SAND2019-14590PE

# Aerosol jet printing: From fundamentals to graded multimaterial patterning


Ethan B. Secor

Advanced Materials Laboratory, Sandia National Laboratories



Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.

# Acknowledgements

## My Background

- **Undergraduate:** Chemistry and Physics, Drake University, Des Moines, IA
- **Graduate:** Materials Science and Engineering, Northwestern University, Evanston, IL
- **Current:** Advanced Materials Laboratory, Sandia National Laboratories, Albuquerque, NM

Research in printing system design, materials development, and device integration

**Advanced Materials Lab:**

- Materials chemistry, ink formulation, and advanced manufacturing
- Collaboration with University of New Mexico students

Rebecca R. Tafoya

Bryan J. Kaehr

Adam W. Cook

P. Randall Schunk

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

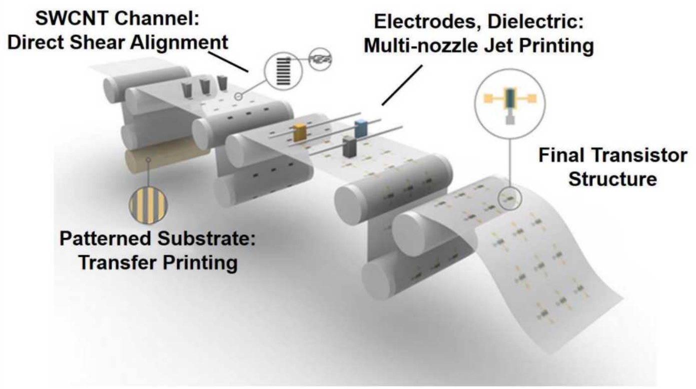
Funding generously provided by the Sandia LDRD program through the Truman Fellowship

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ___________

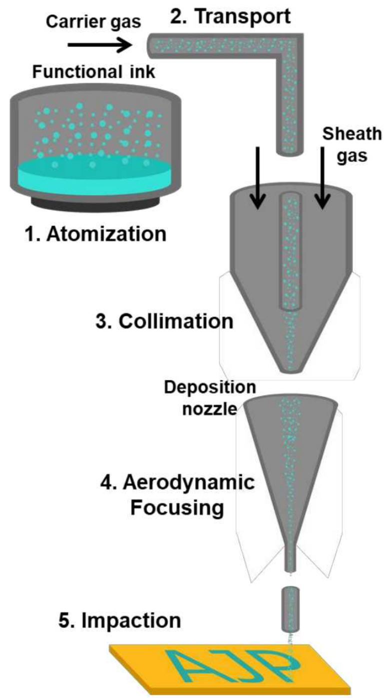
# Outline

## Printed Electronics

- General concept
- Application areas
- Printing methods
- Broader scope





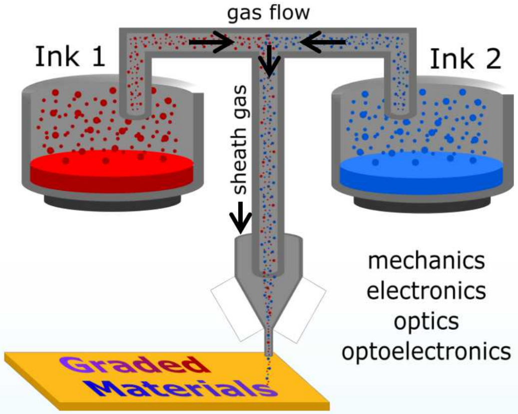



## Aerosol Jet Printing

- General mechanism
- Process models
- Print reliability
- Process monitoring
- Future work

## Multimaterial Patterning

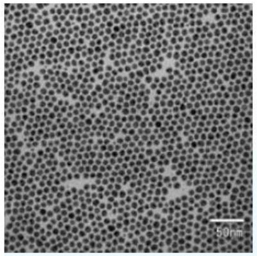
- Concept and motivation
- Printhead design
- Proof-of-concept
- Functional gradients
- Future work

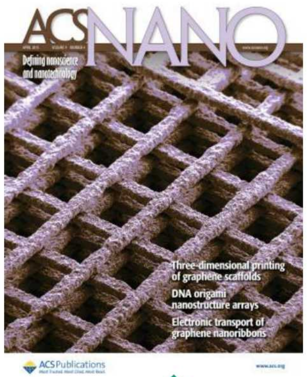


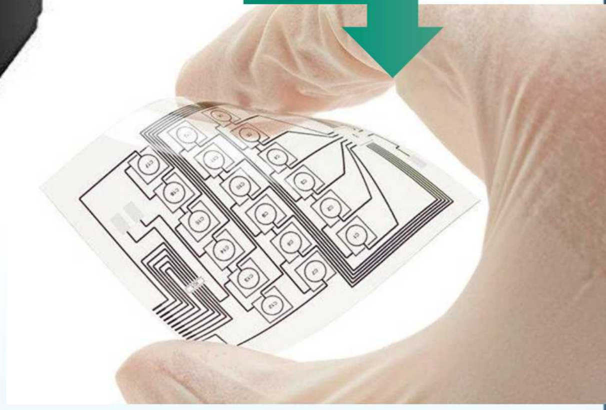
# Printed Electronics: Concept



Ag



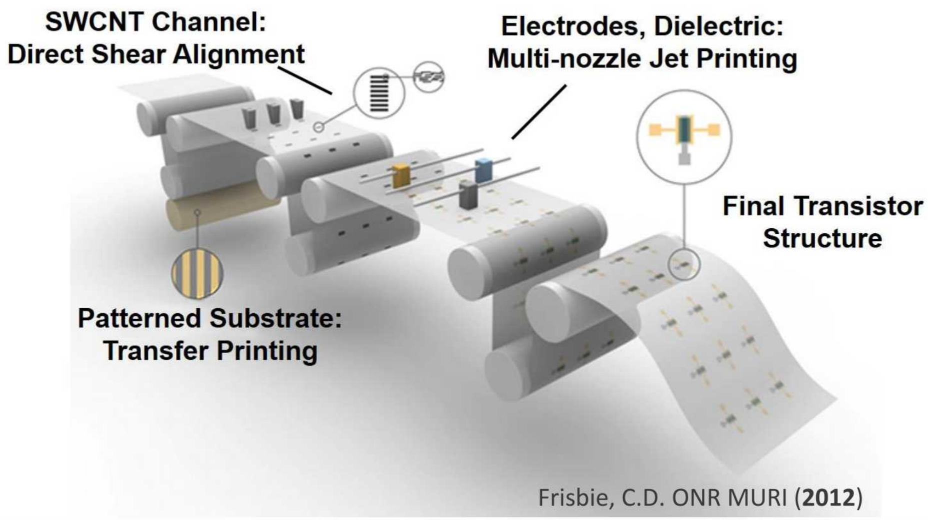



Leverage graphic arts printing methods for functional materials

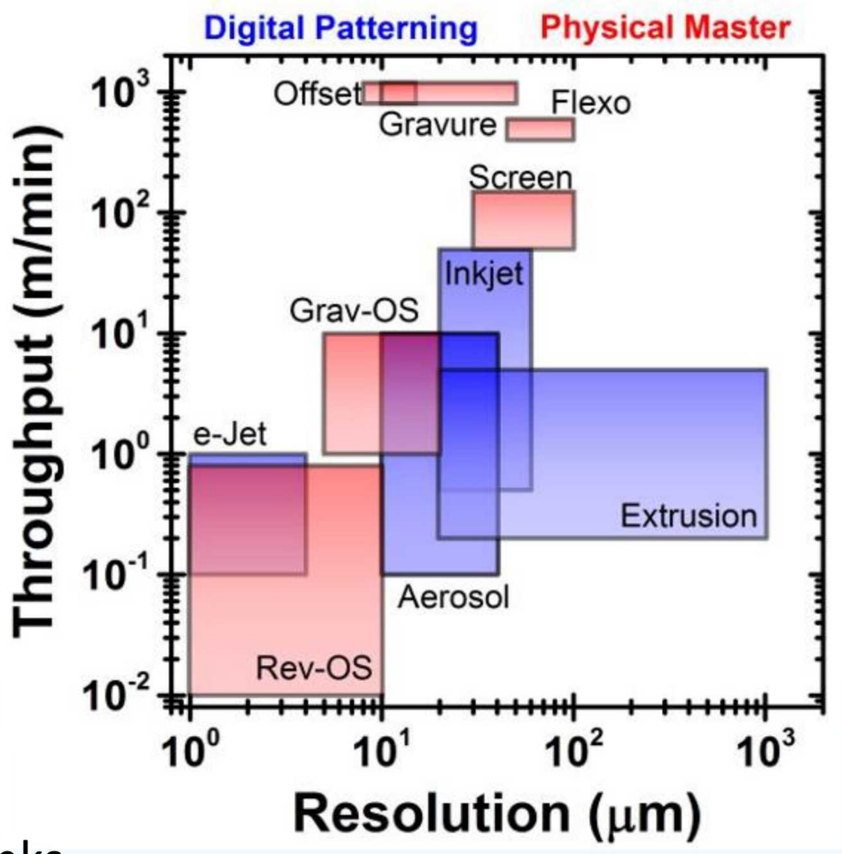
U.S. DEPARTMENT OF ENERGY
NNSA
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ___________
Sandia National Laboratories

# Printed Electronics: Methods

Master-based and digital deposition methods provide wide scope of scalability and customization




Frisbie, C.D. ONR MURI (**2012**)

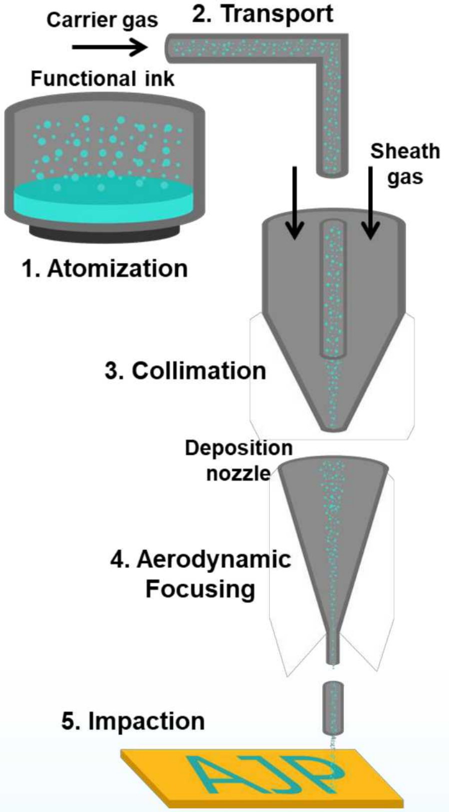


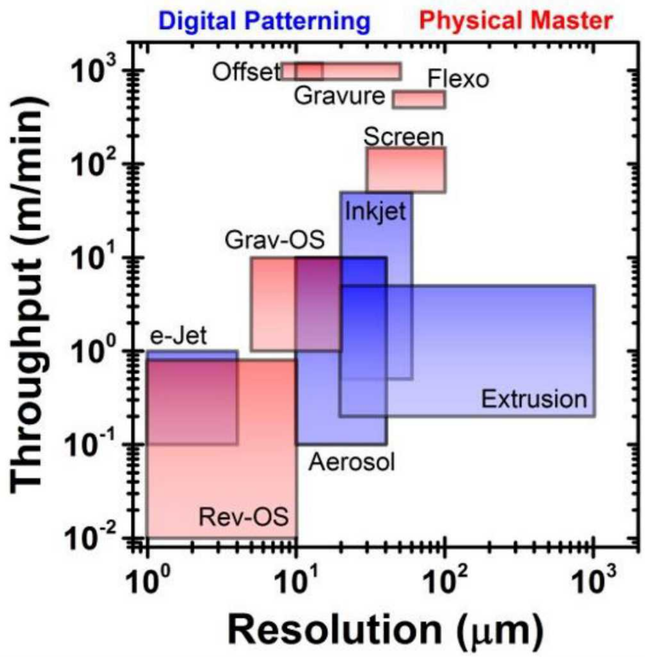

Liquid phase printing with functional inks
Hybrid integration offers microelectronics performance

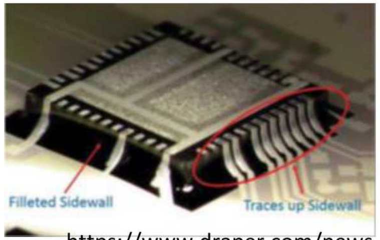
U.S. DEPARTMENT OF ENERGY
NNSA
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ________
Sandia National Laboratories

# Aerosol Jet Printing: Background

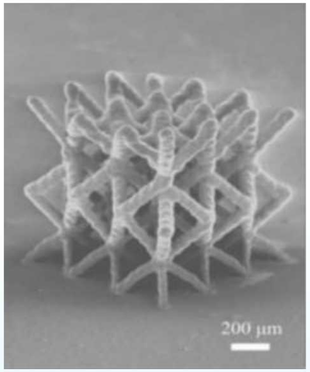
Aerosol jet printing (AJP) uses focused deposition of micron-scale ink droplets suspended in a carrier gas flow




https://www.draper.com/news


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

AJP is a versatile technology for prototyping functional devices

Benefits:

- Digital
- Non-contact
- High-resolution
- Versatile

Limitations:

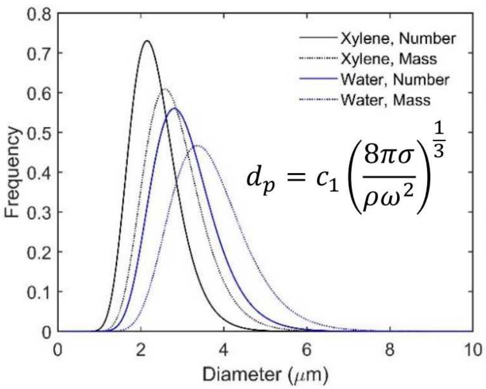
- Process drift
- Low throughput

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ____________

# Aerosol Jet Printing: Physics

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

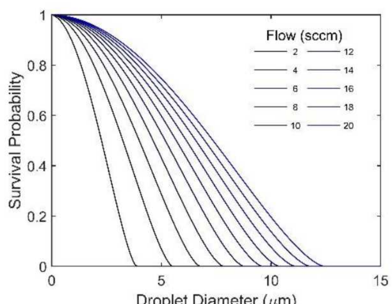
### 1. Atomization




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

### 2. Transport

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

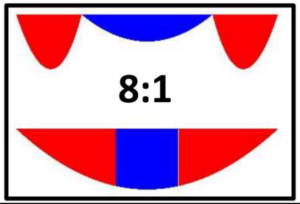



$$where\ \alpha = \left(\frac{3Lu_{TS}}{8u_aR}\right)^{\frac{1}{3}}; \qquad \beta = \sqrt{1-\alpha^2};$$

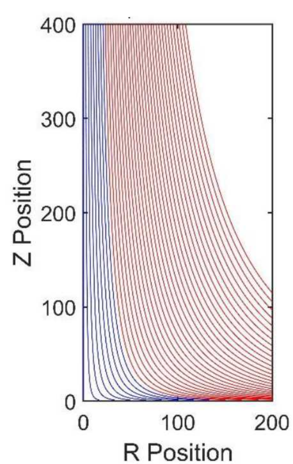
### 3. Collimation

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

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



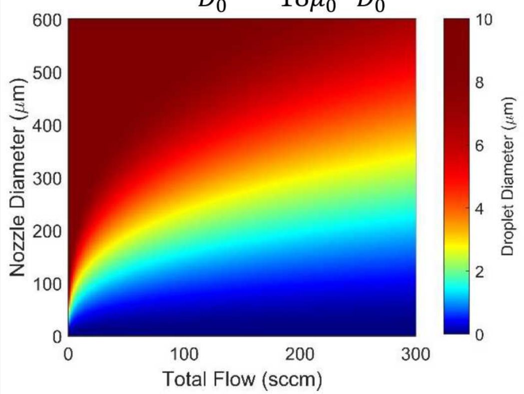

### 5. Impaction

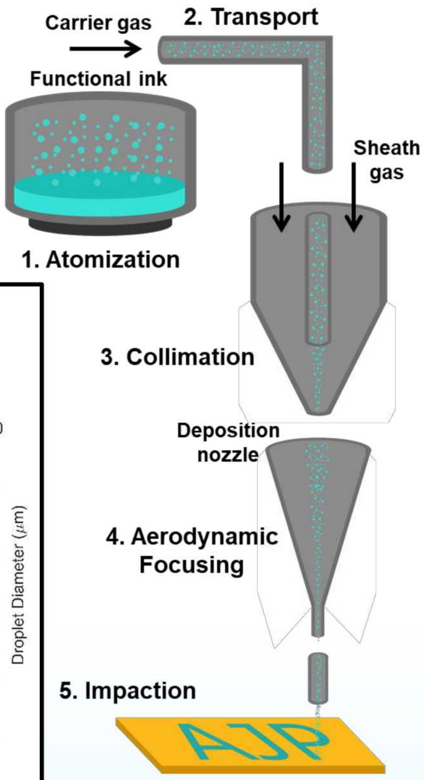



$$r_0^* * \exp[-p] * \left\{\cosh(pq) + \frac{1}{q}\sinh(pq)\right\}$$

### 4. Focusing

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



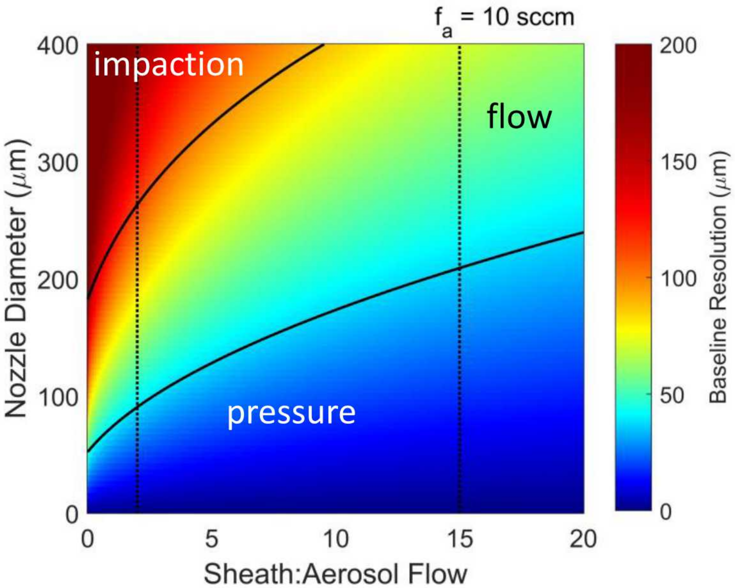

Fundamental description guides printer and process design

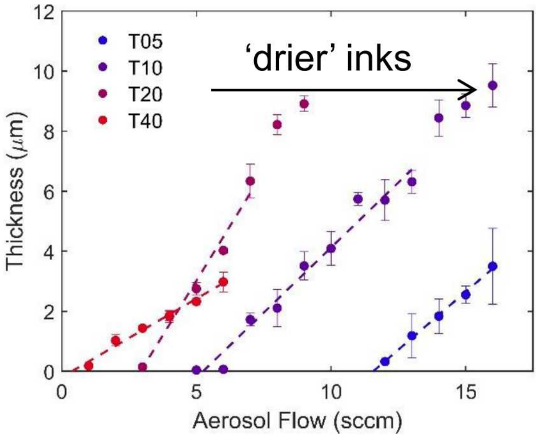
U.S. DEPARTMENT OF ENERGY
NNSA
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ________

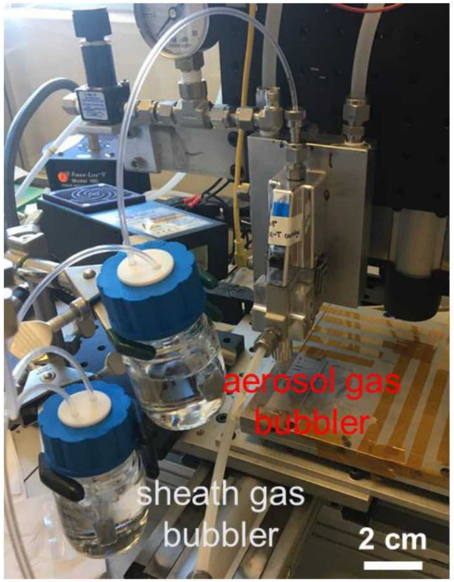
Secor, E.B. *Flex. Print. Electron.* (**2018**) 3, 035002.

# Aerosol Jet Printing: Physics

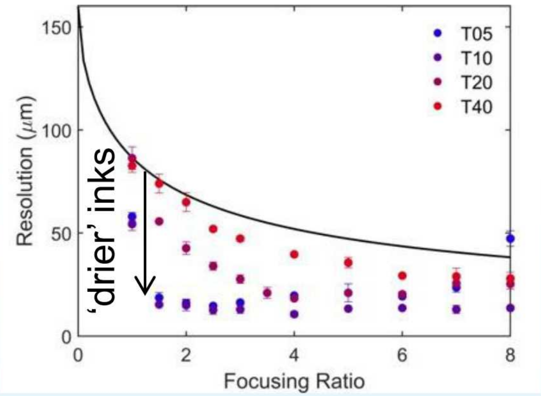
Models identify factors limiting print quality and resolution

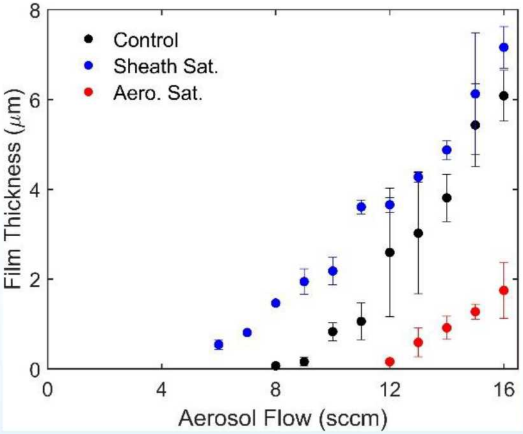



More volatile inks deviate from expected behavior



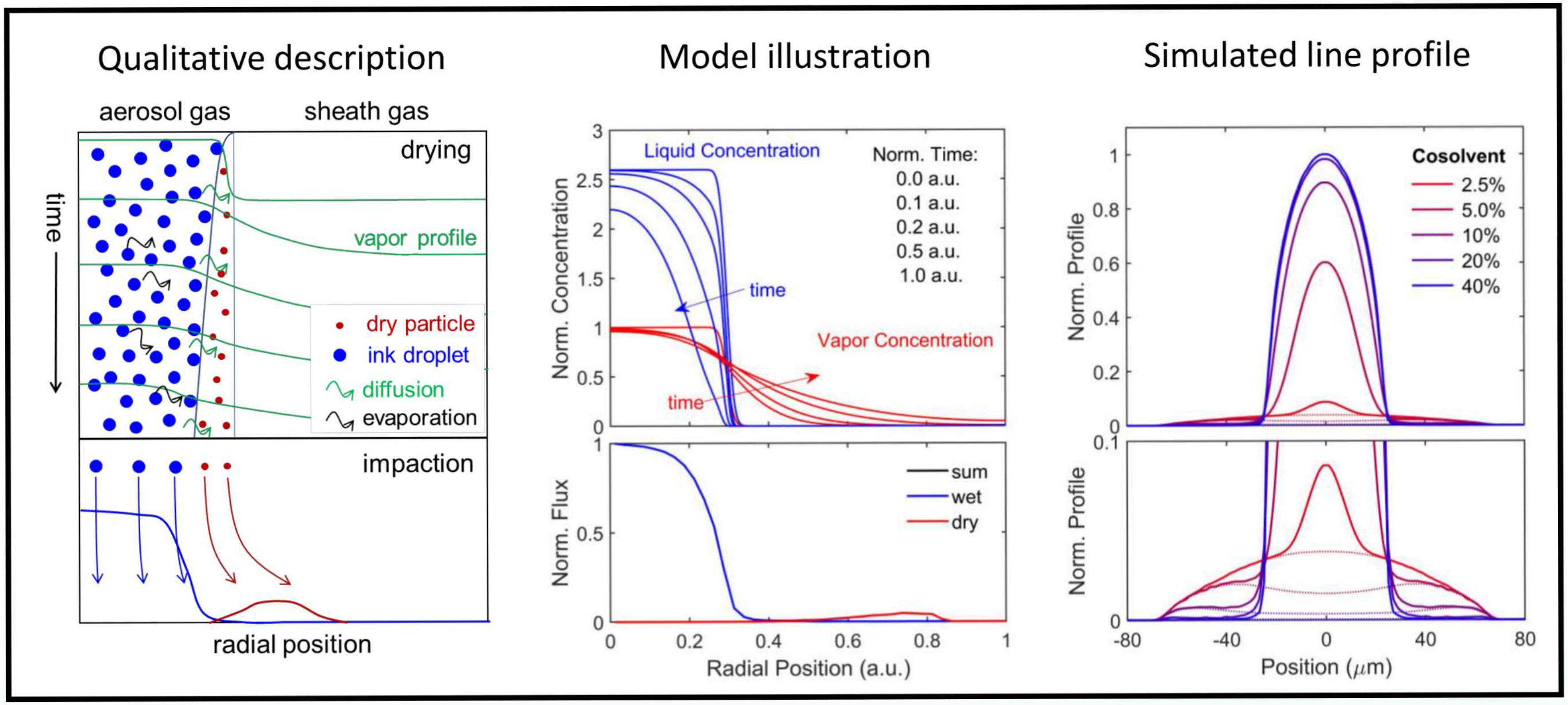




Transport effects within the printhead can strongly effect process outcomes

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ___________

# Aerosol Jet Printing: Physics

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



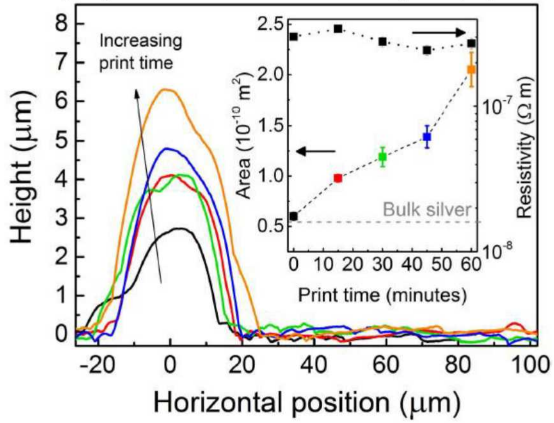

- Radial drying within the printhead is induced by the sheath gas
- Peripheral droplets can be completely dried before vapor saturates

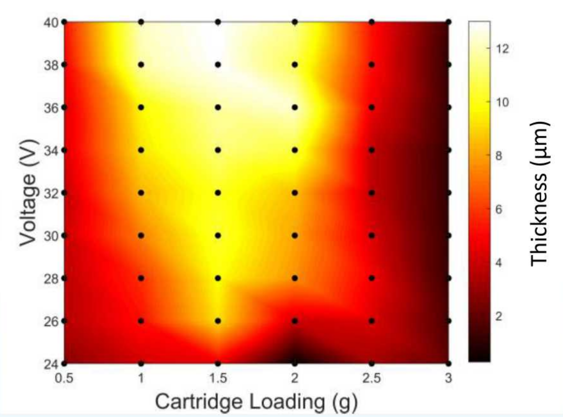
U.S. DEPARTMENT OF ENERGY
NNSA
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ________
Sandia National Laboratories

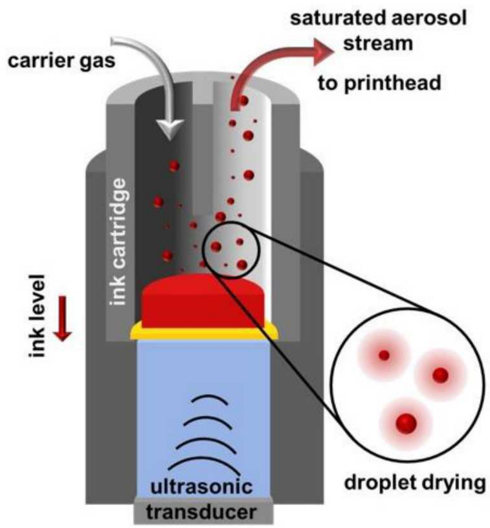
# Aerosol Jet Printing: Reliability

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

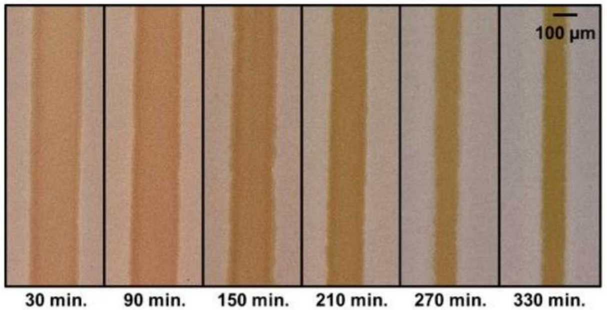
Smith, M., et al. *Flex. Print. Electron.* (**2017**) 2, 015004.

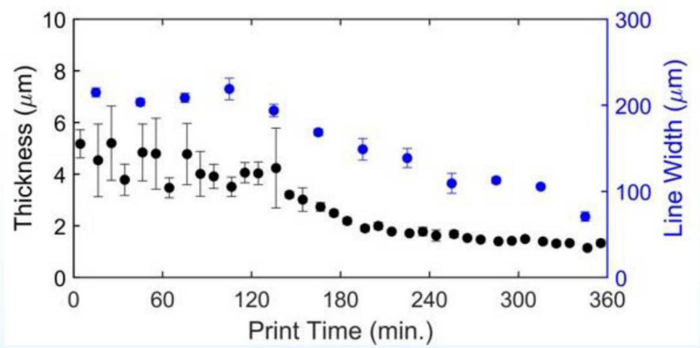



Decrease in both deposition rate and line width over 6 hours of printing



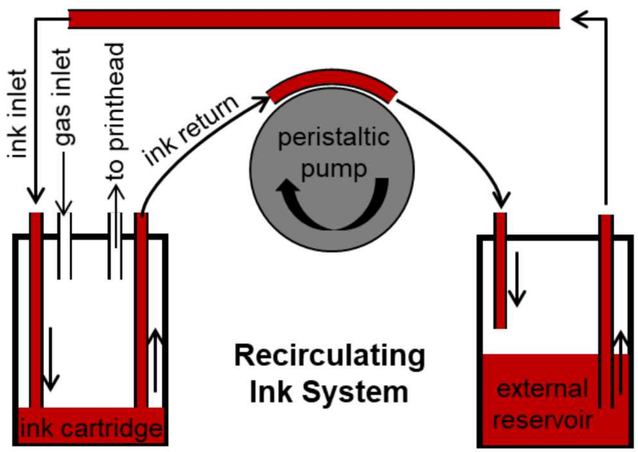




Ink level reduction leads to changes in atomization

U.S. DEPARTMENT OF ENERGY
NNSA
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ____
Sandia National Laboratories

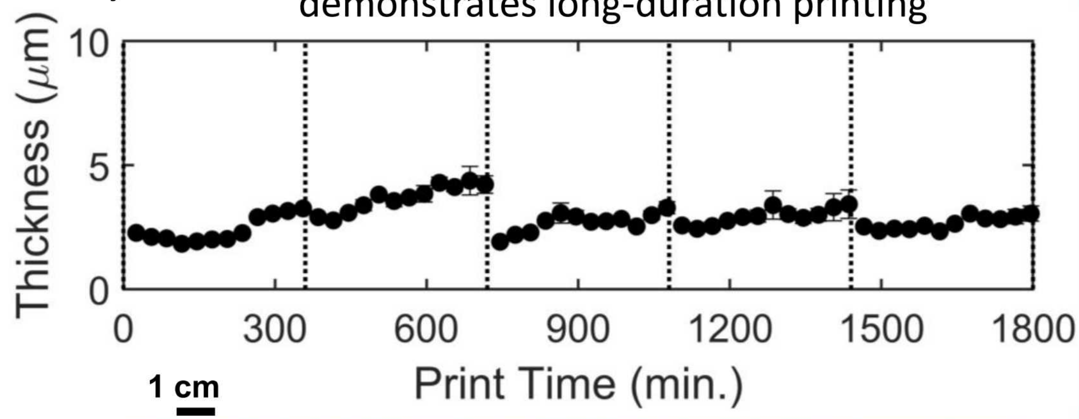
# Aerosol Jet Printing: Reliability

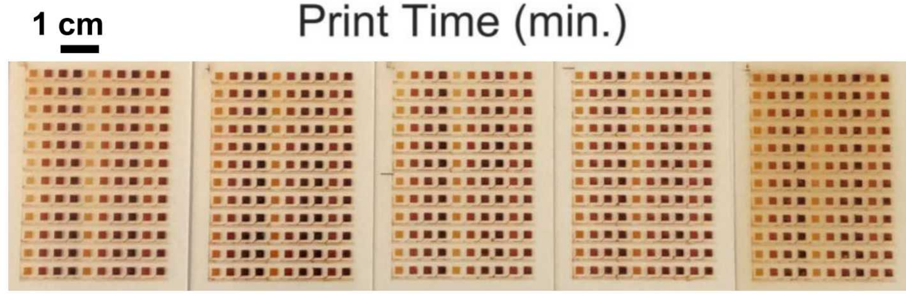
Custom system design provides flexibility to address causes of printing drift

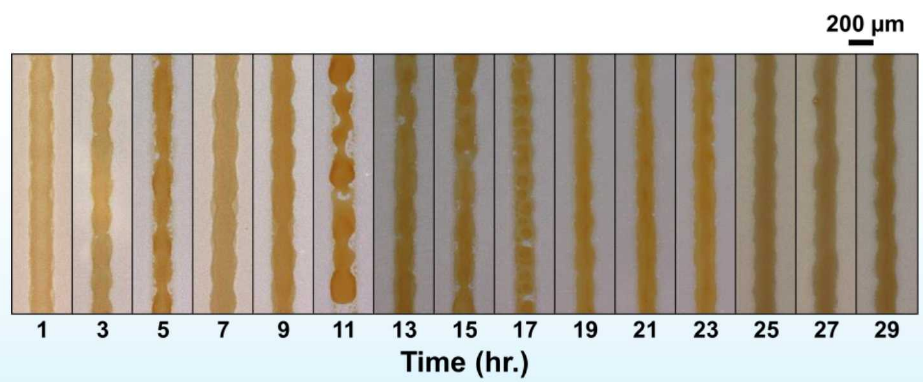



- Maintain consistent ink level within cartridge
- Buffer changes in composition due to drying


30 hr print test over 5 sessions demonstrates long-duration printing



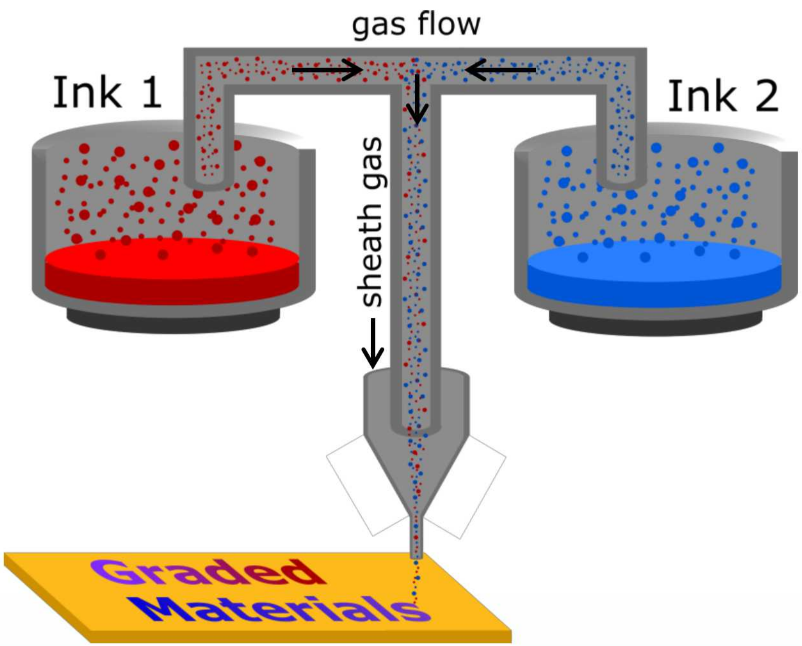




Recirculating ink cartridge shows promise for extending print duration

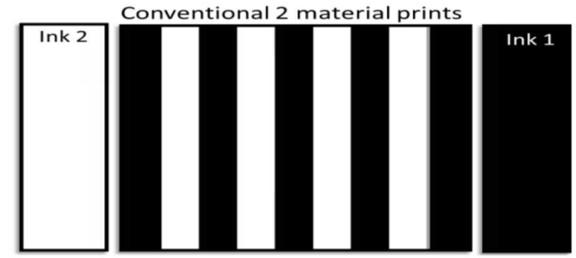
U.S. DEPARTMENT OF ENERGY
NNSA
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology & Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ________
Sandia National Laboratories

# Multimaterial Printing: Concept

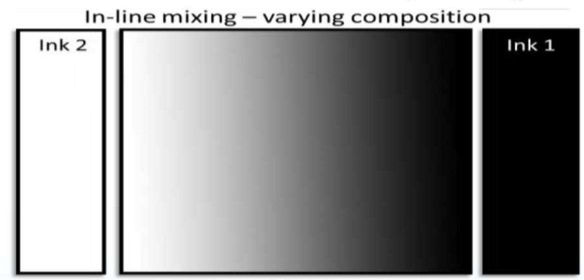
In-line mixing of aerosols upstream of the printhead for simultaneous codeposition of distinct inks




Binary multimaterial printing




Graded multimaterial printing

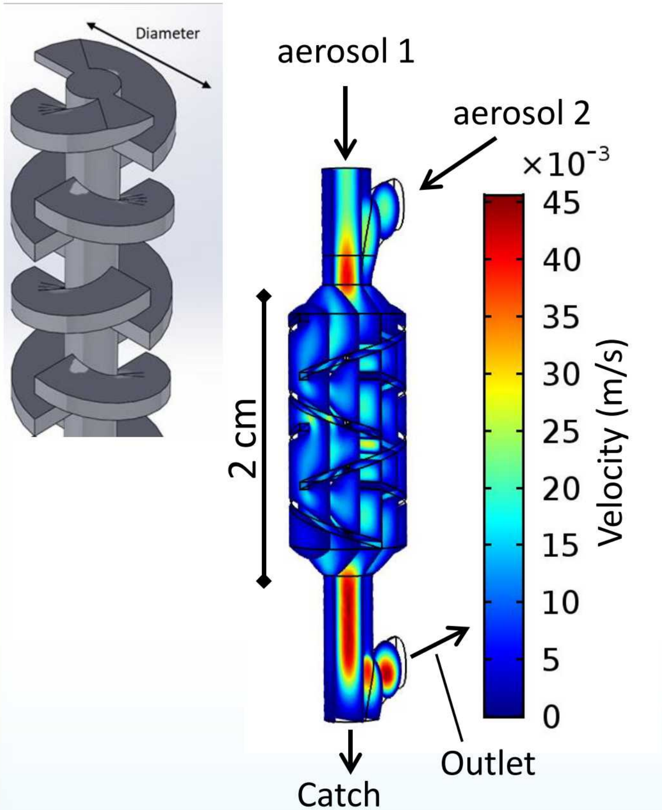


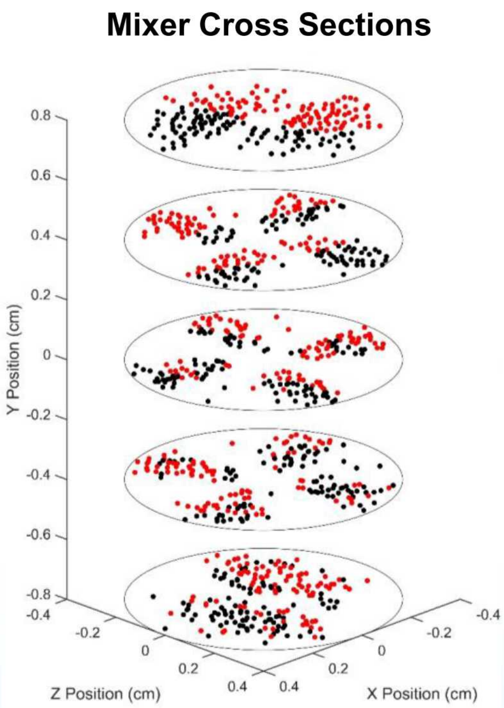

Unique multimaterial printing platform for graded patterning with micron-scale mixing, digital control

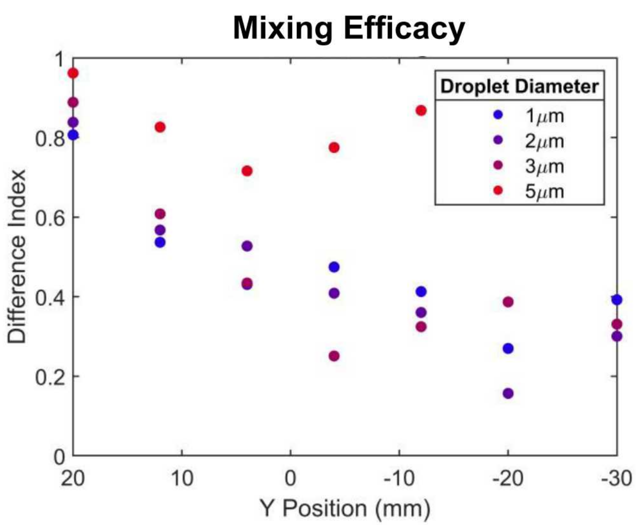
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ___________

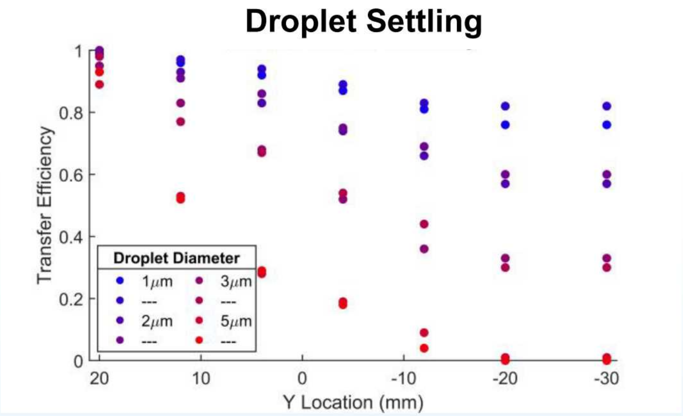
# Multimaterial Printing: Printhead Design

Laminar static mixers modeled for aerosol applications using COMSOL to design custom mixing printhead



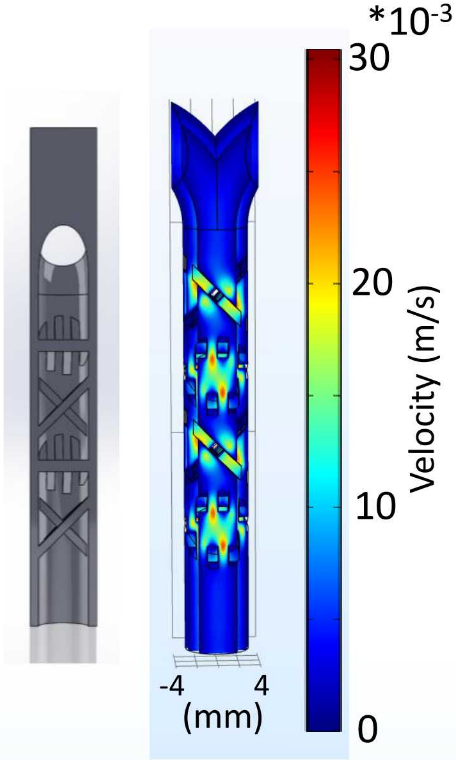



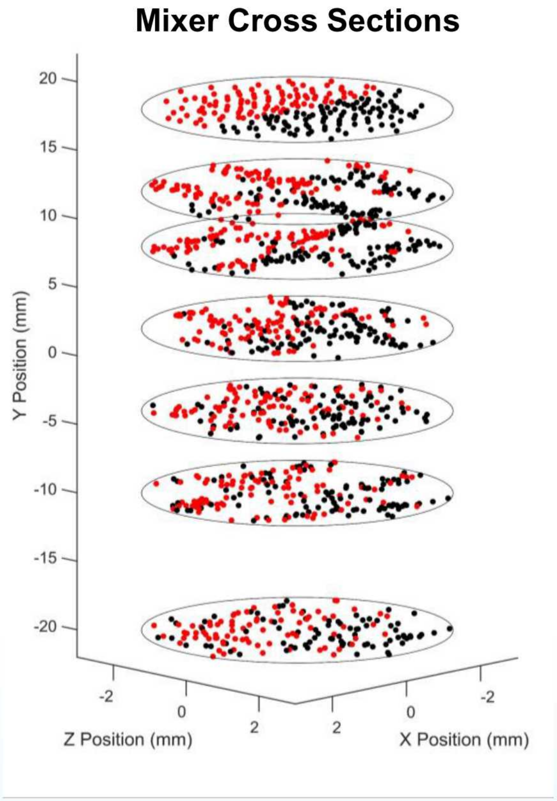

A laminar static mixer provides effective mixing of micron-scale aerosol droplets

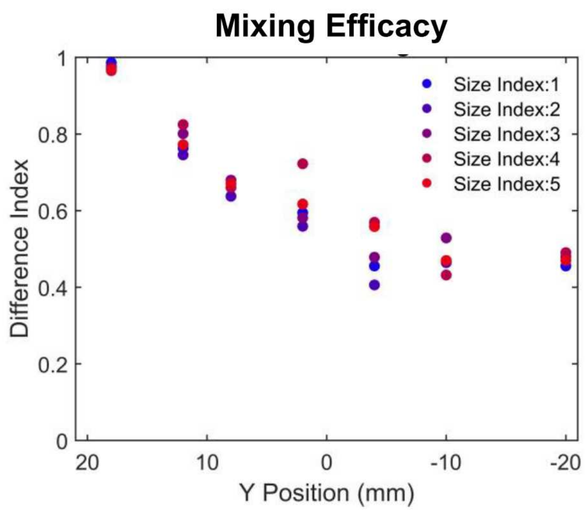
Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ____________

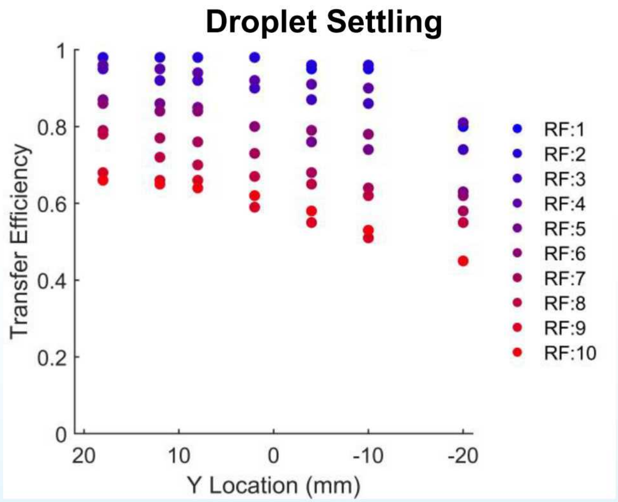
# Multimaterial Printing: Printhead Design

Modeling streamlines design optimization under mixing efficacy, settling, and volume constraints




3D-printing provides simple route to experimentally test mixer designs

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ___________

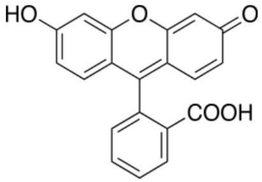
# Multimaterial Printing: Proof of Concept

Initial demonstration with optical materials for straightforward characterization

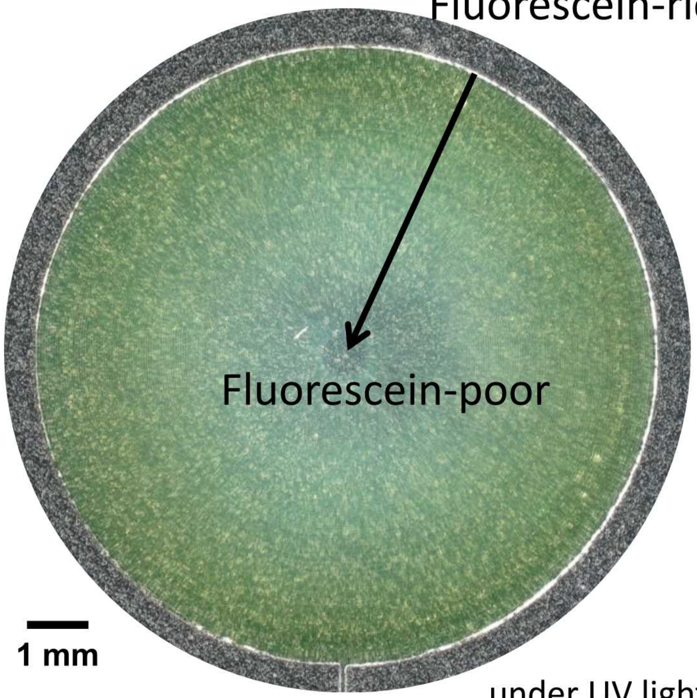
Ink 1: Norland optical adhesive NOA 61

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

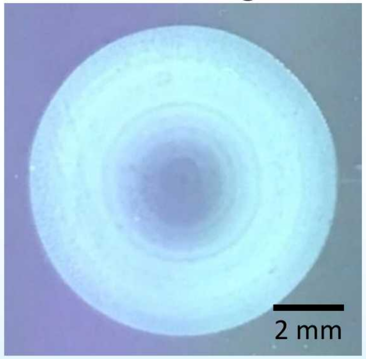
- Fluorescence microscopy to measure amount of fluorescein-containing ink
- Thickness measurement for overall deposition rate
- Calibration required to deconvolute thickness and composition

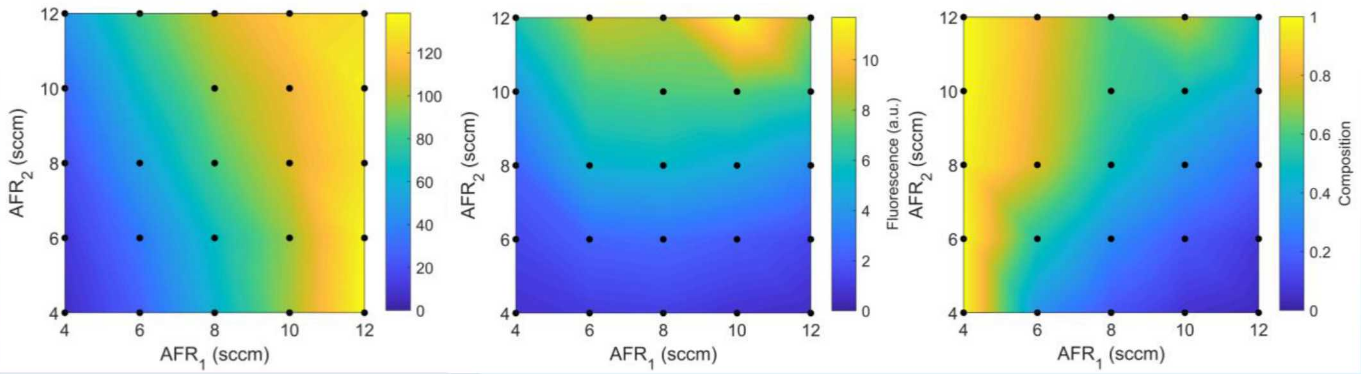



Fluorescein dye




under UV light



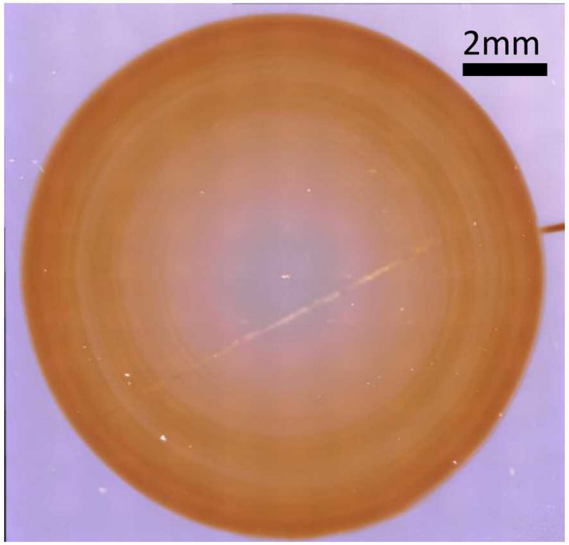



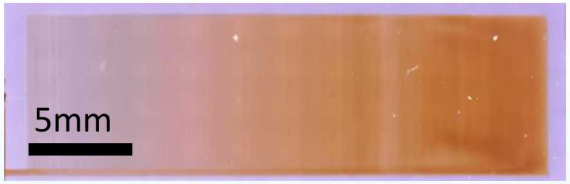

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ____________

# Multimaterial Printing: Functional Gradients

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

Magnetite composite

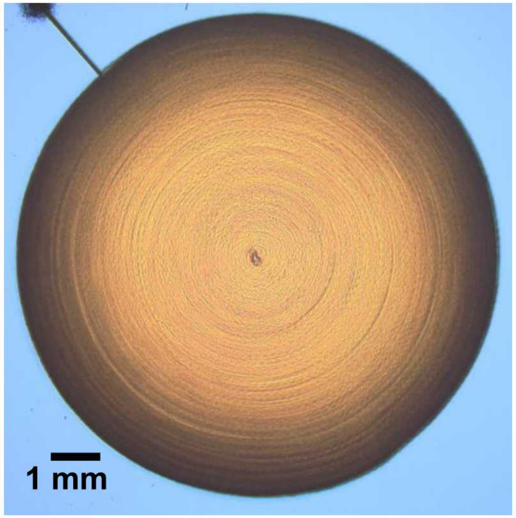



Broad scope of compatible materials

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

Graphene/magnetite composite




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

Rebecca R. Tafoya

# Thanks for your attention!

Bryan J. Kaehr

Adam W. Cook

LABORATORY DIRECTED RESEARCH & DEVELOPMENT

Contact: ebsecor@sandia.gov

P. Randall Schunk

Thanks to Rebecca R. Tafoya, Adam W. Cook, Bryan J. Kaehr, and P. Randall Schunk

Funding from the Sandia LDRD program through the Truman Fellowship

Sandia National Laboratories is a multimission laboratory managed and operated by National Technology &Engineering Solutions of Sandia, LLC, a wholly owned subsidiary of Honeywell International Inc., for the U.S. Department of Energy's National Nuclear Security Administration under contract DE-NA0003525.
SAND No. ____________