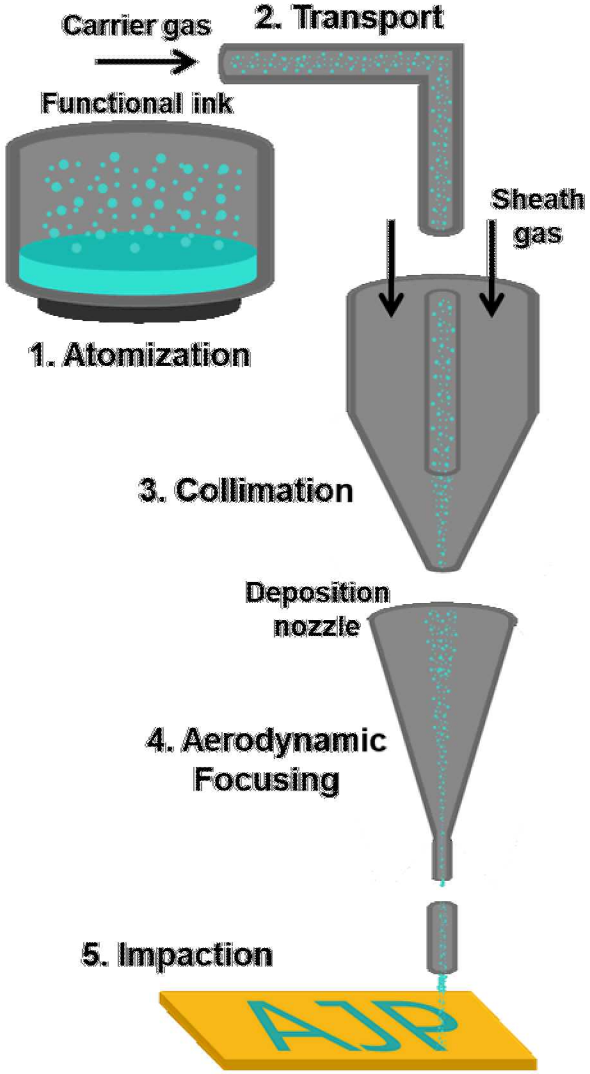
$$r_0^* * \exp[-p] * \left\{\cosh(pq) + \frac{1}{q}\sinh(pq)\right\}$$

4. Focusing

$$St = \tau\frac{U_0}{D_0} = \frac{\rho_p d_p^2 C_c}{18\mu_0}\frac{U_0}{D_0}$$



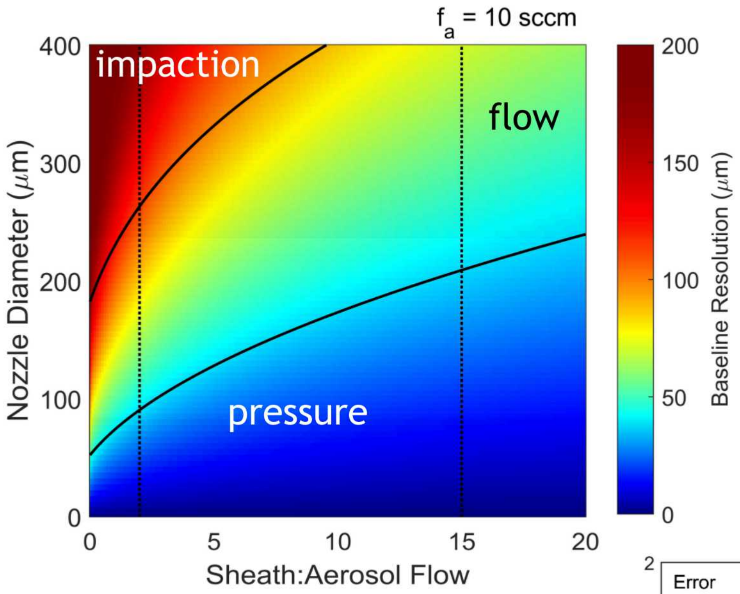
Fundamental description guides printer and process design

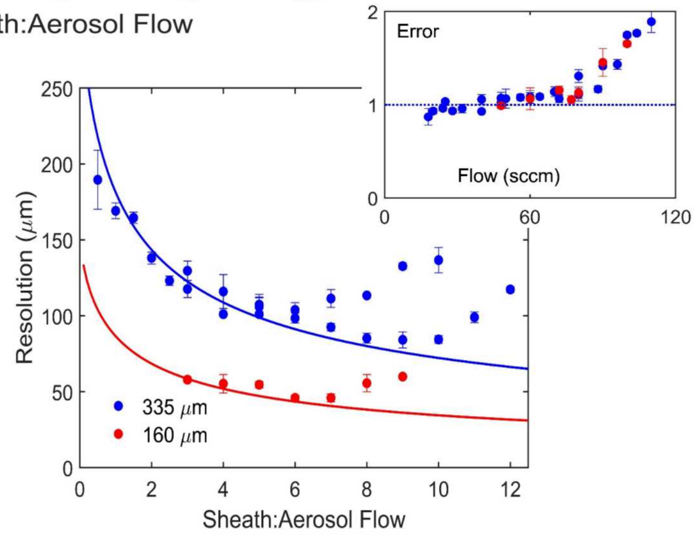


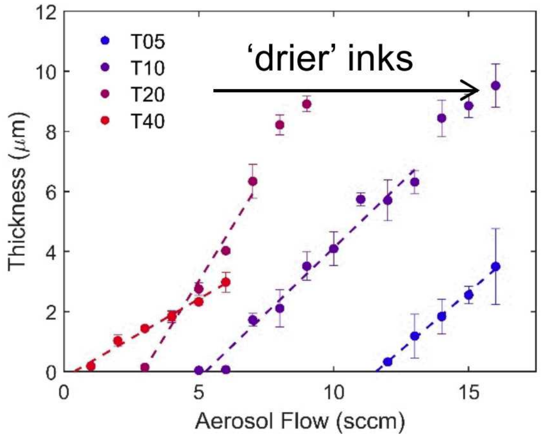
Secor, E.B. *Flex. Print. Electron.* (**2018**) 3, 035002.

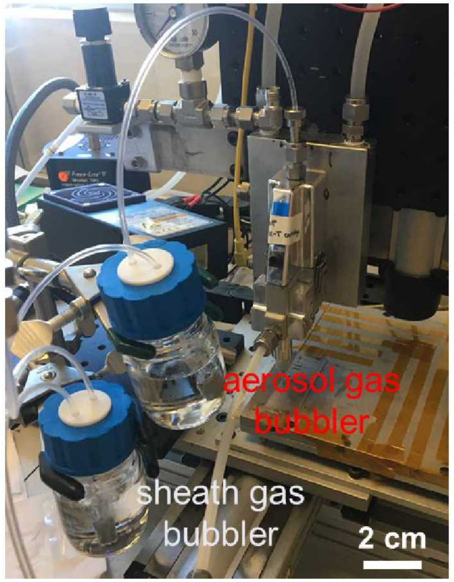
Limitations of aerosol physics perspective

Models identify factors limiting print quality and resolution

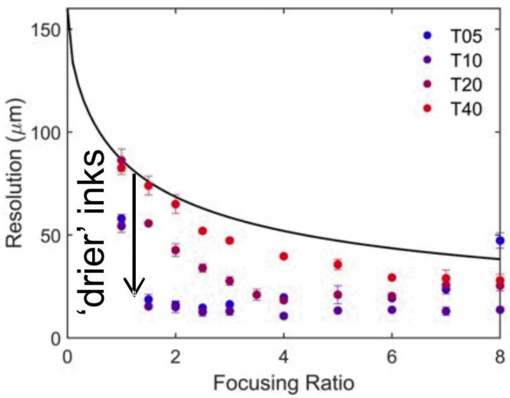


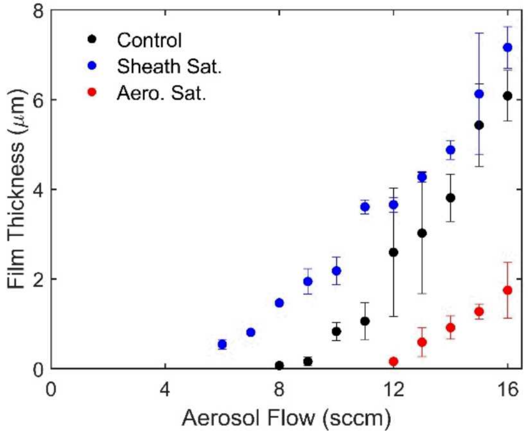






More volatile inks deviate from expected behavior





Transport effects within the printhead can strongly affect process outcomes

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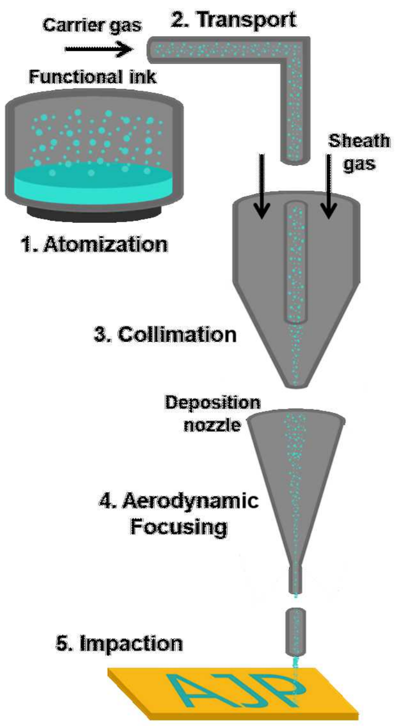

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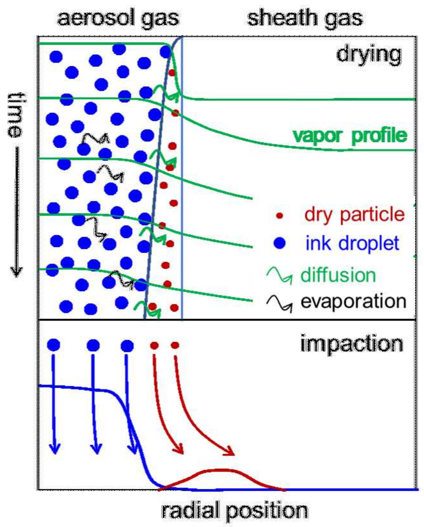

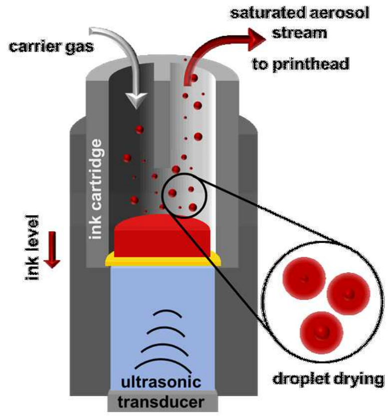

Process drift

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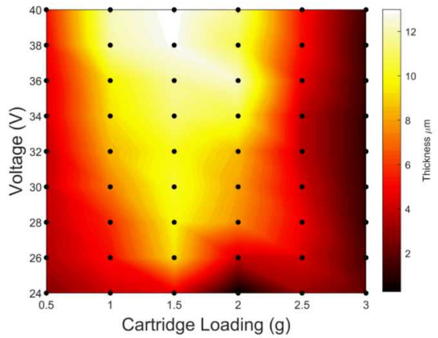

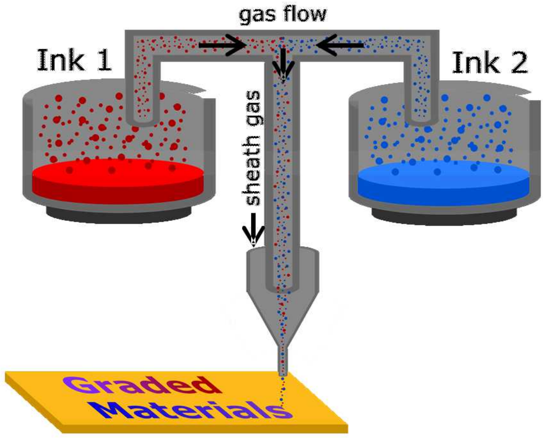

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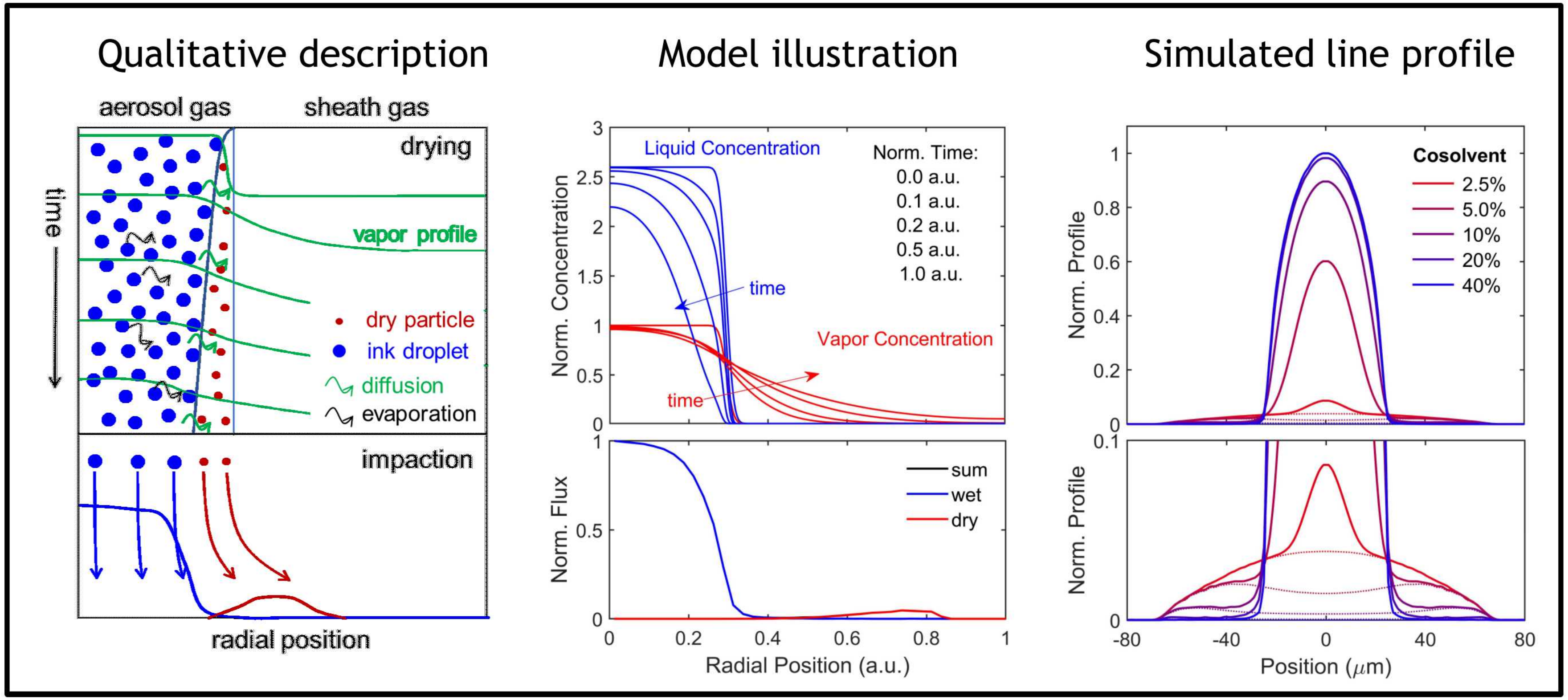
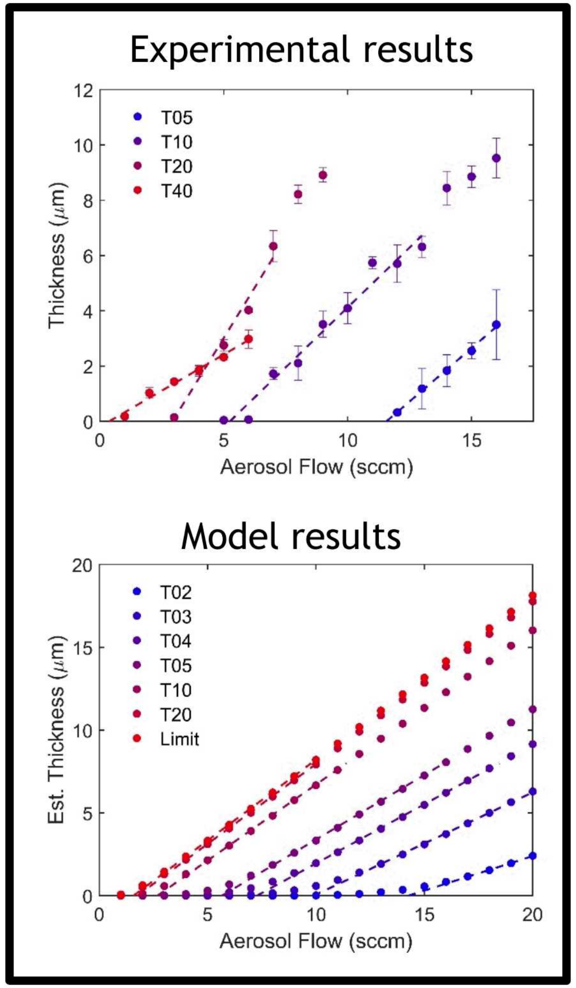
Describing mass transfer effects during printing

A dry sheath gas can induce spatially nonuniform drying within the printhead on timescales of relevance





- Radial drying within the printhead is induced by the sheath gas
- Peripheral droplets can be completely dried before vapor saturates
- Models guide ink formulation, printer design, and process optimization

Secor, E.B. *Flex. Print. Electron.* (**2018**) 3, 035007.

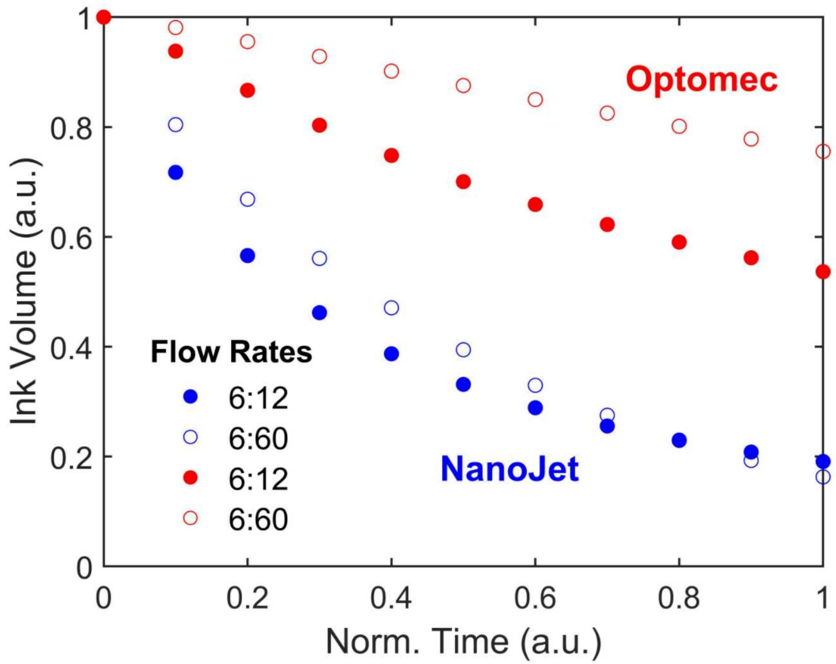
Implications for ink formulation and printhead design

$$c_o = \frac{v_a v_2 V_m}{n_{sat}} * \frac{1}{1+\chi}$$

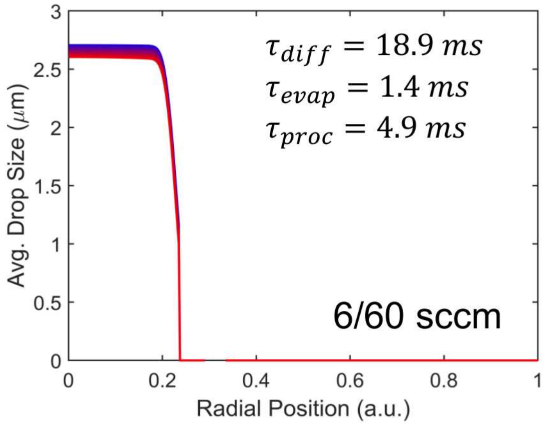
$$\tau_{proc} = \frac{\pi L R^2}{2Q}\sqrt{\frac{1+\chi}{\chi}}$$

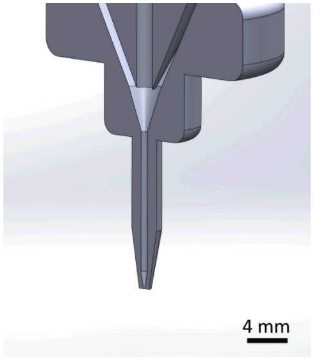
$$\tau_{diff} = \frac{R^2}{D}\left[1-\sqrt{1-\sqrt{\frac{\chi}{1+\chi}}}\right]^2$$

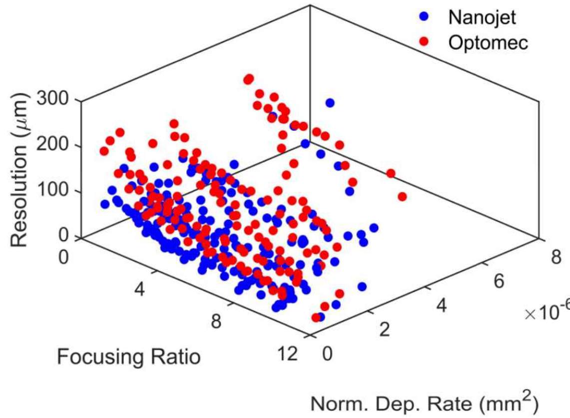
$$\tau_{evap} = \frac{a_0^2}{3Dv_a v_2^{\frac{1}{3}}}$$



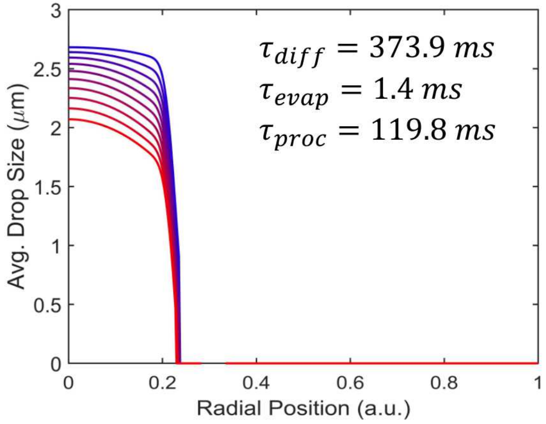
Optomec printhead

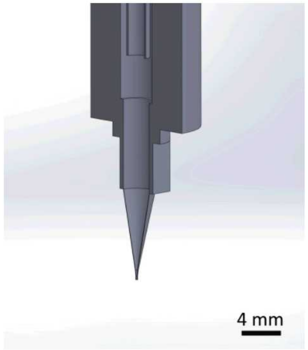


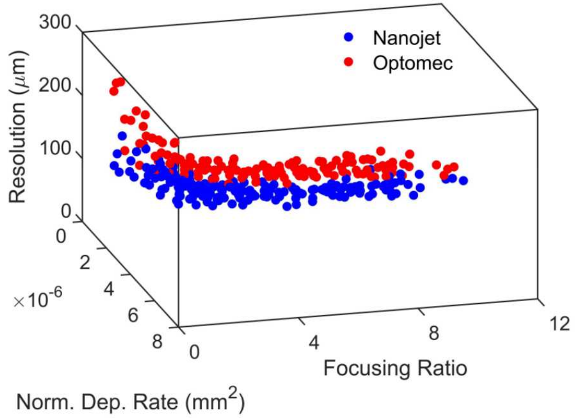




Nanojet printhead







- Ink formulation should account for solvent vapor saturation
- Printhead design affects drying timescales

- Clear difference in printing characteristics aligns with predicted wet/dry deposition

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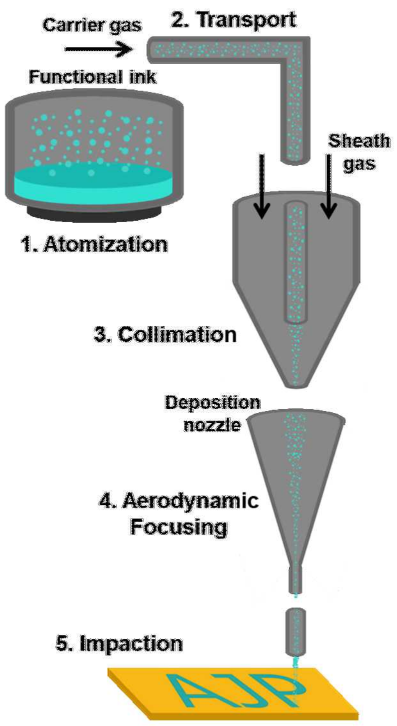

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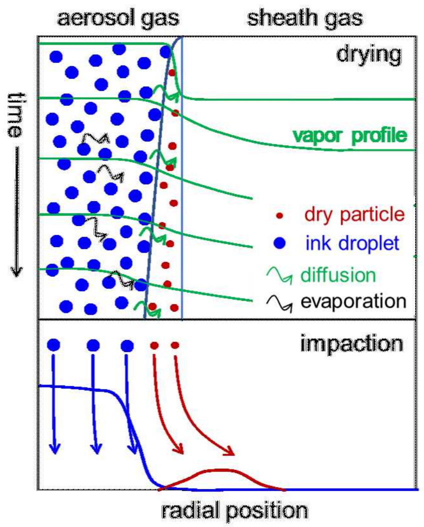

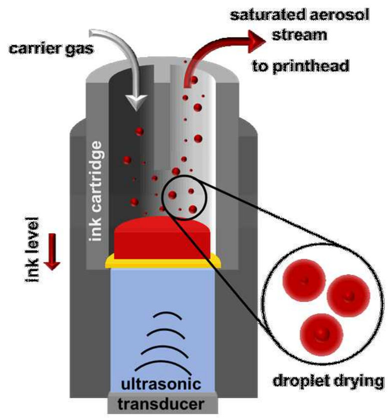

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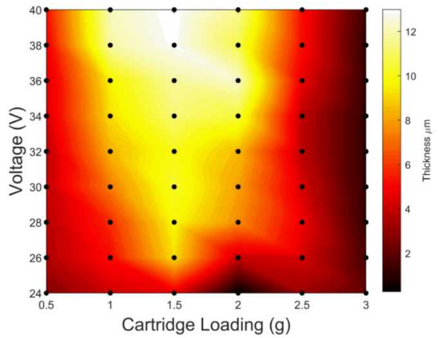

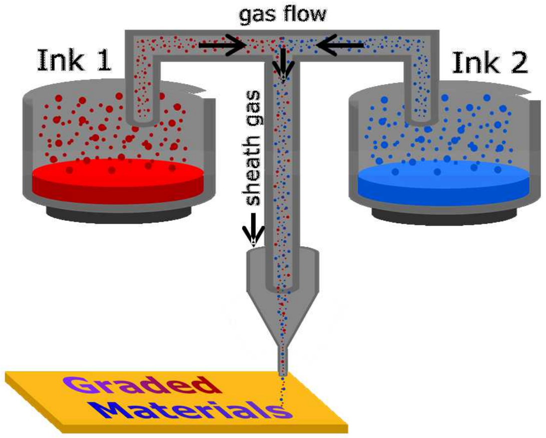

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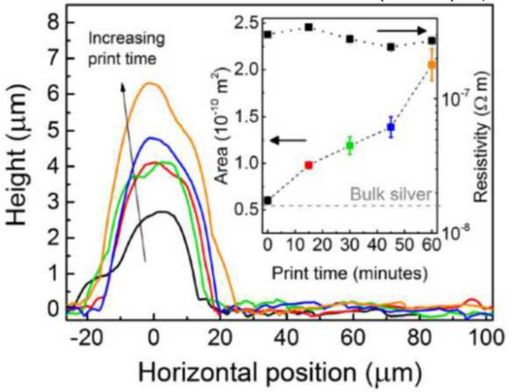
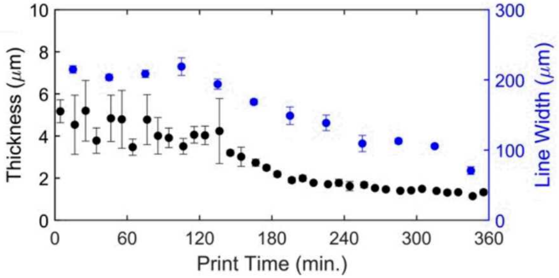
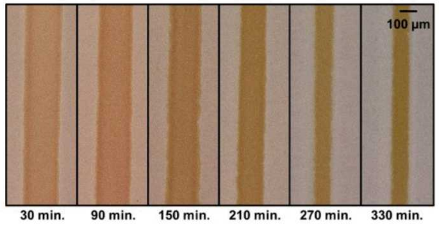
Leveraging understanding to mitigate process drift

Fundamental mechanisms support understanding of process drift, a major limitation of aerosol jet printing

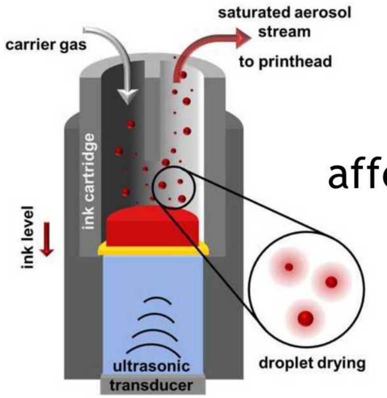
Smith, M., et al. *Flex. Print. Electron.* (**2017**) 2, 015004.



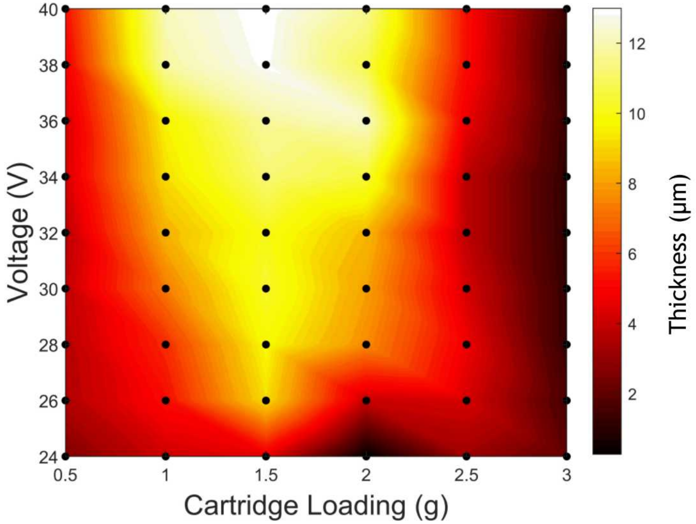


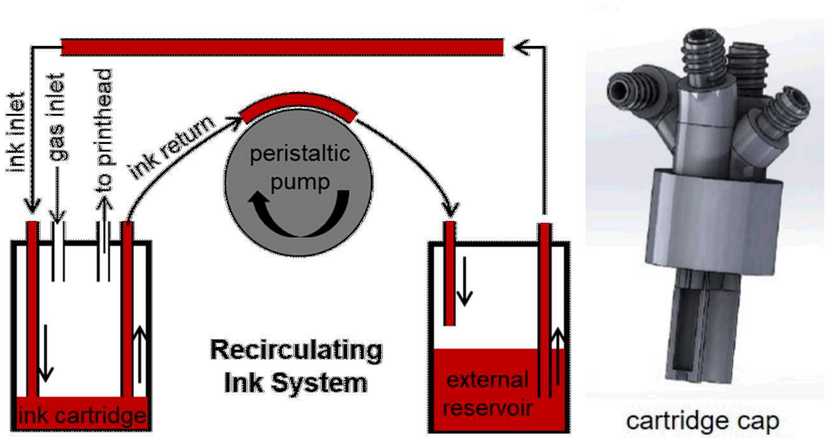


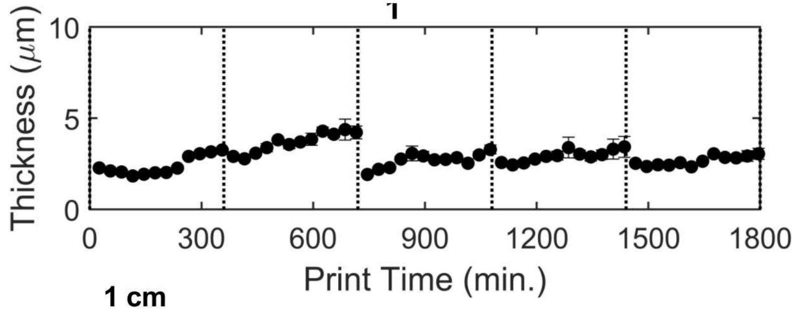
Decrease in both deposition rate and line width over 6 hours of printing

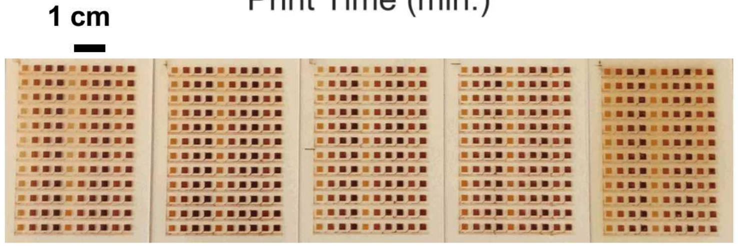


Ink level can affect atomization









Custom recirculating ink system improves consistency in 30 hr print run

Tafoya, R.R. and Secor, E.B. *Flex. Print. Electron.* **(2020)** 5, 015009.

Working towards closed loop process control

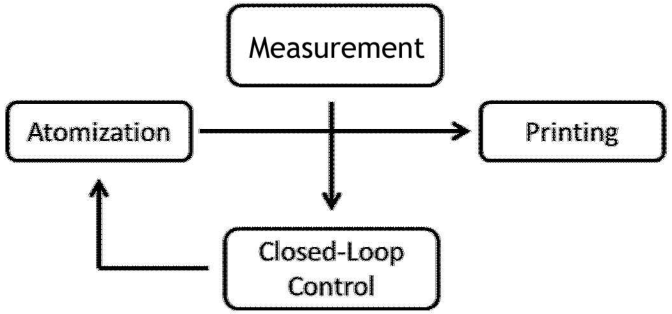
Closed-loop control is highly sought across additive manufacturing processes

Custom system developed to assess aerosol density within the printhead

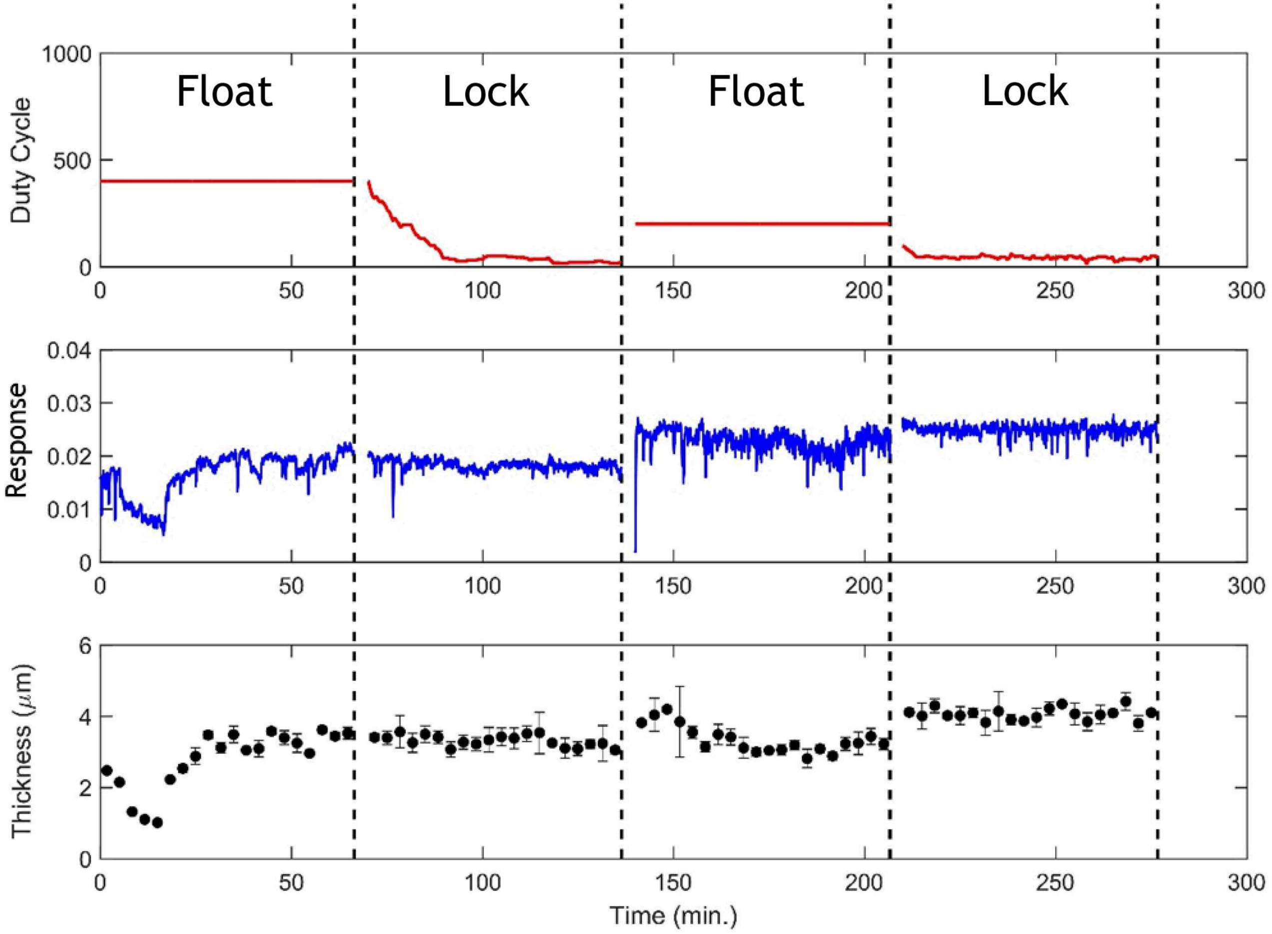
Standard Printing

Susceptible to drift in atomization yield due to temperature changes, electronic drift, atomizer aging, ink composition change, and ink volume change

Closed-Loop Control



Changes in atomization are detected in real time and compensated for if possible; if not possible, allows automatic shutdown or alert to indicate potential problems



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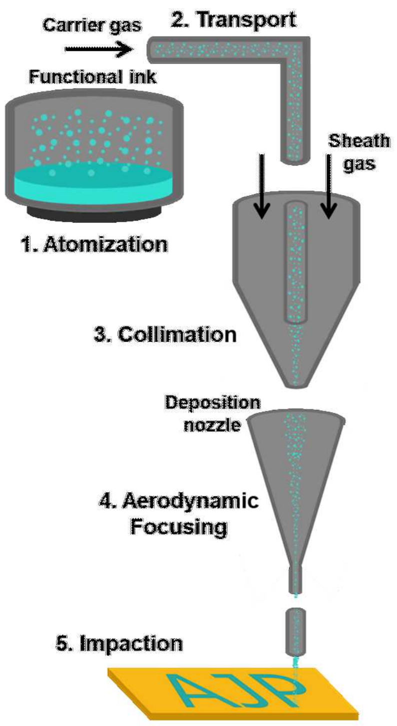

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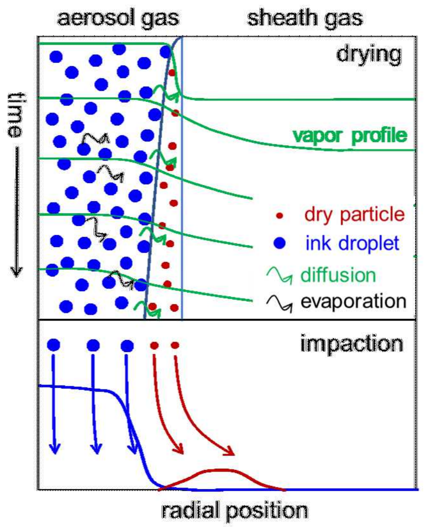

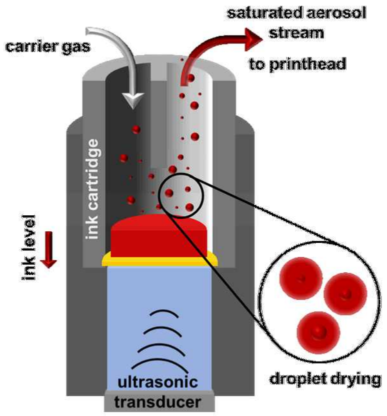

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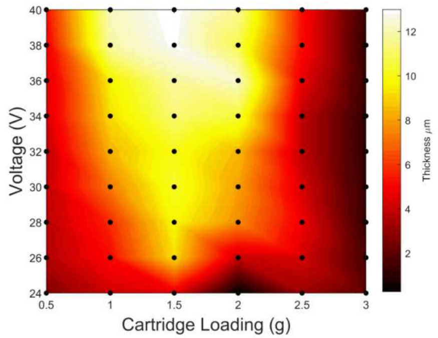
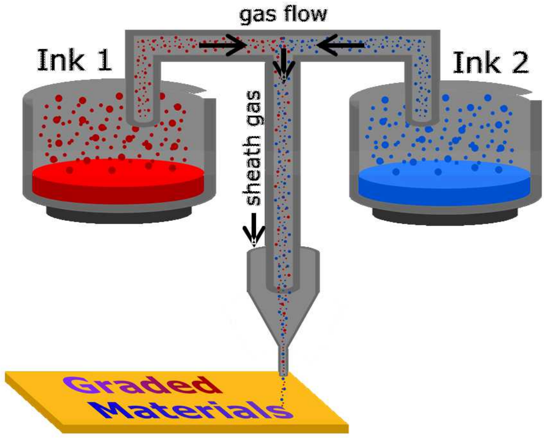
- Closed-loop control



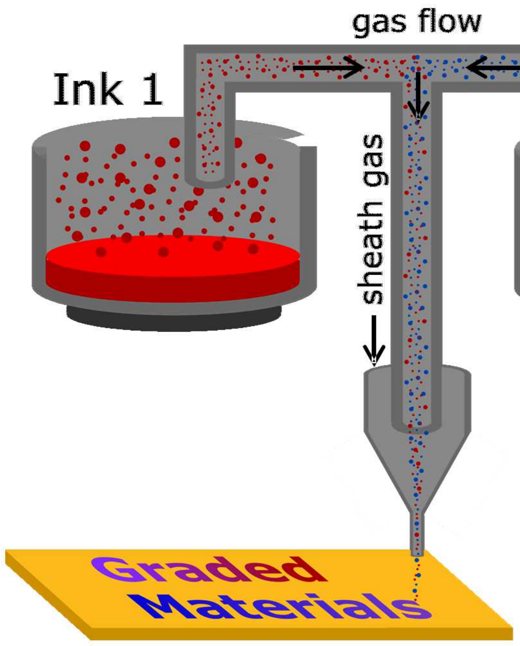


Multimaterial printing

- Proof-of-concept
- Graded functionality
- Application potential

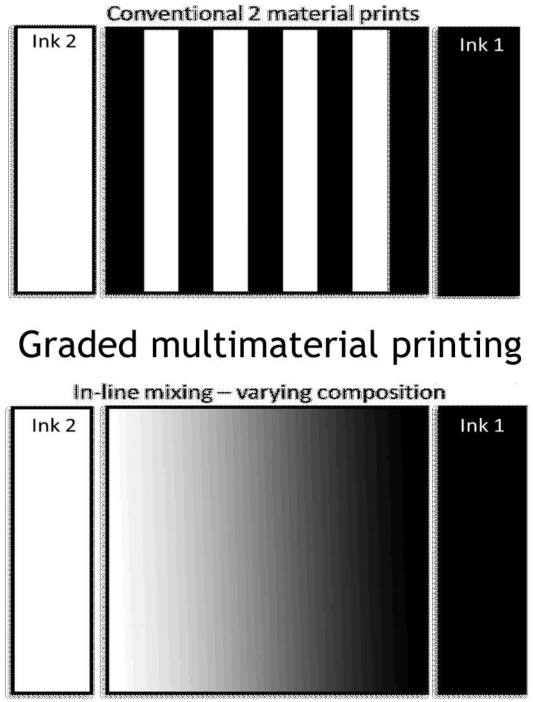
Extending versatility to graded multimaterial patterning

In-line mixing of aerosols upstream of the printhead for simultaneous codeposition of distinct inks

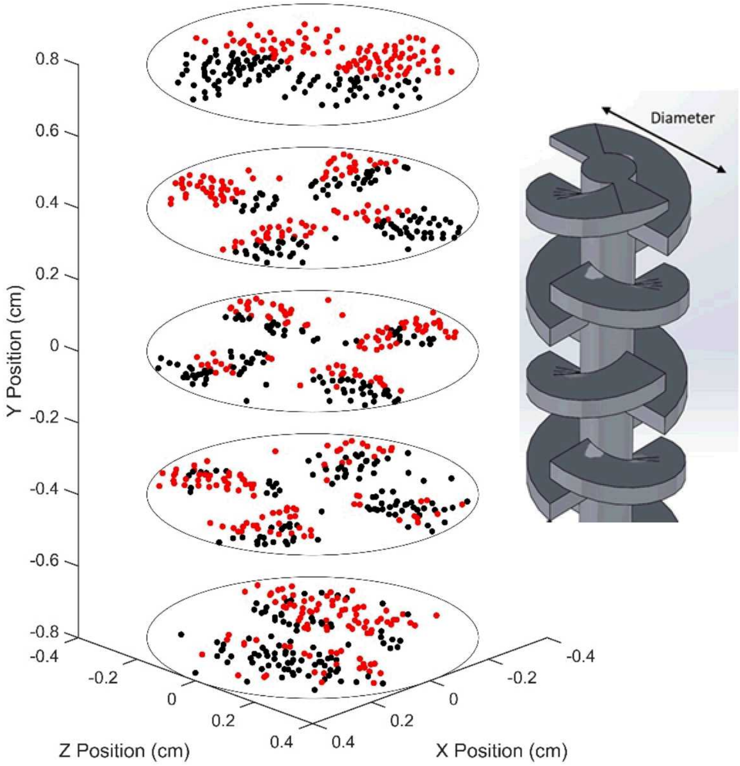


Binary multimaterial printing

Graded multimaterial printing



Mixer Cross Sections



Unique multimaterial printing platform for graded patterning with micron-scale mixing and digital control

Laminar static mixer improves droplet homogeneity

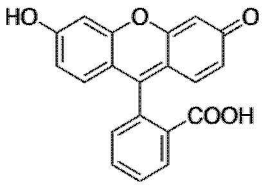
Validation of multimaterial printing concept

Initial demonstration with optical materials for straightforward characterization

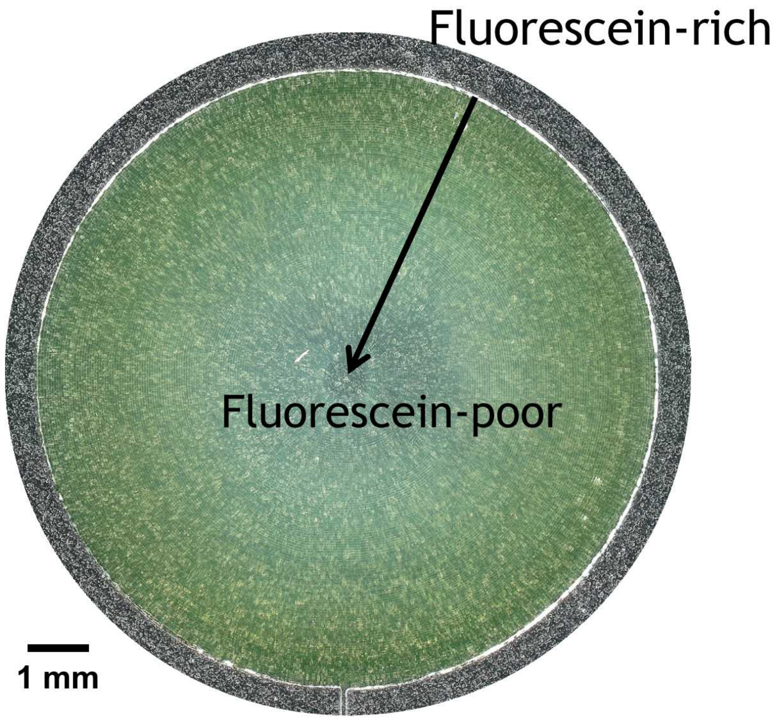
Ink 1: Norland optical adhesive NOA 61

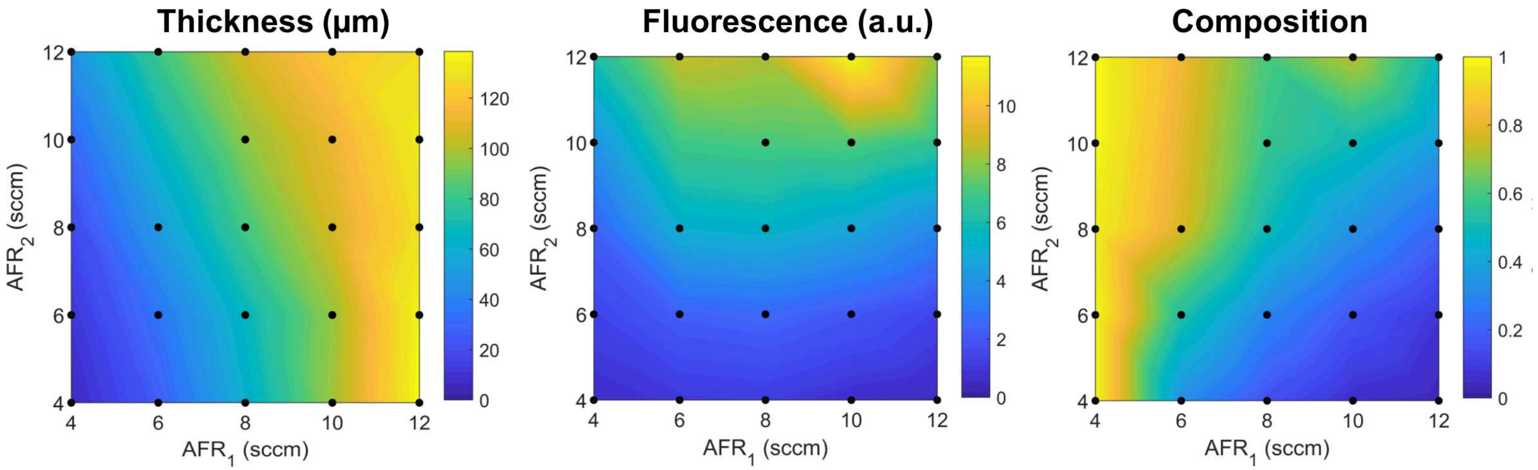
Ink 2: Norland optical adhesive NOA 61 with fluorescein and ZrO_2

- Fluorescence microscopy to measure amount of fluorescein-containing ink
- Thickness measurement for overall deposition rate
- Calibration required to deconvolute thickness and composition

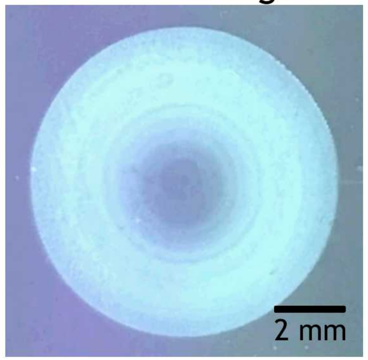


Fluorescein dye





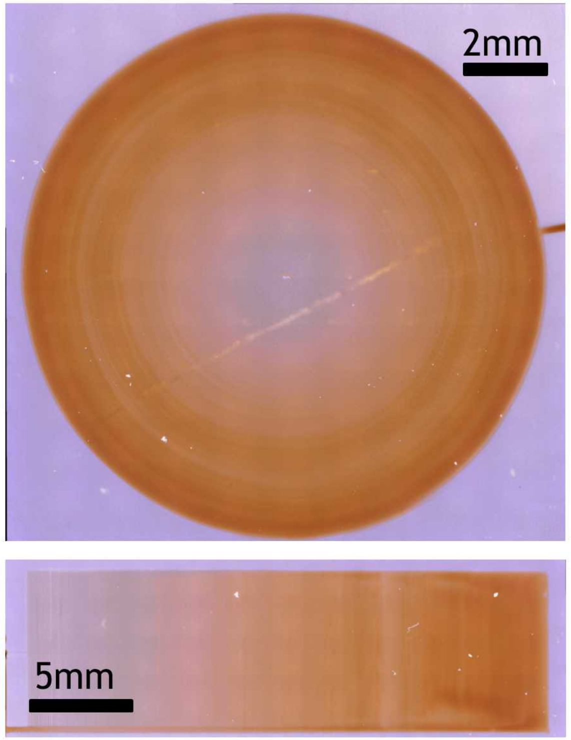
under UV light



Promise for functionally-graded patterning

Widespread opportunities for functionally graded materials based on broad compatibility of aerosol jet printing

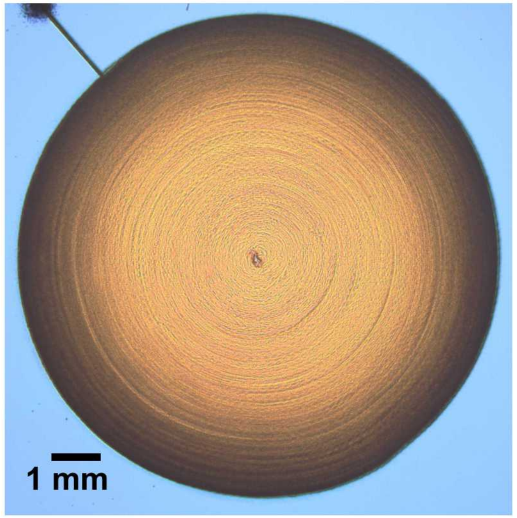
Magnetite composite



Broad scope of compatible materials

Epoxies
Acrylates
Polyimide
PMMA
Magnetite
Silver
Graphene
Gold
Metal oxides
Metal hydrides

Graphene/magnetite composite



Potential application areas

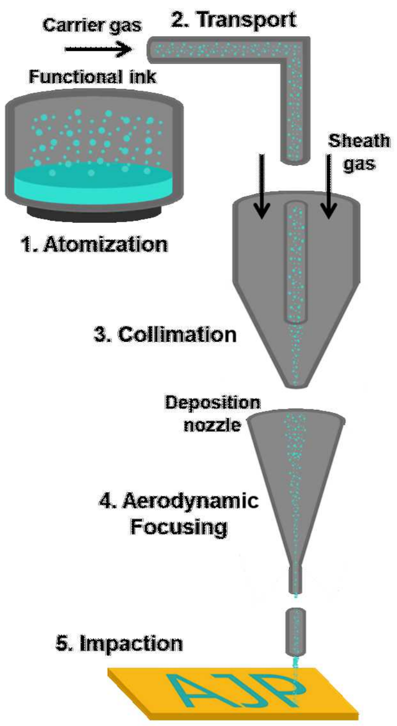
- Mechanical interfaces
- Gradient index optics/RF
- Electronic devices
- Electrochemical systems

Platform for fabricating arbitrary gradients offers extensive design flexibility for widespread applications in mechanical, electronic, magnetic, and thermal systems

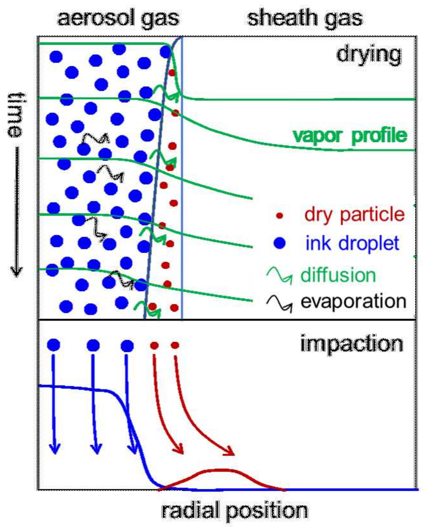
Outline

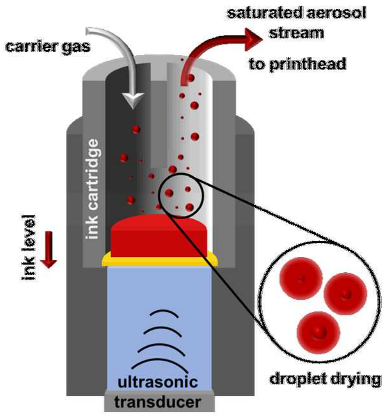
Aerosol jet printing background/motivation

Aerosol physics
- General principles
- Baseline understanding
- Limitations

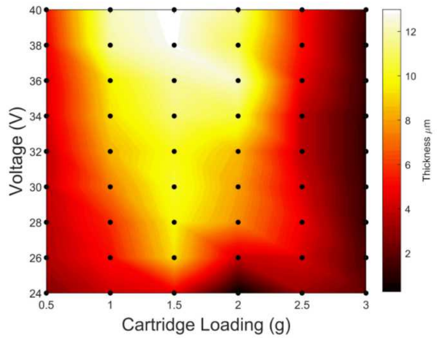


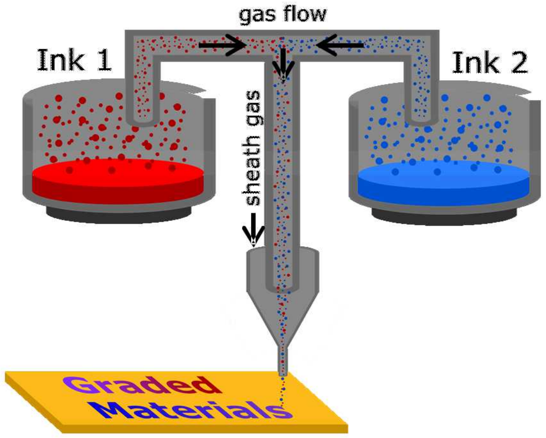
Mass transfer effects
- Conceptual framework
- Ink formulation
- Printhead design





Process drift
- Understanding drift
- Passive strategies
- Closed-loop control





Multimaterial printing
- Proof-of-concept
- Graded functionality
- Application potential

Rebecca R. Tafoya

Adam W. Cook

Bryan J. Kaehr

P. Randall Schunk

Thanks for your attention!

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Funding from the Sandia LDRD program through the Truman Fellowship

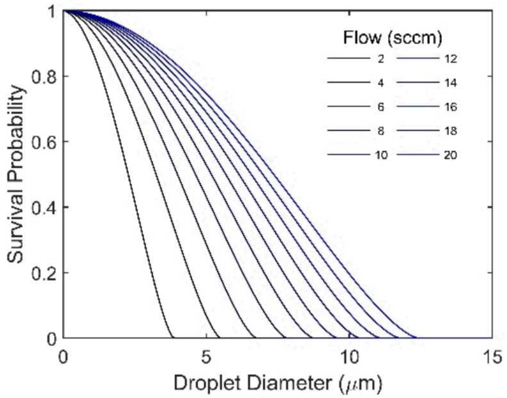
Sandia National Laboratories

LDRD LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Support Slide 1: Aerosol Physics

2. Transport

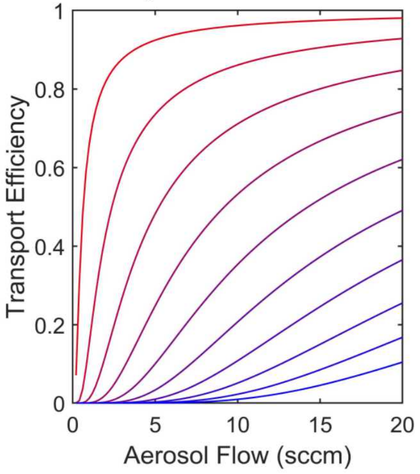
$$F = \frac{2}{\pi}\left(\alpha\beta + \sin^{-1}\beta - 2\alpha^3\beta\right)$$



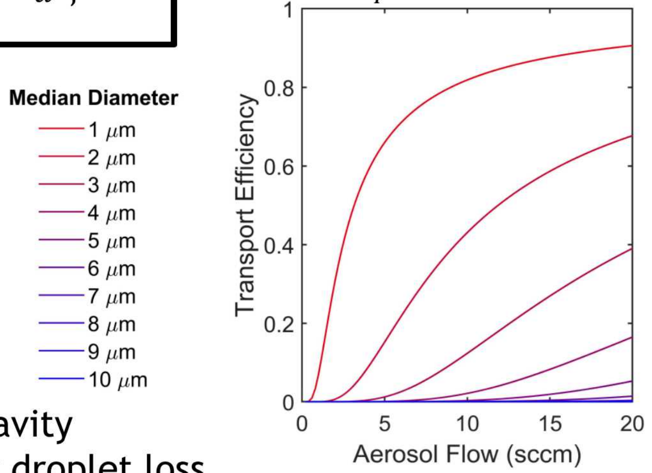
$$where\ \alpha = \left(\frac{3Lu_{TS}}{8u_aR}\right)^{\frac{1}{3}}; \qquad \beta = \sqrt{1-\alpha^2};$$

Thomas, J.W. *JAPCA J. Air Waste Manage. Assoc.* (1958) 8, 32.

$R_H = 3\ mm, L_H = 20\ mm, L_T = 100\ mm$

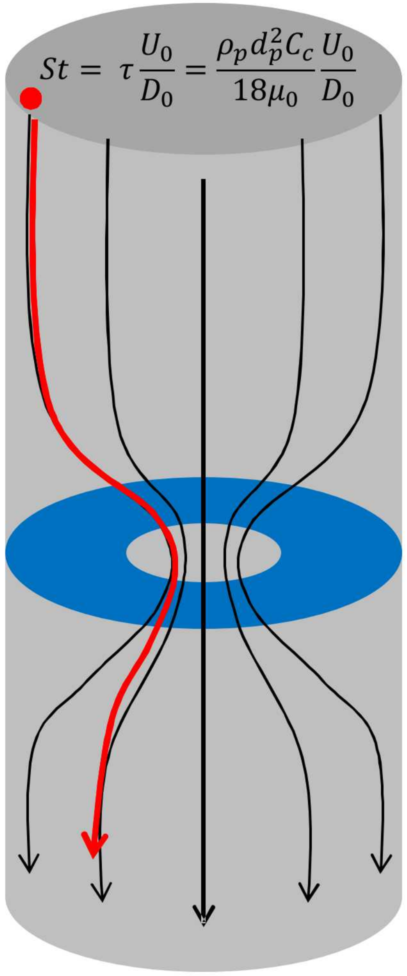


$R_H = 1\ mm, L_H = 200\ mm, L_T = 500\ mm$



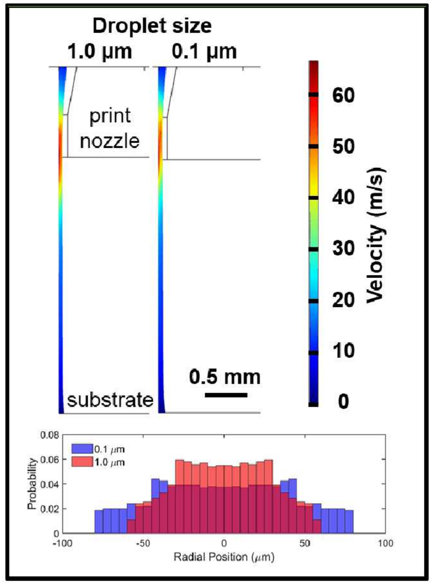
- Large droplets settle under gravity
- System design is important for droplet loss
- Droplet settling can limit print time

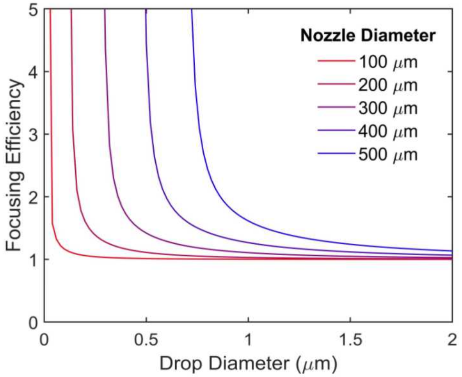
4. Focusing



Israel, G.W. and Friedlander, S.K. *J. Colloid Interface Sci.* (1967) 24, 330.

5. Impaction





- Impaction of droplets on substrate dependent on inertia
- Droplet size, flow rates, and nozzle diameter all affect the process

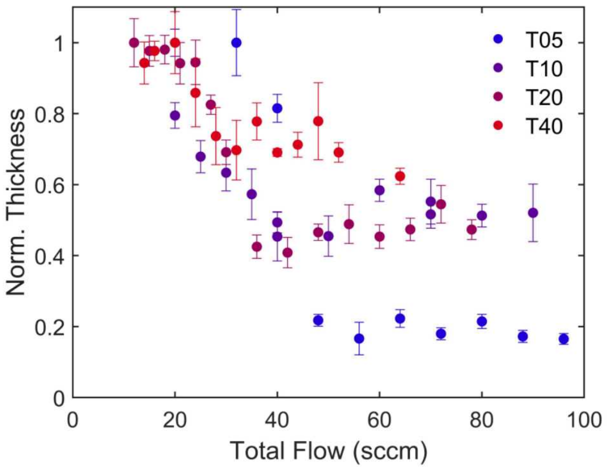
Support Slide 2: Mass Transfer

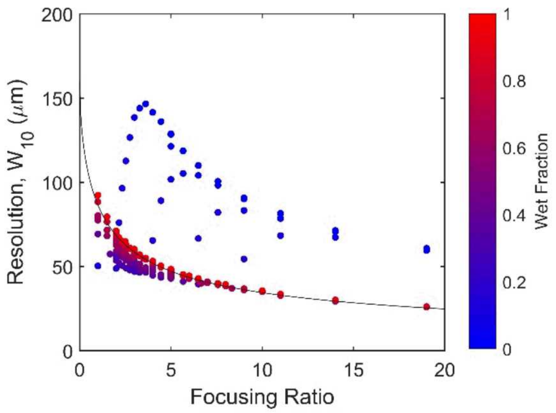
$$c_o = \frac{v_a v_2 V_m}{n_{sat}} * \frac{1}{1+\chi} \qquad \tau_{proc} = \frac{\pi L R^2}{2Q}\sqrt{\frac{1+\chi}{\chi}}$$

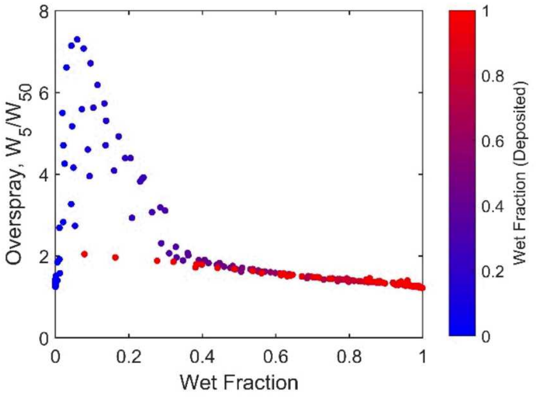
$$\tau_{diff} = \frac{R^2}{D}\left[1-\sqrt{1-\sqrt{\frac{\chi}{1+\chi}}}\right]^2 \qquad \tau_{evap} = \frac{a_0^2}{3 D v_a v_2^{\frac{1}{3}}}$$

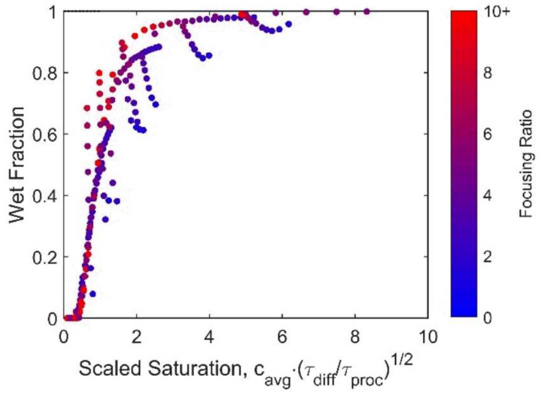
Machine parameters: $\boldsymbol{L, R}$
(length, radius)
Process parameters: $\boldsymbol{Q, \chi}$
(flow, focusing ratio)
Ink parameters: $\boldsymbol{n_{sat}, v_2}$
(vapor saturation conc., volume fraction)
Mixed or poor control: $\boldsymbol{v_a, a_0}$
(aerosol fraction, initial droplet size)

Drying induced by the sheath gas affects deposition rate

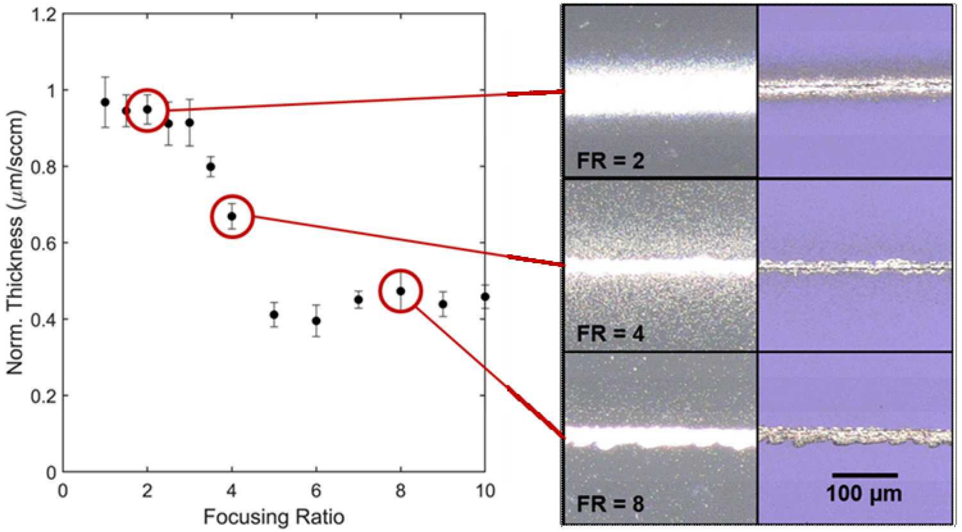


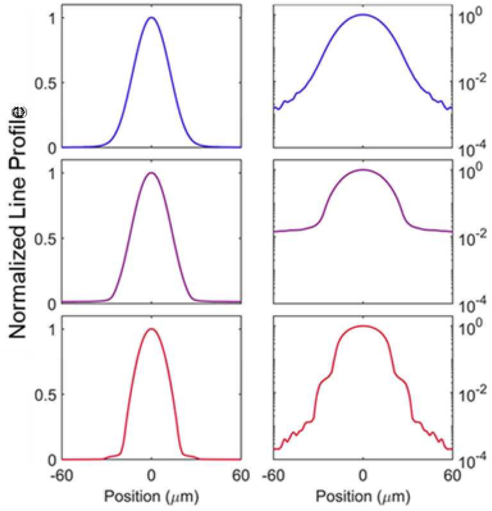




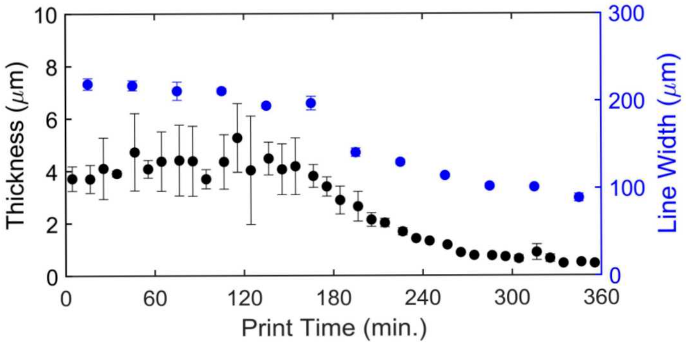


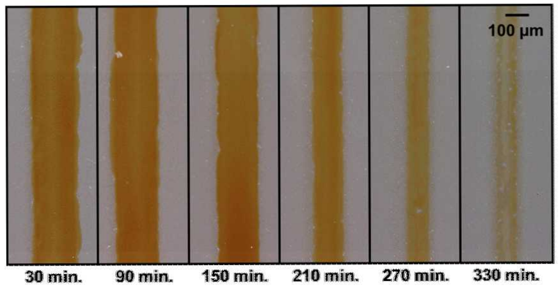
- Understanding from models helps explain some unusual observed print characteristics
- Rebound of dry particles may have a role under some conditions

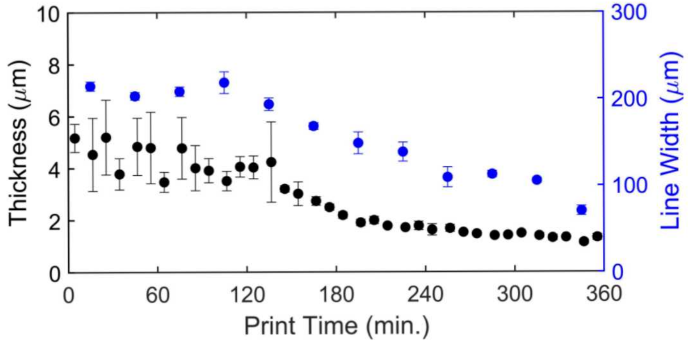


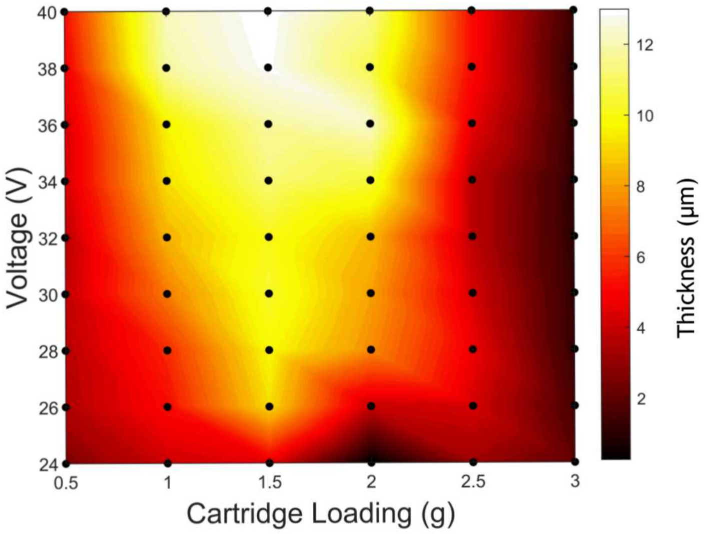


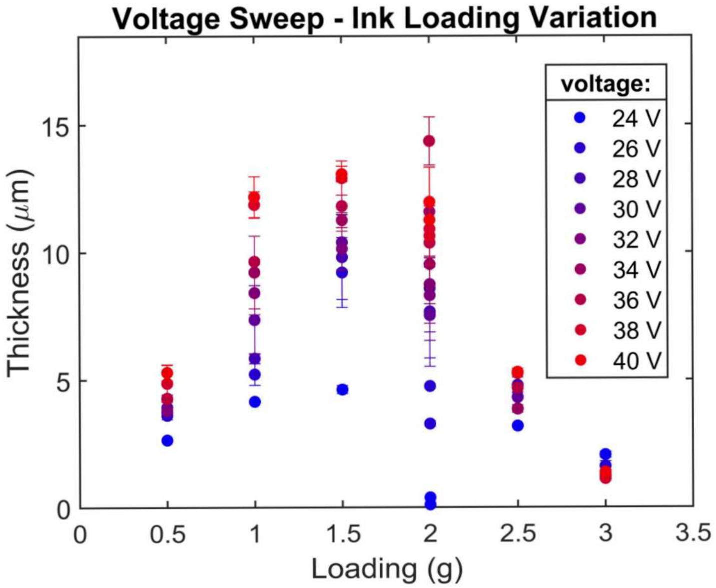
Support Slide 3: Process Drift

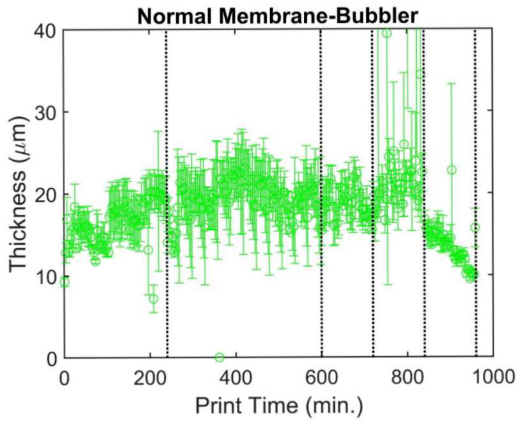




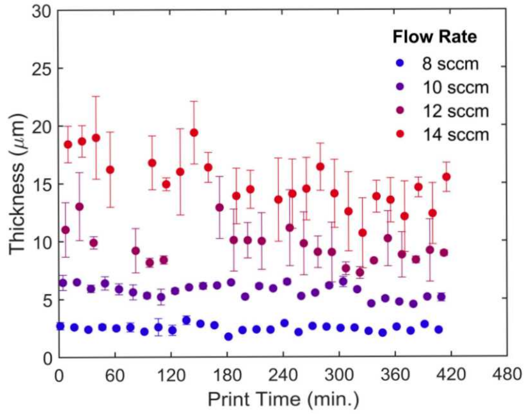




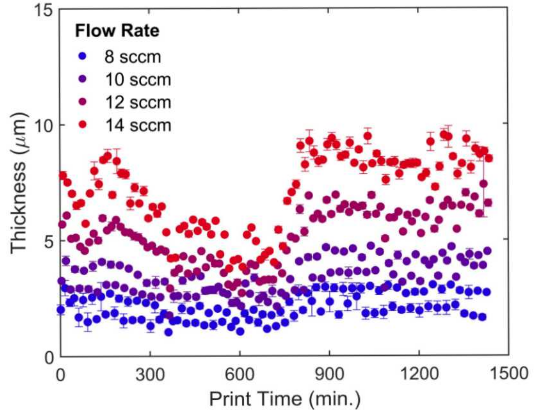




Polyimide

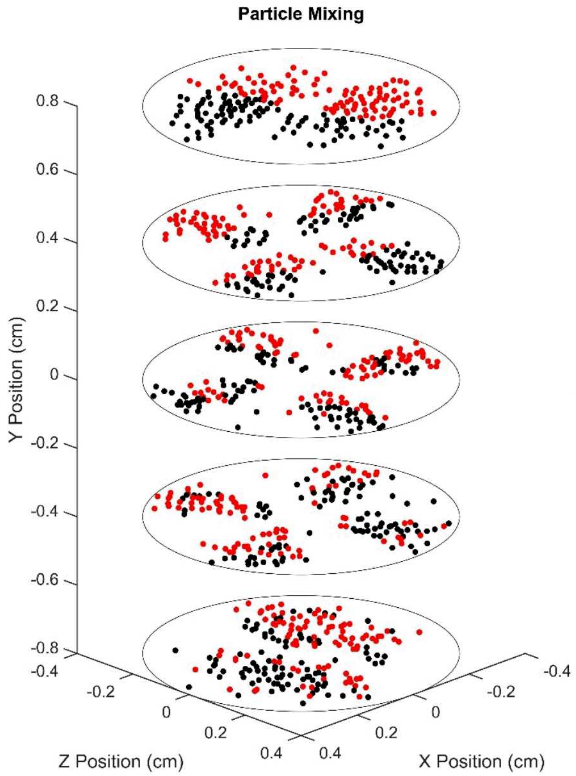


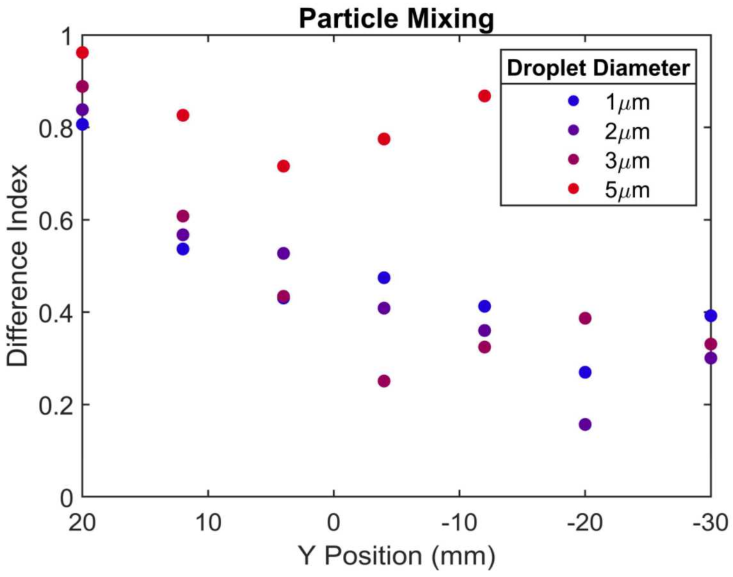
PMMA (44 V)

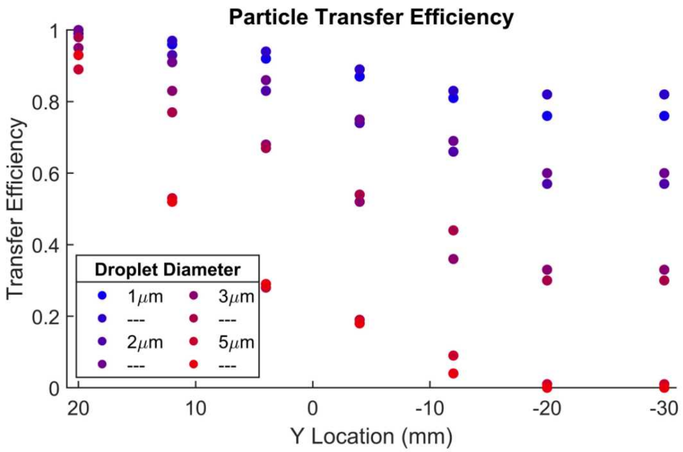


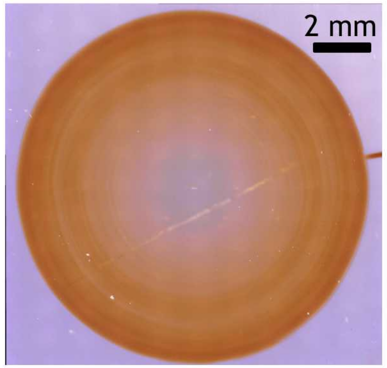
PMMA (40 V)

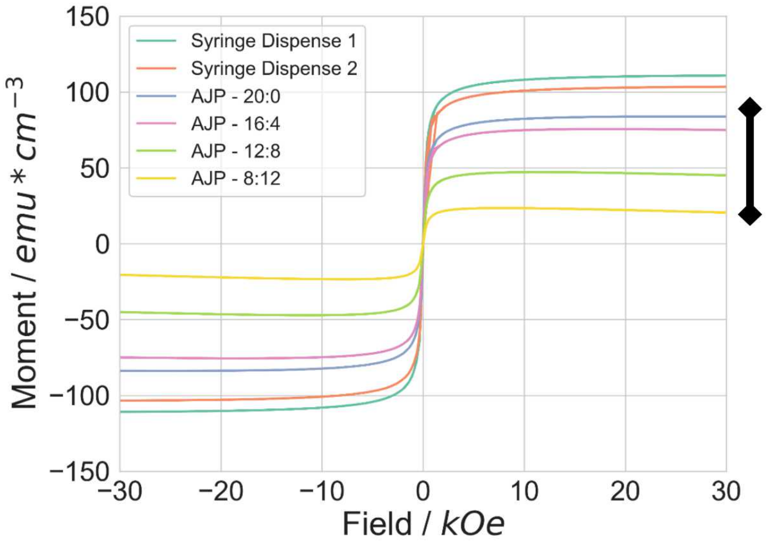
Support Slide 4: Multimaterial Printing











Sample (Fe_3O_4: PMMA)	Fe_3O_4 Loading (mg/cm^2)	St. Dev. (mg/cm^2)
AJP – 20:0	2.39	0.16
AJP – 16:4	1.55	0.08
AJP – 12:8	0.64	0.03
AJP – 8:12	0.35	0.02