# Engineering Controls for Additive Manufacturing/Three-Dimensional (3D) Printing

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BSC Meeting
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National Institute for Occupational Safety and Health (NIOSH)
Division of Applied Research and Technology (DART)

# Outline

- What is additive manufacturing (AM)?
- Different AM technologies
- Materials
- Industry growth
- Studies about 3D printer emissions
- New NIOSH engineering control study of 3D printing/AM

Photo Credit: Additive Manufacturing Magazine

# What is Additive Manufacturing/3D Printing

- Joining materials to make objects from 3D model data, usually layer upon layer (American Society for Testing and Materials ASTM F2792).

Subtractive Manufacturing

Photo: Fabricatingandmetalworking.com

Additive Manufacturing

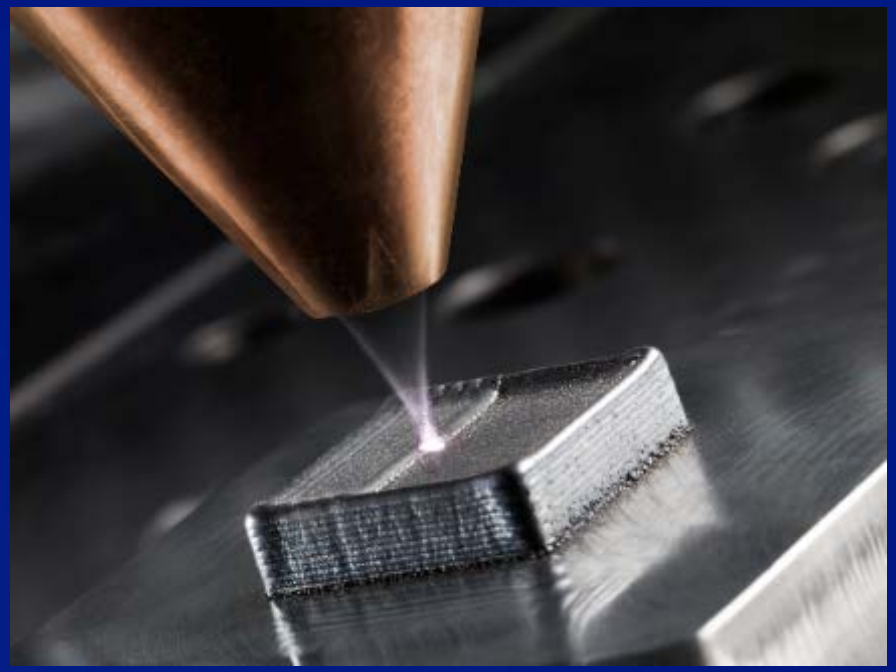


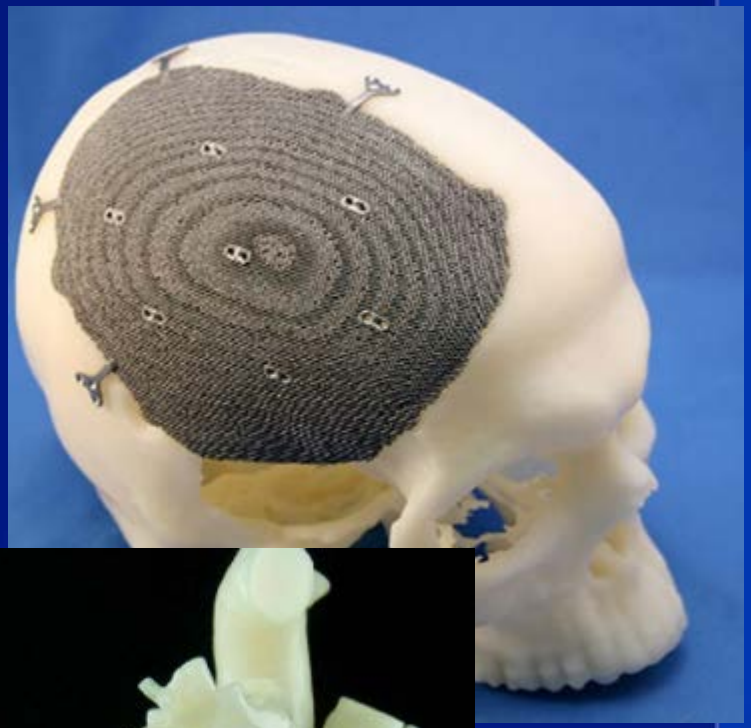
Photo: Canadianmetalworking.com

# Advantages to AM/3D Printing

- **Decreased design to manufacturing times**
  - 3D printers can produce a part immediately after engineers create the 3D computer-aided design (CAD) model.
- **Decreased tool cost**
  - The projected cost of automotive tooling will reach $15.2 billion dollars by 2018 according to MoldMaking Technology Magazine.
- **Less waste: 3D printing only uses the material needed**
- **Reduced energy consumption**
- **Fewer constraints can lead to stronger and lighter parts**
- **Assemblies can be printed using few parts**
- **Rapid prototyping**

# Medical Applications

- Tissue and organ fabrication
- Custom Prosthetics
- Implants
- Anatomical models
- Pharmaceutical drug delivery



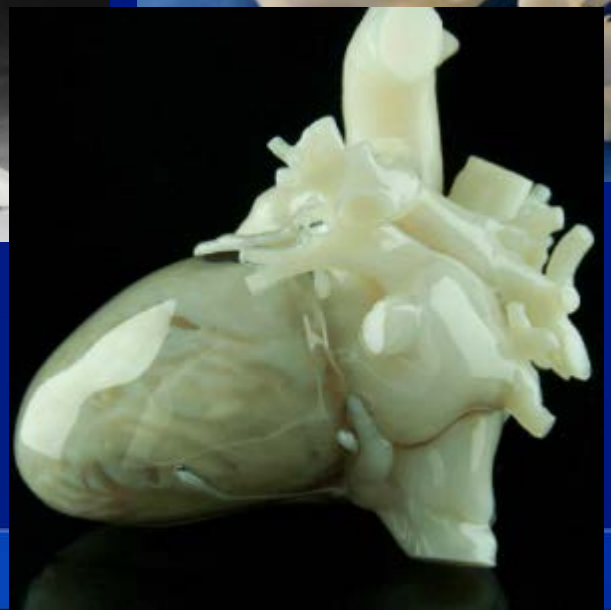


Photo Credits: 3dprintingindustry.com

# Dental Applications

- Digital orthodontics
- Biocompatible resins
- Digital dentures
- Dental implants
- Crowns

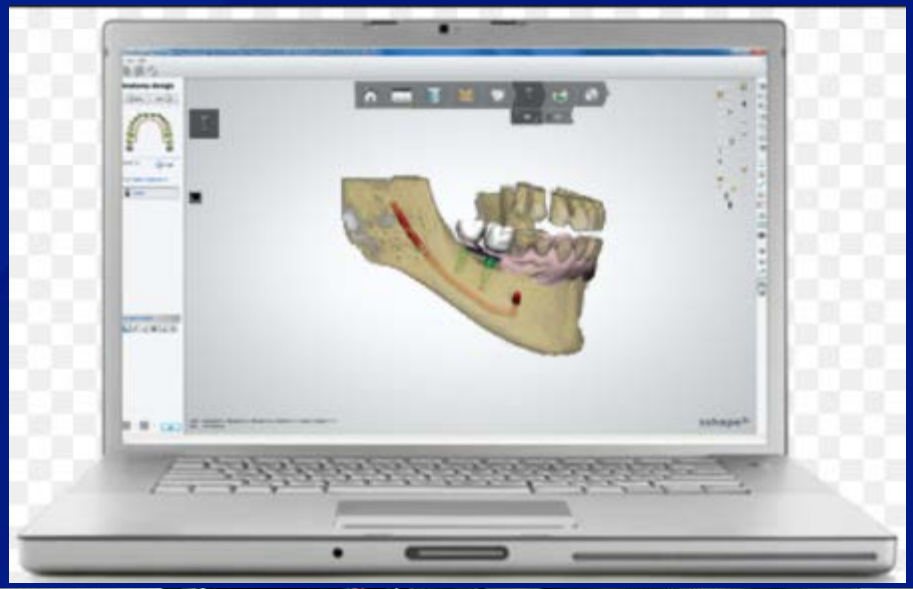


Photo Credits: Stratasys.com

# Aerospace Applications

- According to Boeing, the F/A-18 Super Hornet has approximately 150 parts in the forward fuselage area that have been produced through selective laser sintering.
- More than 20,000 3D printed plastic parts are currently in use in Boeing aircraft.
- Alcoa recently opened a 3D printing production facility for aerospace parts printed from titanium, nickel, and aluminum powders. Source: Alcoa Inc.
- Honeywell recently opened an aluminum 3D printing facility in Phoenix. Source: Honeywell International Inc.

# Defense

- According to the company website, the Raytheon Missile Systems division has already 3D printed almost every part of a guided weapon, including rocket engines, guidance and control systems components, fins, and more.
- Body armor
- Drones
- Housing

Photo Credit: Raytheon Company

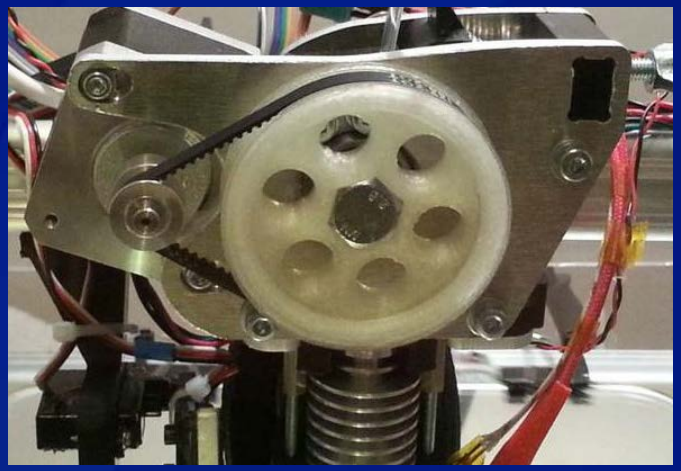
# Other Industries

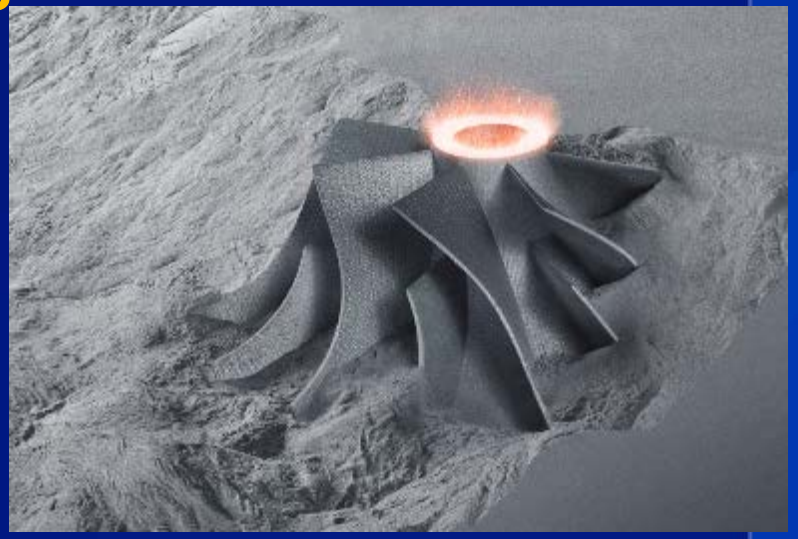
- Automotive
- Fashion
- Art
- Food
- Architecture
- Consumer Goods
- Consumer Electronics
- Education
- Mold Industry
- Archeology

Photo credit: www.3ders.org

# Materials

- Plastics
- Metals
- Alloys
- Sugar
- Silicone
- Ceramics
- Composites
- Glass
- Concrete
- Food





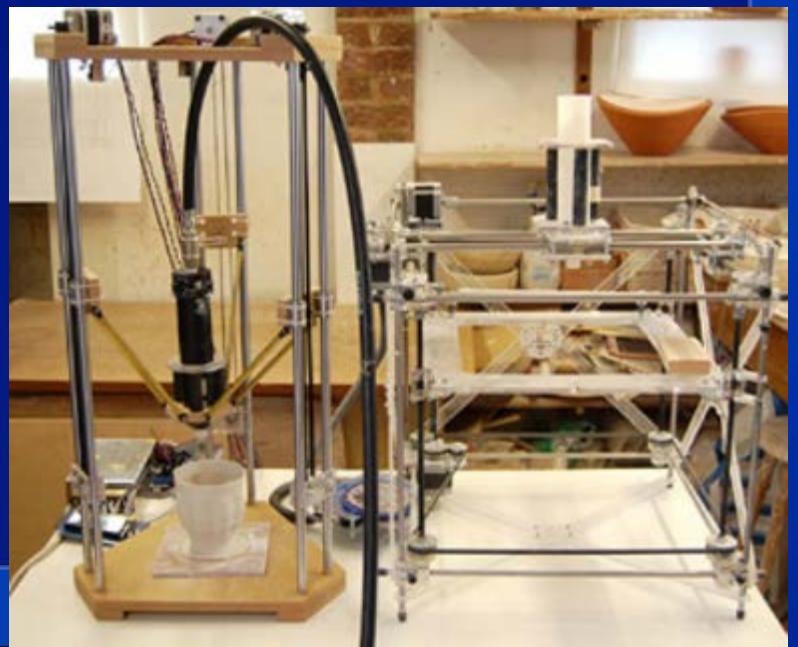


Photo Credits: 3dprintingindustry.com

# Fused Deposition Modeling (FDM), Fused Filament Fabrication (FFF)

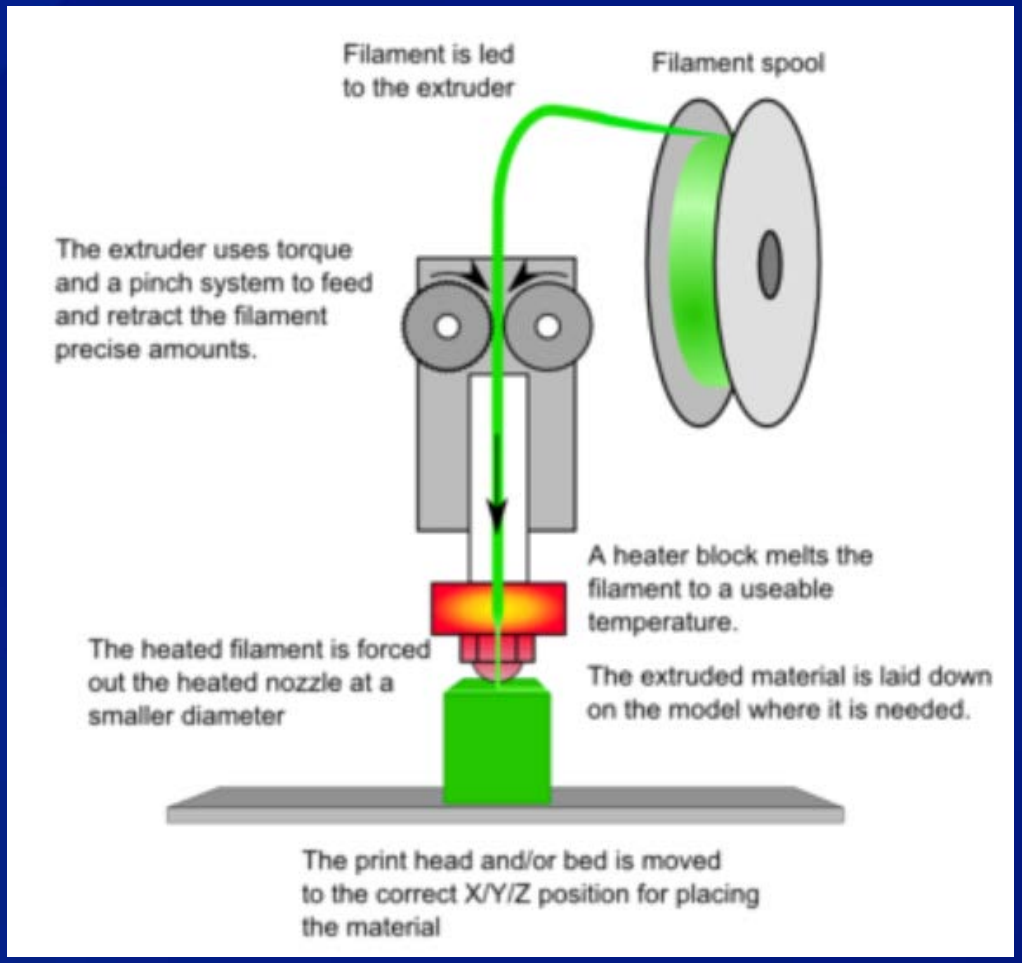
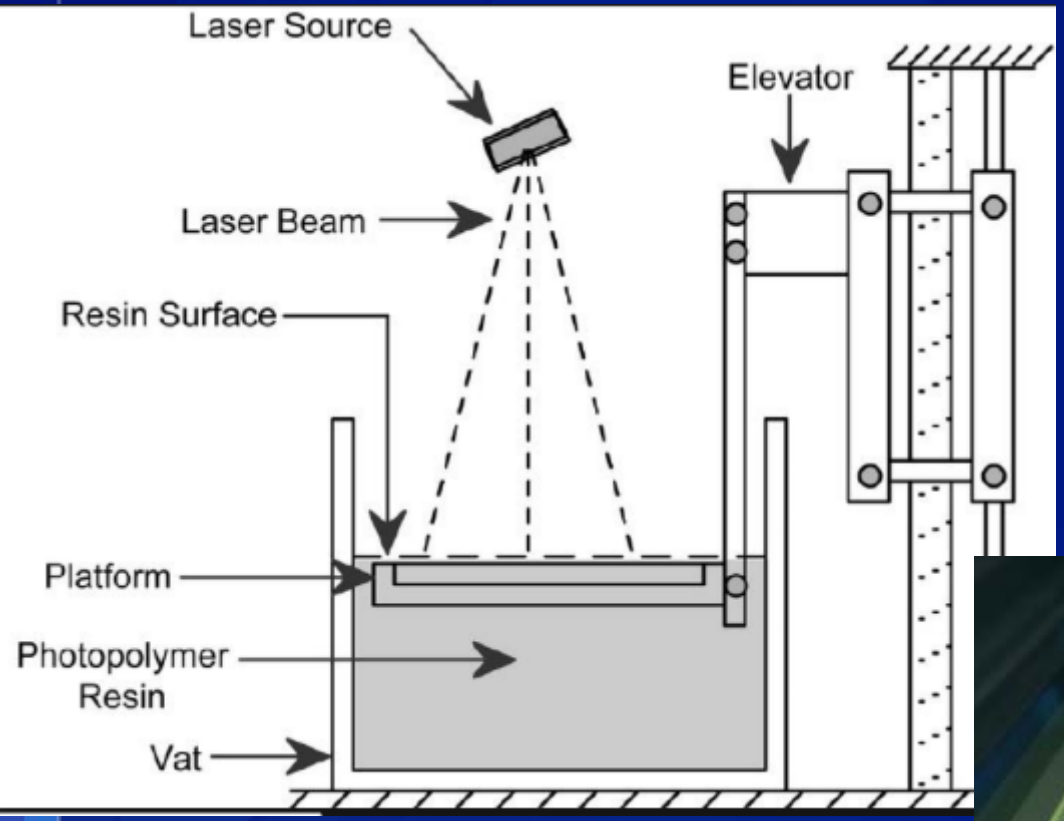
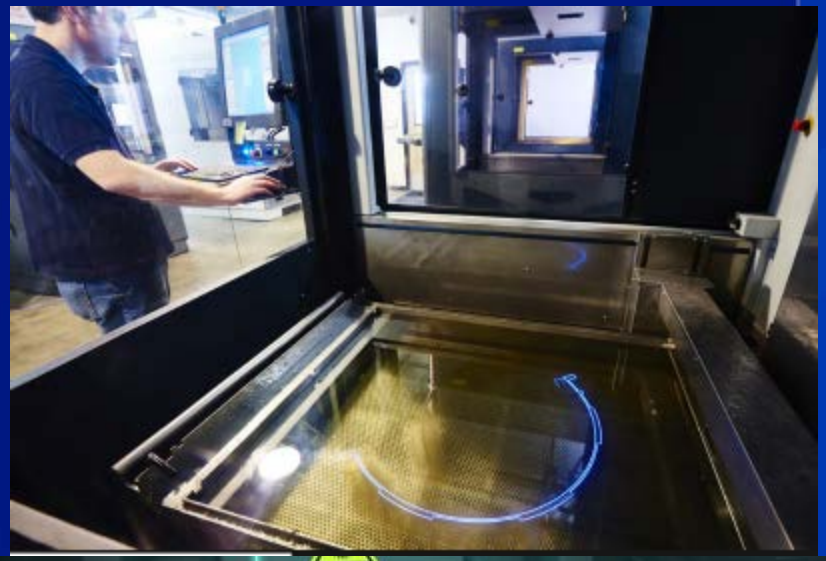




Photo Credits: 3dprinting.com

# Stereolithography (SLA)



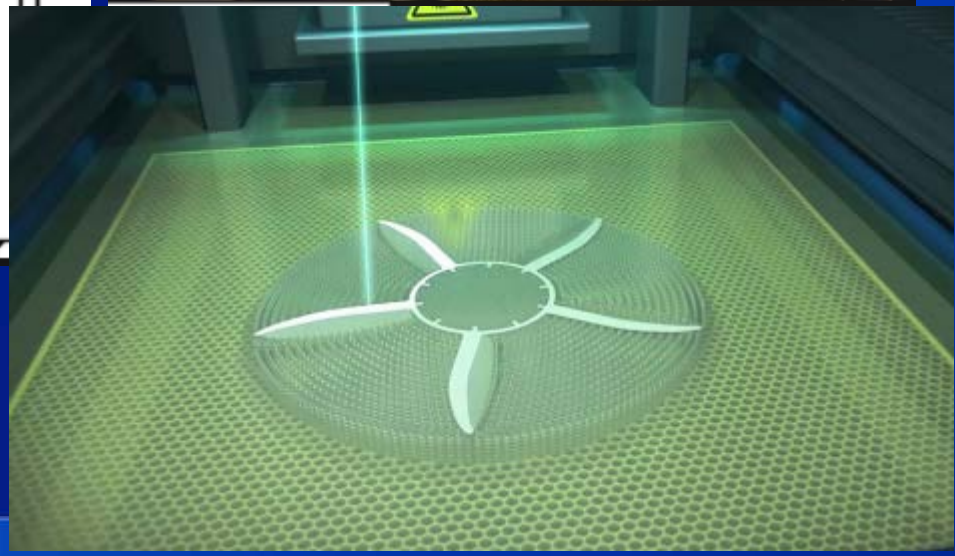


Photo Credit: stratasysdirect.com; whiteclouds.com

# Selective Laser Sintering (SLS or LS)

- SLS uses a high power laser to fuse plastic powders to form 3D shapes.

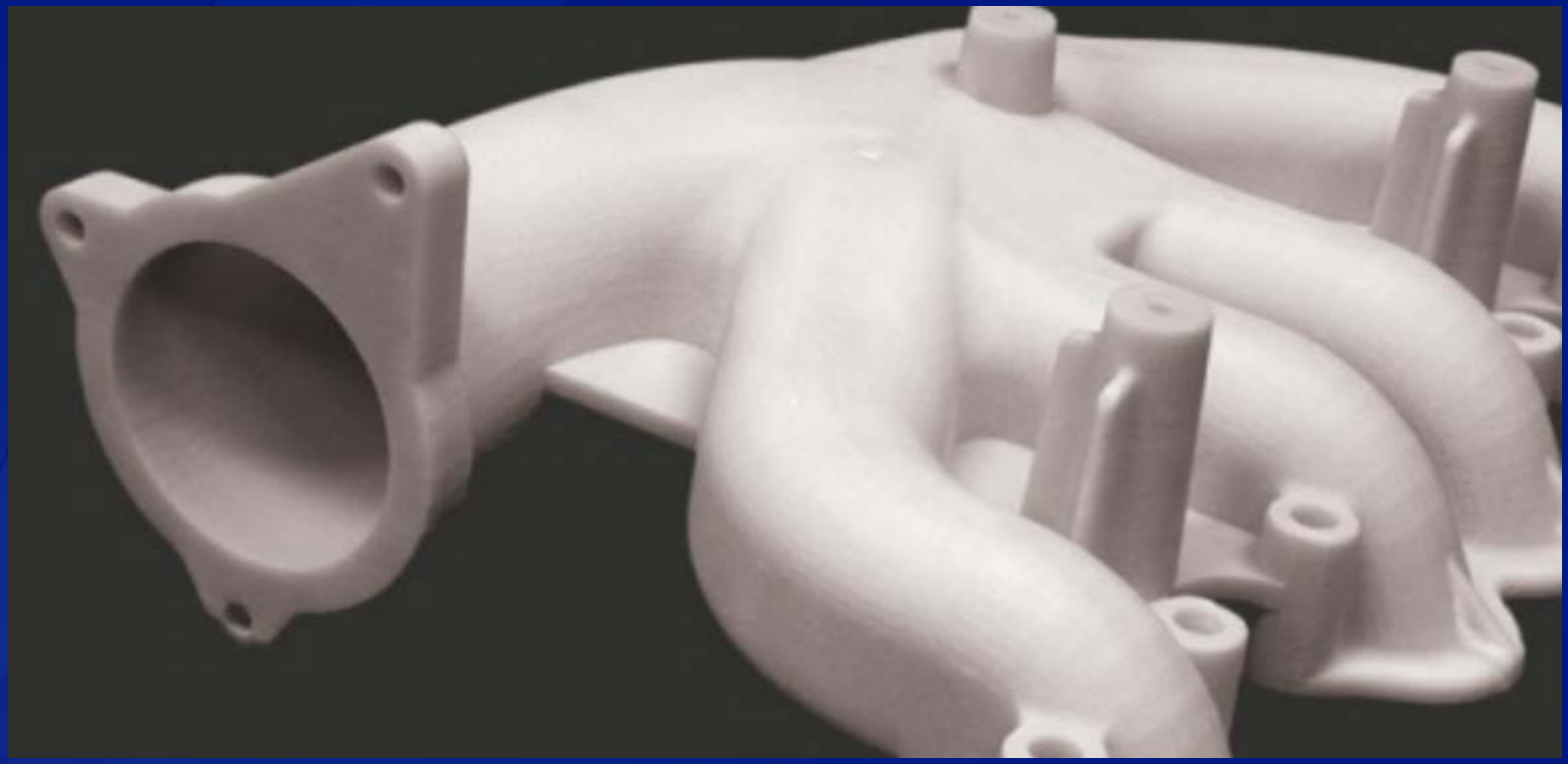


Photo Credit: 3D Systems Inc.

# Direct Metal Laser Sintering (DMLS)

- DMLS uses a high power focused laser to fuse metal powder into 3D shapes.

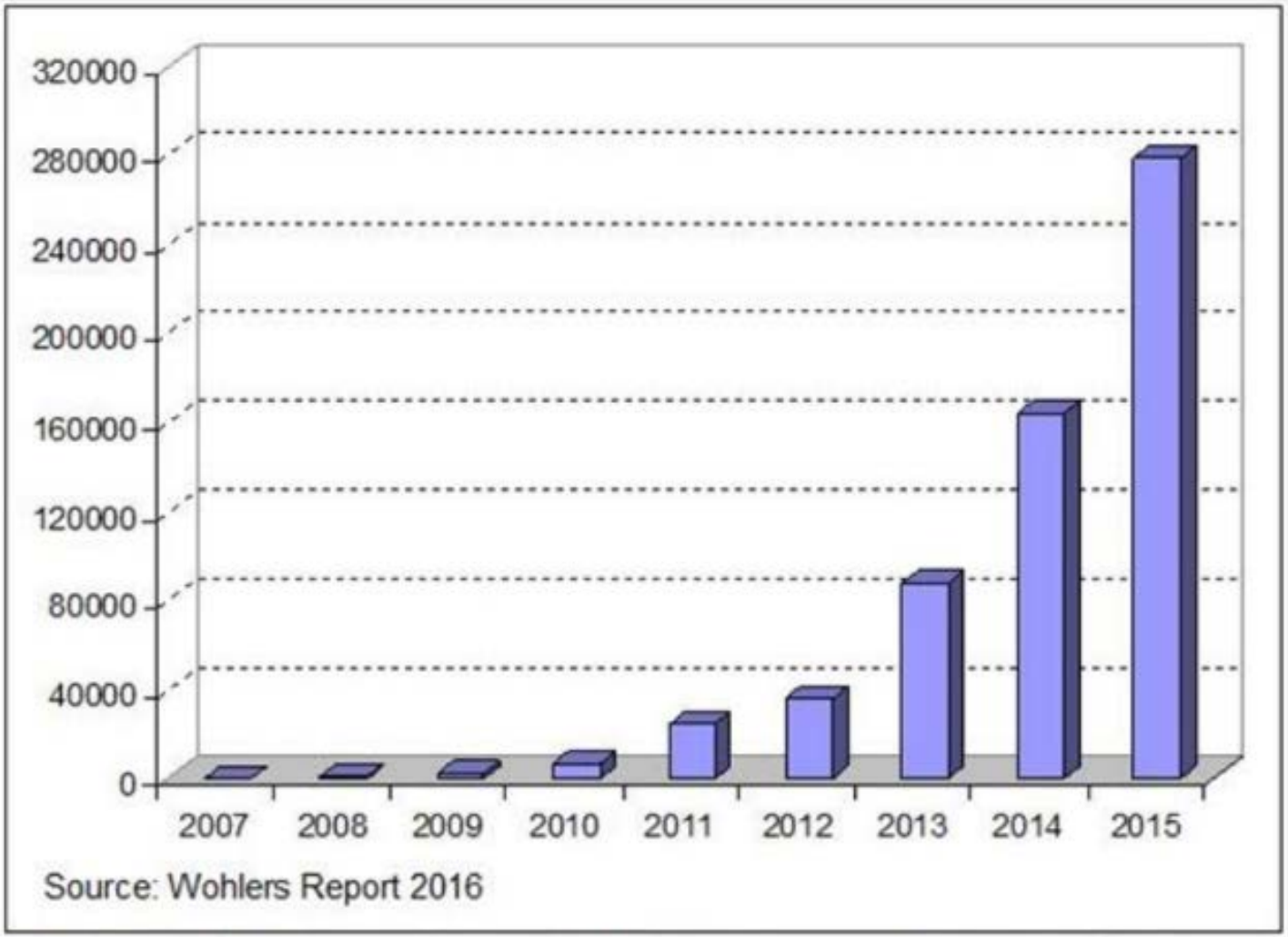

Photo Credits: www.nanalyze.com; www.foundarymagazine.com

# Electron Beam Additive Manufacturing

- An electron beam (EB) gun deposits metal (via wire feedstock), layer by layer, until the part reaches near-net shape.
- Parts and structures up to 19 ft. x 4 ft. x 4 ft.

Photo Credit: Sciaky Inc.

# Worldwide Sales of Desktop 3D Printers

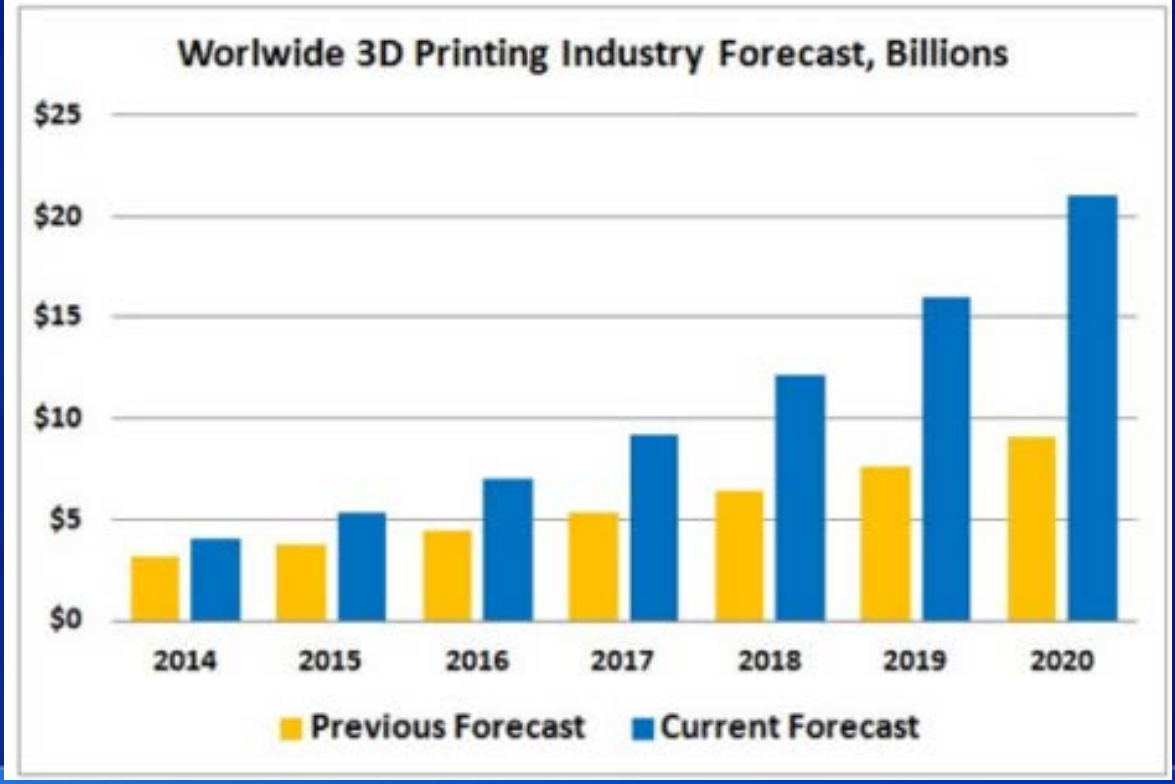



More than 278,000 desktop (under $5,000) 3D printers were sold worldwide last year

Source: Wohlers Report 2016

# Future Predicted Growth of 3D Printing

- Compound annual growth rate (CAGR) from 2012-2014 was 33.8%
- 3D printing industry grew to $4.1 billion in 2015




Source: Forbes Magazine [2015] $4.1 Billion Industry Forecast In Crazy 3D Printing Stock Market. http://www.forbes.com/

# 3D Printing as a Disruptive Technology

- "Three-dimensional printing makes it as cheap to create single items as it is to produce thousands and thus undermines economies of scale. It may have as profound an impact on the world as the coming of the factory did....Just as nobody could have predicted the impact of the steam engine in 1750—or the printing press in 1450, or the transistor in 1950—it is impossible to foresee the long-term impact of 3D printing. But the technology is coming, and it is likely to disrupt every field it touches."

"How a new manufacturing technology will change the world". Economist Technology. 2011-02-10

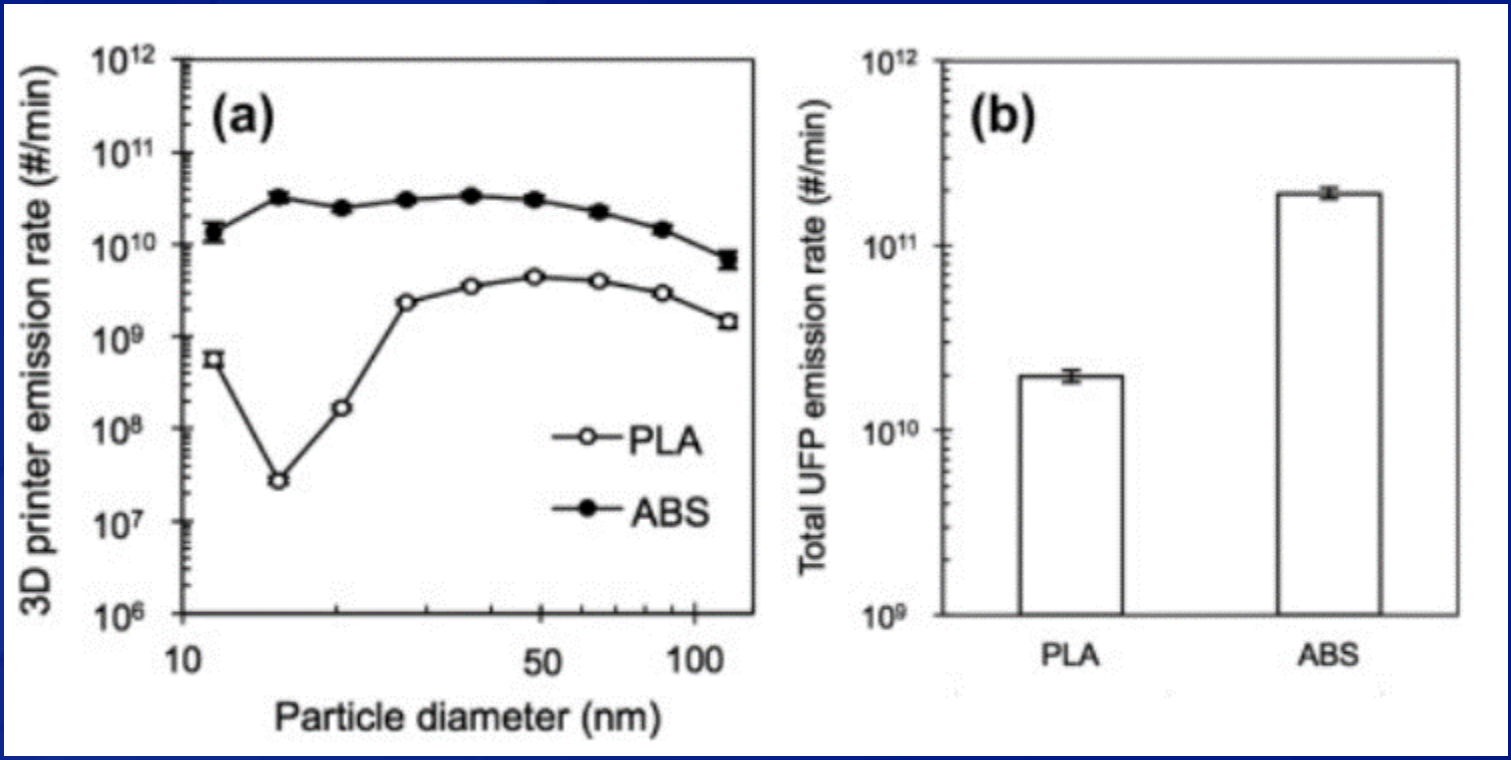
# Are there health and safety concerns?

- 3D printers are often located in schools, libraries, businesses, and home offices
- What are the emissions and exposures?

Photo: TCTmagazine

# Ultrafine Particle Emissions from 3D Printers

- In 2013, Stephens et al. was the first to publish measurements of ultrafine particle emissions (UFPs) from 3D printers.




Stephens B, Azimi P, Orch Z, Ramos T. [2013]. Ultrafine particle emissions from desktop 3D printers. Atmospheric Environment, 79, 334-339.

# 2015 study by Kim et al.

- Particulate and gaseous materials were measured before, during, and after desktop 3D printing with acrylonitrile butadiene styrene (ABS) and polylactic acid (PLA) in an exposure chamber.
- Most particles were nanosize (<100 nm) during ABS (96%) and PLA1 (98%) use, but only 12% for PLA2.
- The emissions rates were $1.67 \times 10^{11}$ particles/g cartridge with the ABS and $3.77–3.91 \times 10^{9}$ particles/g cartridge with the PLA cartridge.
- Their conclusions were that more research and sophisticated control methods are needed.

Kim Y, Yoon C, Ham S et al. [2015]. Emissions of Nanoparticles and Gaseous Material from 3D Printer Operation. Environ Sci and Technol, 49, 12044-12053.

# 2016 study by Azimi et al.

- Measured UFPs and volatile organic compounds (VOCs) from five FDM desktop 3D printers with nine different filaments by controlled experiments in a test chamber.
- Median estimates of time-varying UFP emission rates ranged from ~$10^8$ to ~$10^{11}$ particles per minute varying by filament material and, to a lesser extent, bed temperature.
- VOCs:
  - caprolactam (ranging from ~2 to ~180 μg/min)
  - styrene (ranging from ~10 to ~110 μg/min)
  - lactide (ranging from ~4 to ~5 μg/min)

Azimi P, Zhao D, Claire P et al. [2016]. Emissions of Ultrafine Particles and Volatile Organic Compounds from Commercially Available Desktop Three-Dimensional Printers with Multiple Filaments. Environ. Sci. Technol, 50, 1260−1268.

# 2016 study by Yi et al.

- Emissions were evaluated in a 0.5-$m^3$ chamber and in a room (32.7 $m^3$) using real-time instrumentation to measure UFP emissions.
- UFPs were measured when 3D printing with different ABS and PLA filament colors.
- Filament type and color influenced emissions.
- Use of a cover on the printer reduced total particle emissions by a factor of 2.

Yi J, LeBouf R, Duling M et al. [2016]. Emissions of particulate matter from a desktop three-dimensional (3D) printer. J Tox and Environ Health, Part A, 79:11, 453-465.

# Reasons why a NIOSH study is needed

- **Previous studies have:**
  - Evaluated a limited number of materials (ABS and PLA plastic)
  - Only evaluated one type of 3D printing technology (FDM)
  - Only evaluated desktop 3D printers
  - Not evaluated occupational exposures (primarily chamber studies)
  - Not evaluated effective engineering control solutions
- **Our NIOSH 3D printing study will evaluate:**
  - Emissions from more materials (metals, composites, CNTs, etc.)
  - Additional 3D printing technologies (FFF, SLS, DMLS, SLA, etc.)
  - Occupational exposures and perform chamber emission tests
  - Existing 3D printer engineering controls in multiple industries
  - Develop new engineering controls where needed
  - Provide recommendations to companies and in publications

# Specific Aims

- Specific Aim 1: Conduct field studies to better understand existing engineering controls used to contain industrial 3D printer emissions.
- Specific Aim 2: Evaluate the effectiveness of engineering control techniques for containing industrial 3D printer nanoparticle emissions and develop new approaches as needed.
- Specific Aim 3: Conduct laboratory evaluations of engineering controls and containment techniques for a variety of common desktop and industrial 3D printers that are known to emit nanoparticles.

# Laboratory Emissions Test Chamber

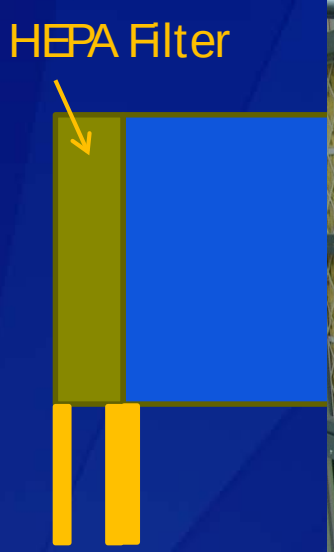



Photo and Diagram Credit: Chaolong Qi (NIOSH)

# Equipment for Particle Measurements during Chamber and Field Studies

- Condensation Particle Counter (CPC) 10 nm to >1 µm
- Fast Mobility Particle Sizer (FMPS) 5.6 to 560 nm with a time of resolution of 1 second.
- Nanoscan Particle Sizer (SMPS) 10 to 420 nm with a time of resolution of 60 seconds for 13 size channels or 1 second for a single channel scan.
- Optical Particle Sizer (OPS) 0.3 – 10 µm in up to 16 channels of resolution.
- Sioutas Cascade Impactor: Four stages (< 0.25, 0.25–0.5, 0.5–1.0, and 2.5–10 µm aerodynamic diameter) and operated at 9 liters per minute.

# Field Studies

- **12 sites (4 per year for 3 years)**
  - Include small, medium and large companies
  - Include local site visits
- **Each site visit will include:**
  - (1) identification and quantification of emission sources and emission rates;
  - (2) characterization of task-based exposures by direct-reading instruments and filter-based sampling;
  - (3) assessment of plant ventilation; and
  - (4) characterization of engineering controls.

# Characterization of engineering controls

- Tracer gas
  - Sulfur Hexafluoride
  - Miran SapphIRe
  - Photoacoustic analyzer
- Smoke release
- Particle measurements

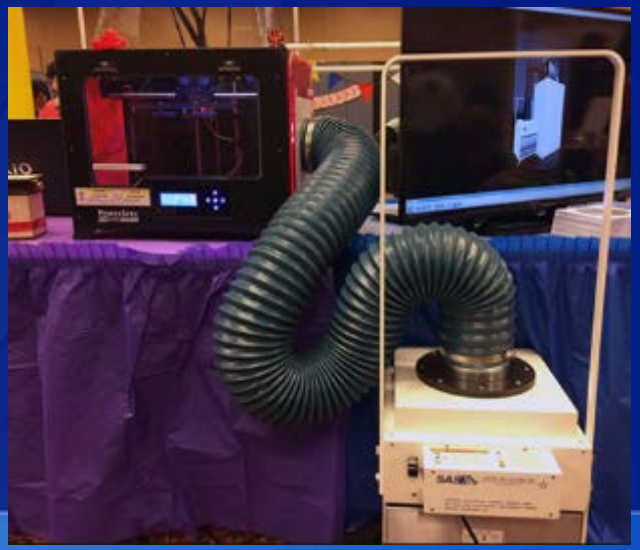


Photo Credits: Sentryair.com

# Plant ventilation evaluation

- Characterize plant supply and make-up air
  - Balometer air capture hood (Model EBT 731, TSI, Inc.)
- Pitot traverse of the exhaust ducts
- Air velocity measurements across the face of the exhaust duct opening
- Evaluate re-entrainment
  - Tracer gas
  - Smoke
- Zone pressurization

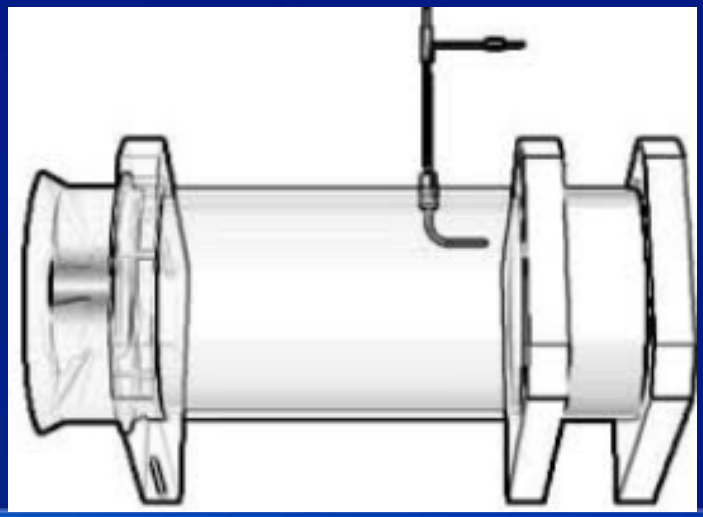


Photo: Flowkinetics.com

Photo: Globalspec.com

# Methods for engineering control evaluations will be tailored to the needs of individual companies


Photo credit: 3dprintingindustry.com

# Provide Additional Recommendations to 3D Printing Companies

Photo credit: 3dprintingindustry.com

# Conclusions

- 3D printing is a rapidly growing field with new technologies and new materials.
- Occupational exposures to 3D printer emissions may pose risks for workers.
- This new NIOSH research project will provide evaluations and recommendations to protect workers from exposure to 3D printer emissions.

# Requested input from the BSC

- 1) Several companies have already approached NIOSH asking for information about how to reduce worker exposure to 3D printer emissions. We would appreciate input on developing a strategy to effectively and efficiently move our engineering control solutions into practice as they are developed.
- 2) What mix of studies in larger companies that are already developing engineering controls and smaller start-ups that do not have expertise within the company would be most effective in gaining knowledge that would be most beneficial?

# Thank you

**For more information please contact the National Institute for Occupational Safety and Health**

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