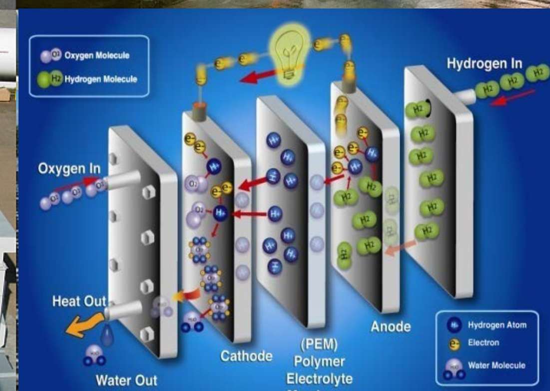
# FUEL CELL TECHNOLOGIES OFFICE

U.S. DEPARTMENT OF ENERGY | Energy Efficiency & Renewable Energy





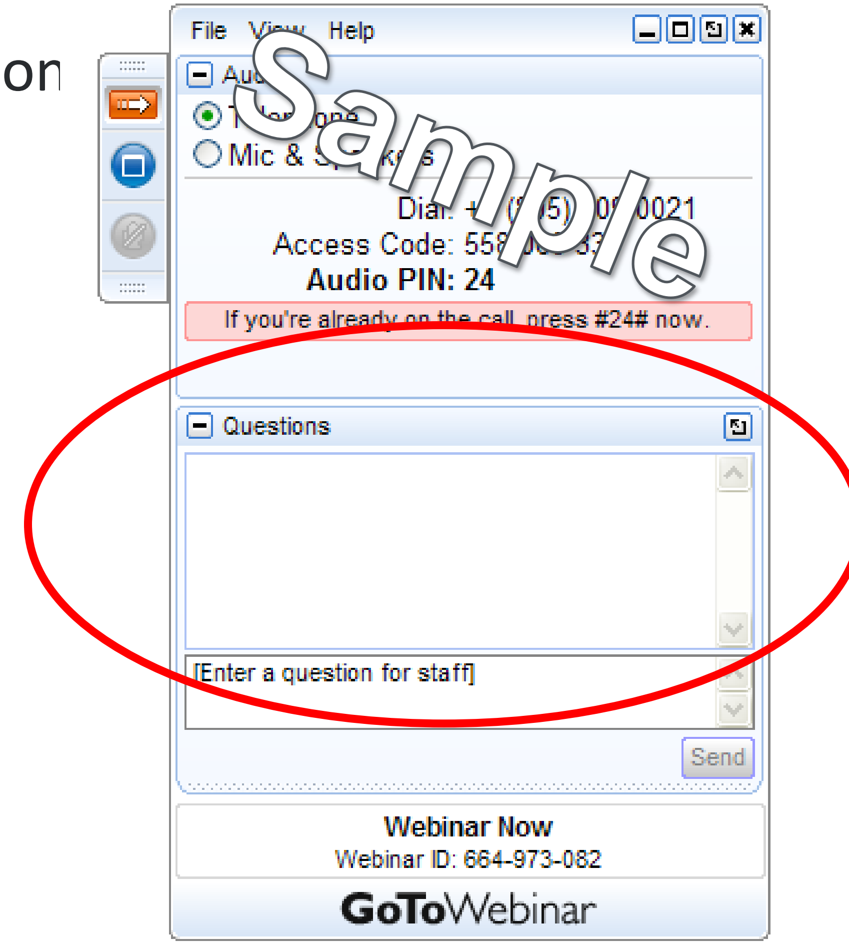



## Unlocking the potential of additive manufacturing in the fuel cells industry

**Blake Marshall**
U.S. Department of Energy
**Bradley Wright**
Eaton
**Benjamin Lunt**
Nuvera Fuel Cells

# Question and Answer

- Please type your question into the question box




hydrogenandfuelcells.energy.gov

# Outline

- What is additive manufacturing?
- Why additive manufacturing?
- DOE perspectives
- Eaton perspectives
- Nuvera perspectives

# What is Additive Manufacturing?

# What is Additive Manufacturing?

Additive manufacturing, commonly known as "3D Printing," is a **set of emerging technologies** that fabricate parts using a layer-by-layer technique, where material is placed precisely as directed from a 3D digital file.

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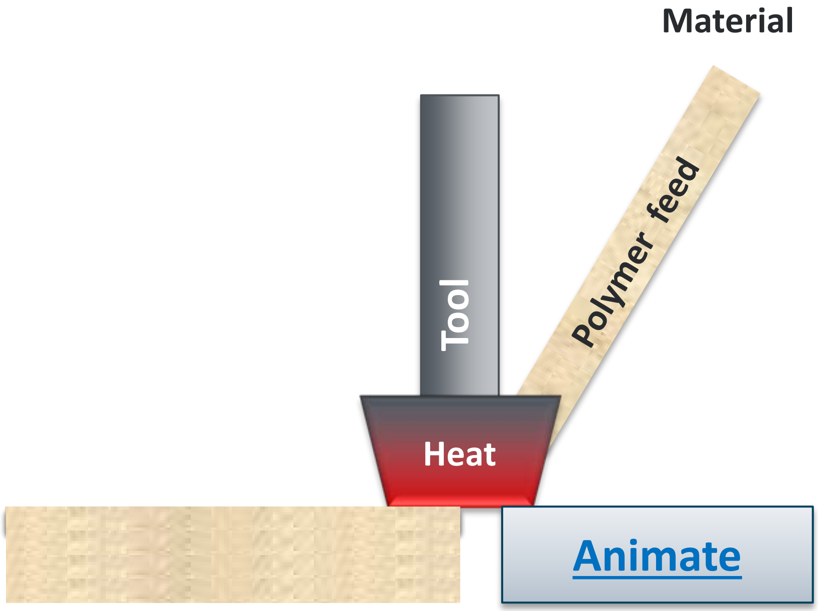
# What is Additive Manufacturing?

## Example Process: Material Extrusion

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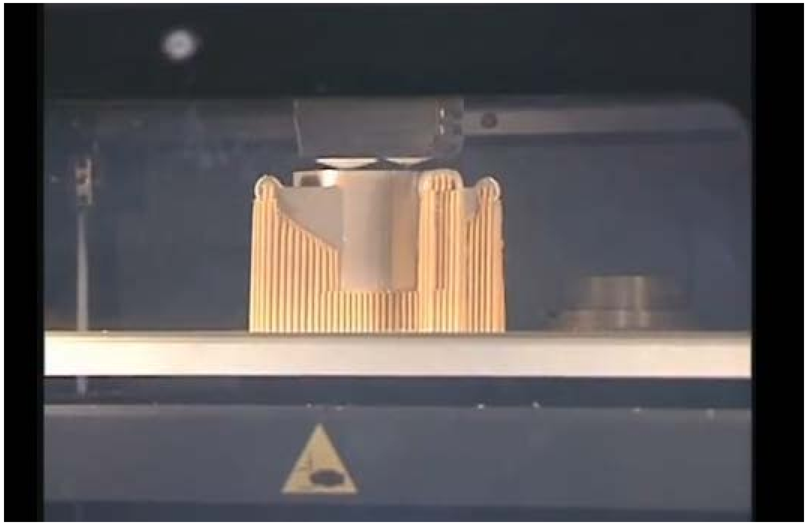
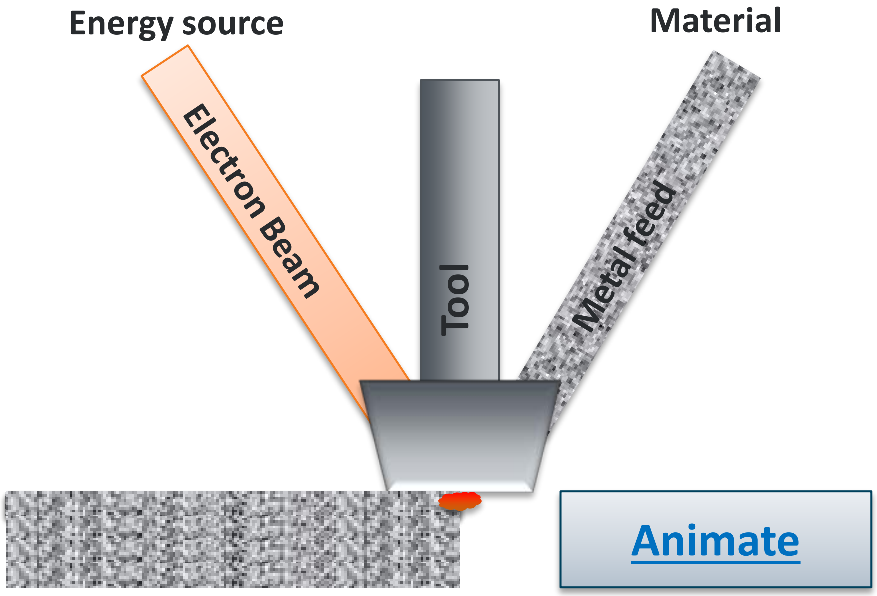
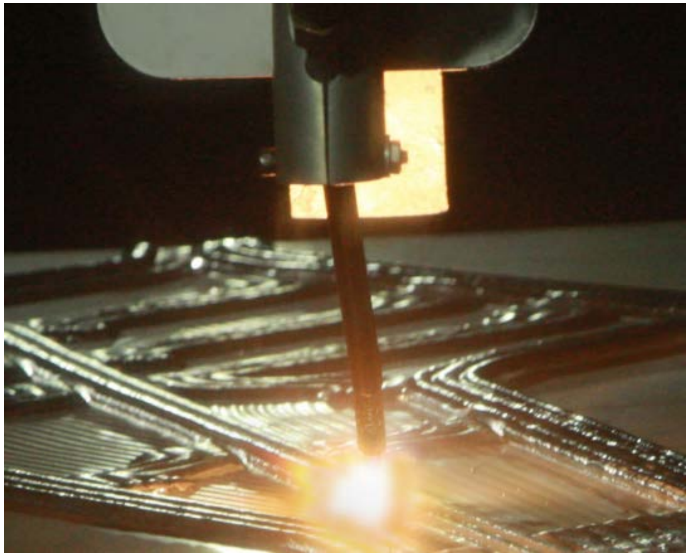


Process Photos: Stratasys

# What is Additive Manufacturing?

## Example Process: Directed Energy Deposition

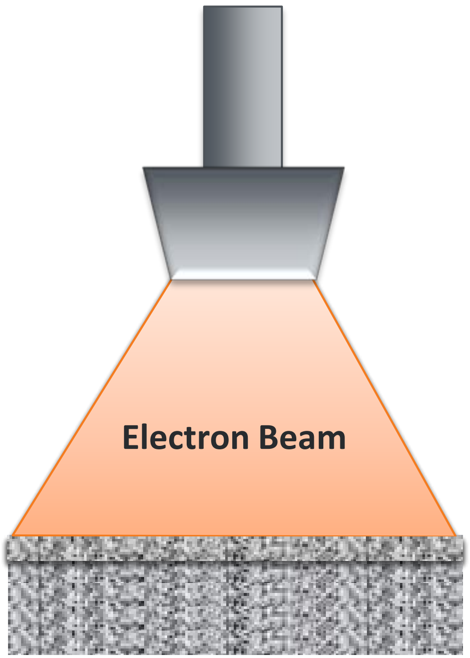


Process Photos: Sciaky

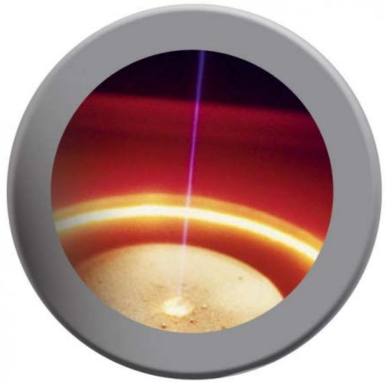
# What is Additive Manufacturing?

## Example Process: Powder Bed Fusion





**Animate**




Process Photos: Arcam

# What is Additive Manufacturing?

| Process Type | Ex. Companies | Materials | Market |
|---|---|---|---|
| **Powder Bed Fusion** | EOS (Germany), 3D Systems (US), Arcam (Sweden) | Metals, Polymers | Direct Part, Prototyping |
| **Directed Energy Deposition** | Optomec (US), POM (US) | Metals | Direct Part, Repair |
| **Material Extrusion** | Stratasys (Israel), Bits from Bytes (UK) | Polymers | Prototyping |
| **Vat Photopolymerization** | 3D Systems (US), Envisiontec (Germany) | Photopolymers | Prototyping |
| **Binder Jetting** | 3D Systems (US), ExOne (US) | Polymers, Glass, Sand, Metals | Prototyping, Casting Molds, Direct Parts |
| **Material Jetting** | Objet (Israel), 3D Systems (US) | Polymers, Waxes | Prototyping, Casting Patterns |
| **Sheet Lamination** | Fabrisonic (US), Mcor (Ireland) | Paper, Metals | Prototyping, Direct Part |

- 7 Process Categories by ASTM F42 these vary by: materials, speed to build, accuracy, finished part quality, cost, accessibility and safety, multi-color or multi-functional part capabilities

# Why Additive Manufacturing?

# Why Additive Manufacturing?

- **Enables entirely new designs**
- **Short lead time and fast prototyping**
- **Higher performance parts**
- **Supply chain and inventory benefits***

*Great for design innovation, complex parts, smaller runs, customized components, and consolidation of complex assemblies.*

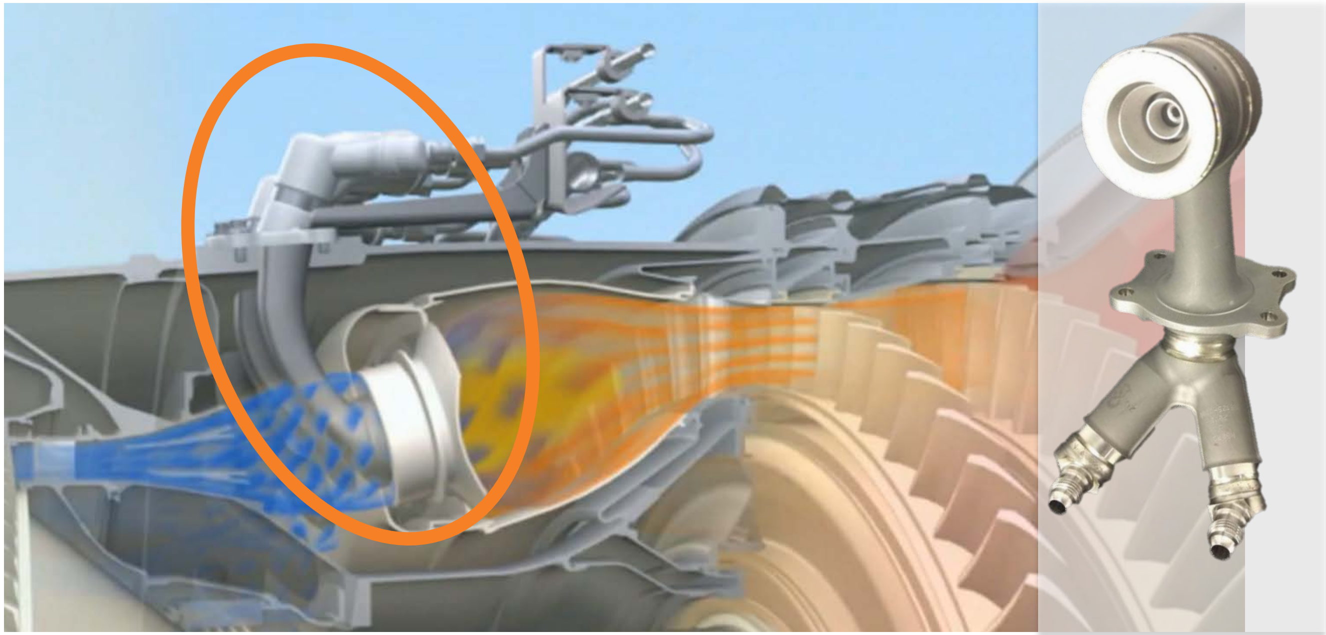
However, Additive Manufacturing is not suited for all markets and applications at this time. The toolset is promising and highly publicized but still emerging.

*Outside of the scope of this webinar

# Why Additive Manufacturing?

## Enables entirely new designs: Ex.GE LEAP Fuel nozzle

- New topology that was previously impossible
- Consolidation of assemblies into single parts: 20 to 1
- Frees constraints imposed by traditional processes



*"I need very complex shapes. I need shapes that a machine tool cannot generate."*

-Joshua Mook, Lead Engineer

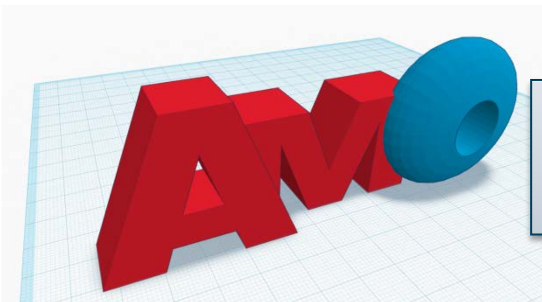
GE Aviation

https://www.asme.org/engineering-topics/media/aerospace-defense/video-printing-high-performance-fuel-nozzle. Photo credit: GE Aviation

# Why Additive Manufacturing?

## Short lead time & fast prototyping:

### Ex. Advanced Manufacturing Office logo prototype




From start of design to in-hand prototype in 2.5 hours

Photo credits: AMO & ExOne


### Ex. ExOne Case Study

ExOne

Additive Manufacturing Case Study: Metal

**Pump Manufacturer**

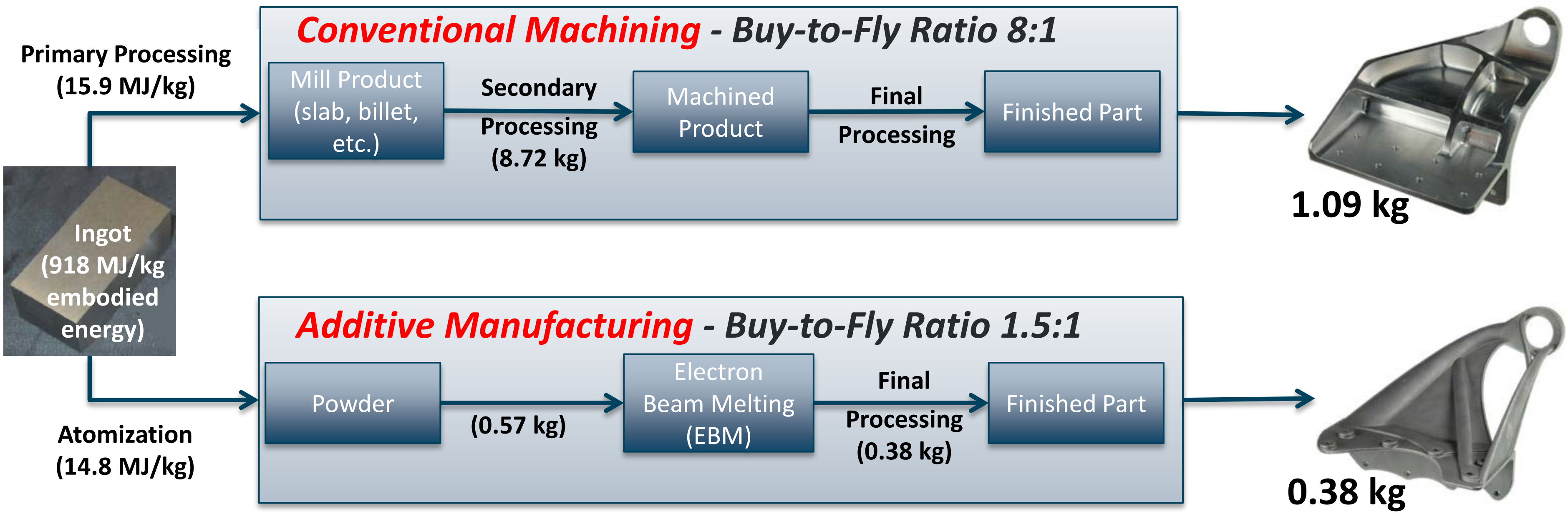
- **Reduce Impeller Prototype Costs Up to 90%**
- **Decrease Lead Time by More Than 4 Weeks**



http://www.exone.com/sites/default/files/Case_Studies/metal_PumpMfr.pdf

# Why Additive Manufacturing?

## Higher performance parts: Ex. Aircraft Bracket




| Process | Final part (kg) | Ingot consumed (kg) | Raw mat'l (MJ) | Manuf (MJ) | Transport (MJ) | Use phase (MJ) | Total energy per bracket (MJ) |
|---|---|---|---|---|---|---|---|
| Machining | 1.09 | 8.72 | 8,003 | 952 | 41 | 217,949 | **226,945** |
| EBM (Optimized) | 0.38 | 0.57 | 525 | 115 | 14 | 76,282 | **76,937** |

*Source: MFI and LIGHTEnUP Team*

# Bracket Case Study References and Key Assumptions

**Key assumptions:**

- Ingot embodied (source) energy 918 MJ/kg (255 kWh/kg)[5]
- Forging 1.446 kWh/kg[5] , Atomization 1.343 kWh/kg[6,7,8], Machining 9.9 kWh/kg removed[9], SLM 29 kWh/kg[10, 11], EBM 17 kWh/kg[10]
- 11 MJ primary energy per kWh electricity
- Machining pathway buy-to-fly 33:1[15], supply chain buy point = forged product (billet, slab, etc.)
- AM pathway buy-to-fly 1.5:1, supply chain buy point = atomized powder
- Argon used in atomization and SLM included in recipes but not factored into energy savings in this presentation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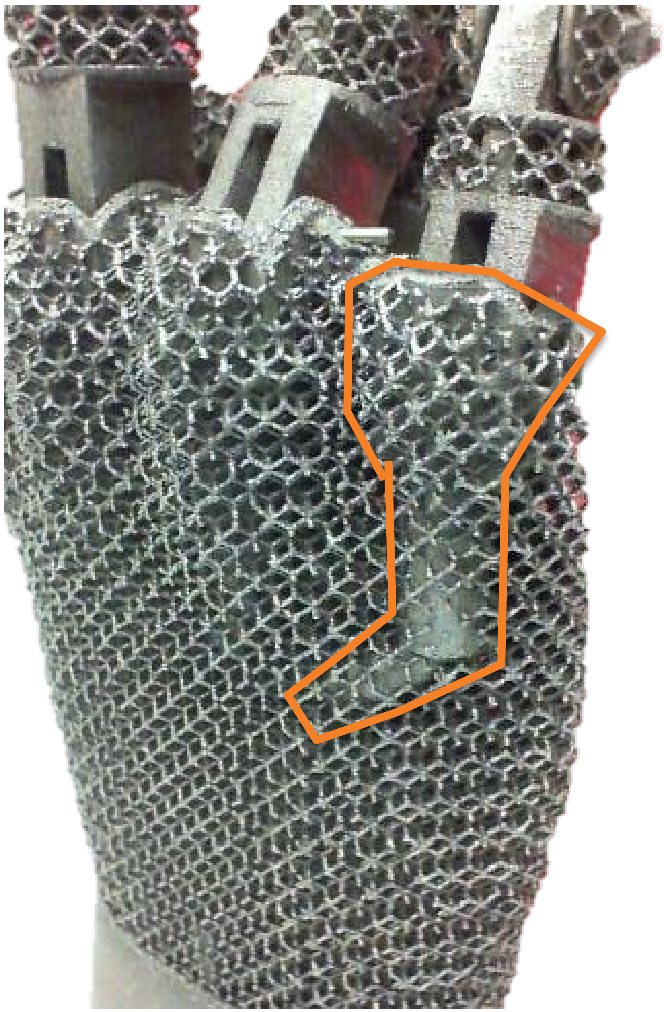
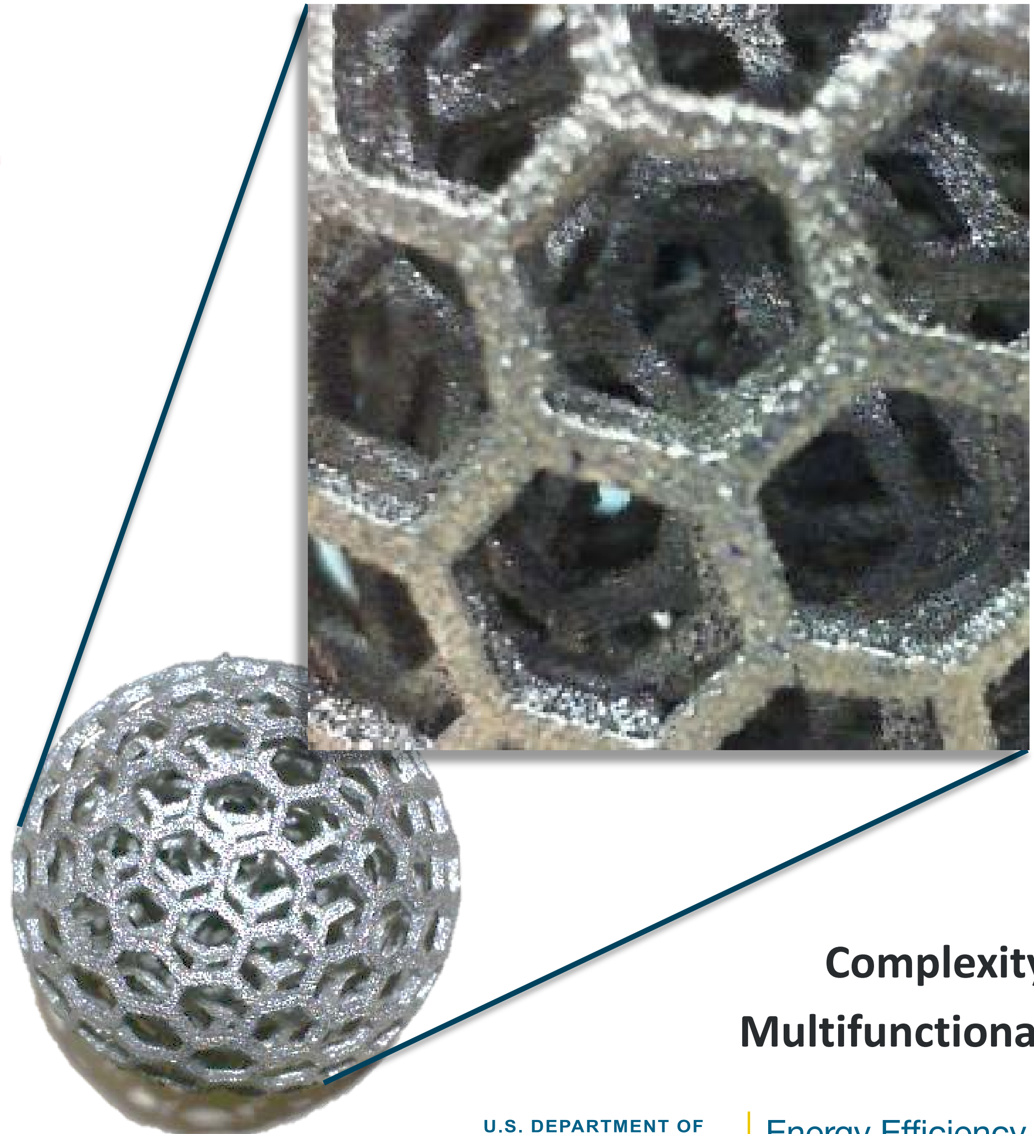
# Why Additive Manufacturing?

## Other Examples





**Complexity**

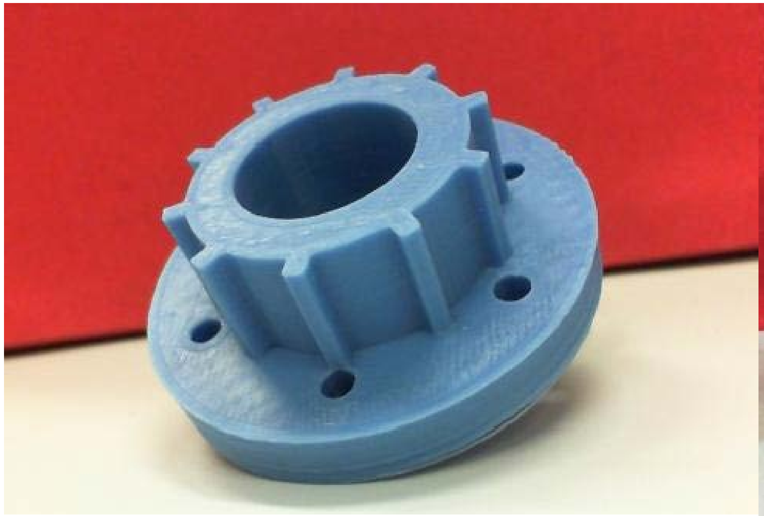
**Multifunctional**

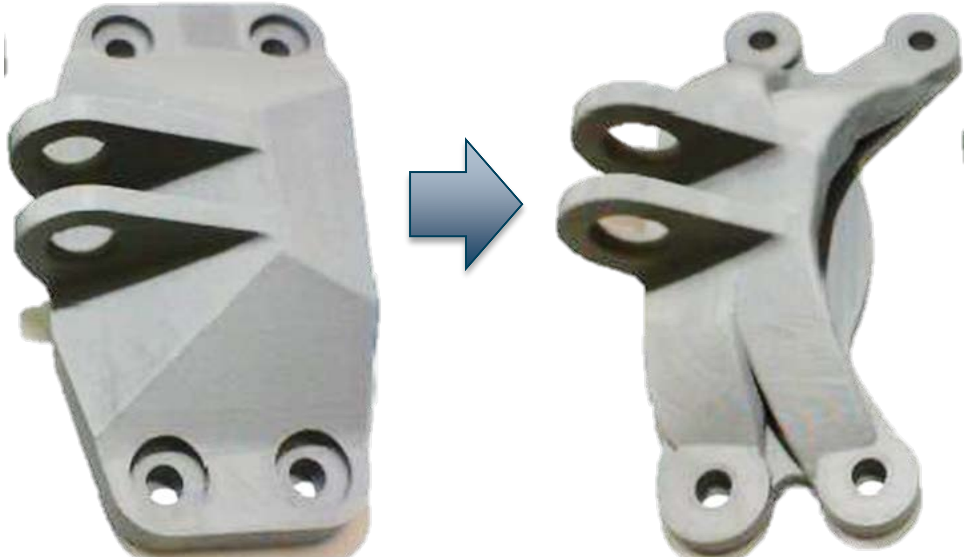


Photo credit: AMO

# Why Additive Manufacturing?

## Other Examples





**Lightweight features**

**Optimization**

Photo credit: AMO

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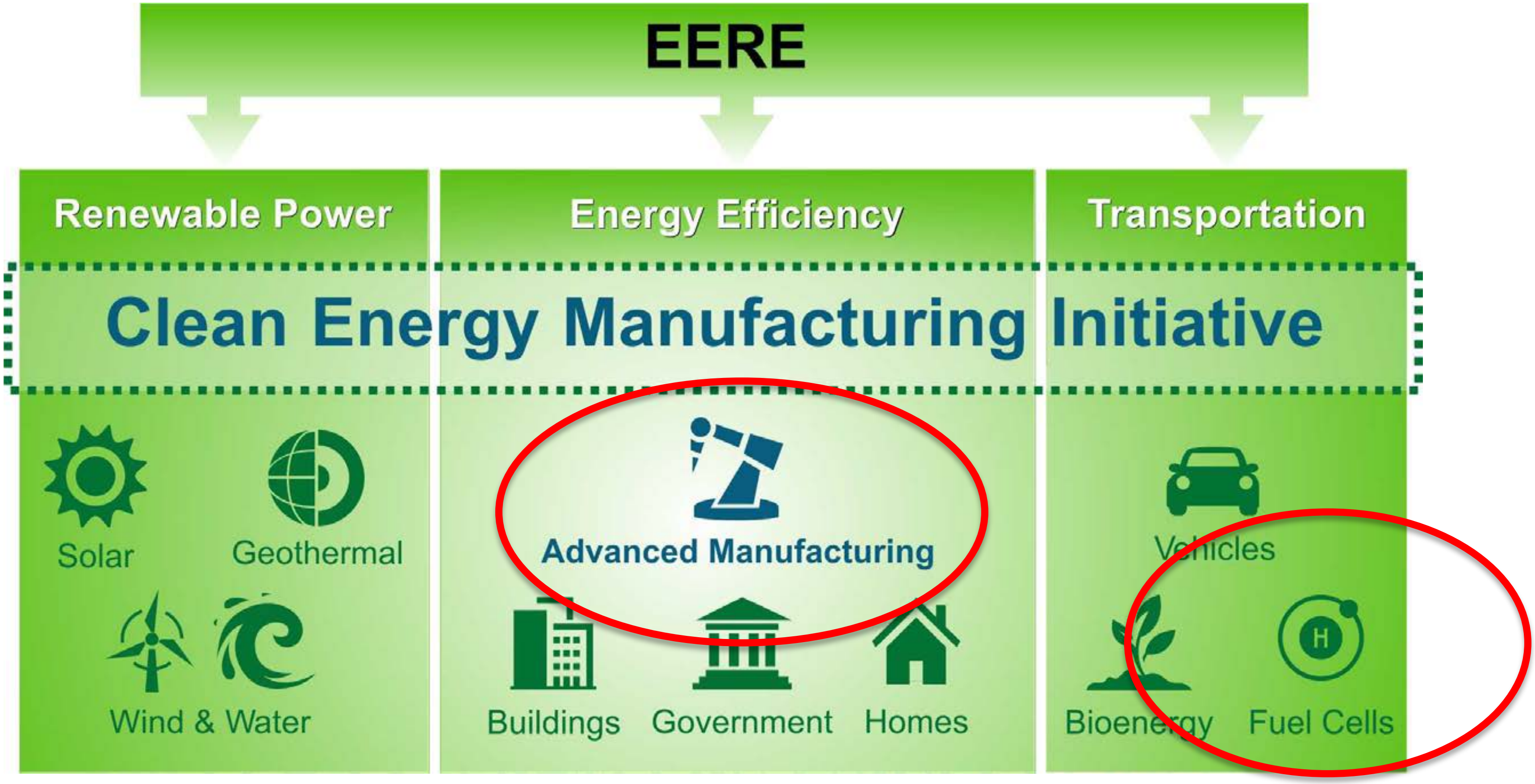
# DOE Perspectives on Additive Manufacturing

# DOE Perspectives on Additive Manufacturing

Energy Efficiency and Renewable Energy (EERE), Fuel Cell Technologies Office, and the Advanced Manufacturing Office (AMO)

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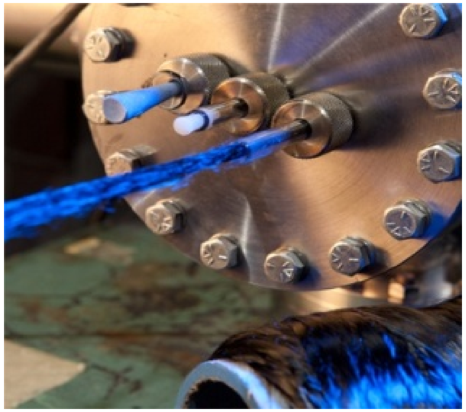
# DOE Perspectives on Additive Manufacturing



Carbon Fiber exiting Microwave Assisted Plasma (MAP) process

POM laser processing Additive Manufacturing equipment

AMO's Purpose is to Increase U.S. Manufacturing Competitiveness through:

- **Industrial Efficiency - Broadly Applicable Technologies and Practices**
  - examples: industrial motors, combined heat and power (CHP), efficient separations, microwave processing
- **Efficiency - for Energy Intensive Industries**
  - examples: Aluminum, Chemicals, Metal Casting, Steel
- **Cross-cutting Manufacturing Innovations - for Advanced Energy Technologies**
  - examples: carbon fiber composites, advanced structural metals/ joining, wide bandgap semiconductors/ power electronics, **additive manufacturing**



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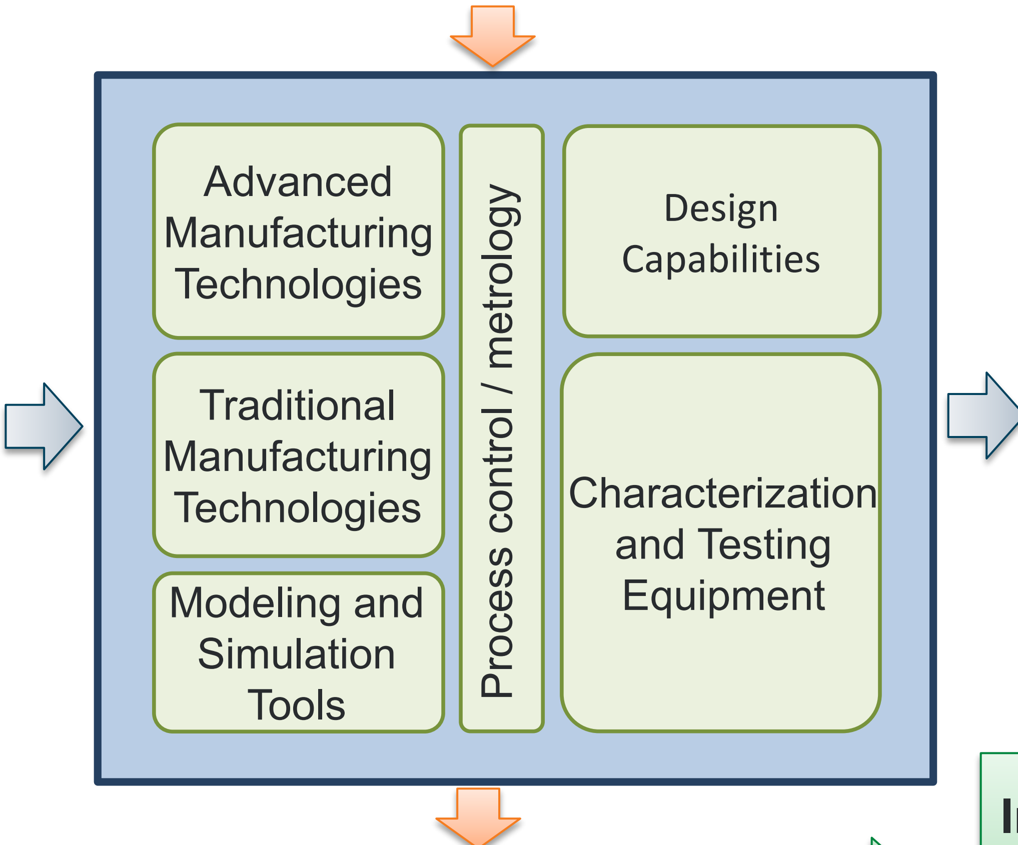
# DOE Perspectives on Additive Manufacturing

## AMO Shared R&D Facilities

INPUT: AM OEMs install machines for others to try

INPUT: Fuel cells industry tries machines for new designs and approaches




OUTPUT: Data to demonstrate **business case for manufacturing new/ improved fuel cells technology:**

- Processes established
- Production rate data
- Cost estimates based on production data
- Risks understood / quantified
- Partners Identified

**Innovative products to market**

OUTPUT: ***Market adoption*** of AM technology

# DOE Perspectives on Additive Manufacturing

## AMO Shared R&D Facilities

**Address Market Barriers by providing:**

- Proving ground – to demonstrate the costs and efficiency gains of new technologies
- Affordable access – to capital-intensive technologies and capabilities
- Focus – to a sector, or set of sectors, around common technical challenges
- Accelerated partnership development and supplier relationships
- Workforce training location for advanced manufacturing

**Positively Impact U.S. competitiveness:**

- Increased domestic manufacturing capabilities and expertise
- Increased manufacturing collaboration between small, medium and large businesses, and university and government
- Positive feedback loop – between production and research/design accelerates both
- Accelerated adoption – of energy efficient technologies and manufacturing processes in existing U.S. manufacturing

# DOE Perspectives on Additive Manufacturing

## Two AMO R&D Facility activities focused on Additive Manufacturing

**America Makes**

The National Accelerator for Additive Manufacturing & 3D Printing



www.americamakes.us

http://web.ornl.gov/sci/manufacturing/mdf.shtml

# DOE Perspectives on Additive Manufacturing

**Contact me with any questions: blake.marshall@ee.doe.gov**

## Manufacturing Demonstration Facility

## At Oak Ridge National Lab

**Contact: blake.marshall@ee.doe.gov**

**Website: http://web.ornl.gov/sci/manufacturing/mdf.shtml**

## America Makes

**Contact: kelly.visconti@ee.doe.gov**

**Website: www.americamakes.us**

# Eaton Perspectives on Additive Manufacturing


# Additive Manufacturing in Research & Development

By Brad Wright

02/11/2014

# Additive Manufacturing
## Research & Development


### Abstract

This presentation discusses the utilization of additive manufacturing of mechanical components in the area of research and development. It covers the use of plastic based additive manufacturing for demonstration/customer models, packaging studies, design models and prototyping of test components. It weighs the pros/cons of additive manufacturing with respect to prototyping vs. billet construction in plastic and metal substrates and its use in low volume manufacturing and customer engineering samples.

# Additive Manufacturing
## Research & Development

### Agenda

- Plastic Substrates
  - Internal Capability
  - Applications
  - Testing with FDM ABS
  - Low Volume Manufacturing
- Metallic Substrates
  - Supplier Techniques (DMLS & Rapid Cast)
  - Testing & Observations
- Value Proposition
  - Considerations

# Additive Manufacturing
## Plastic Substrates

### Internal Capability

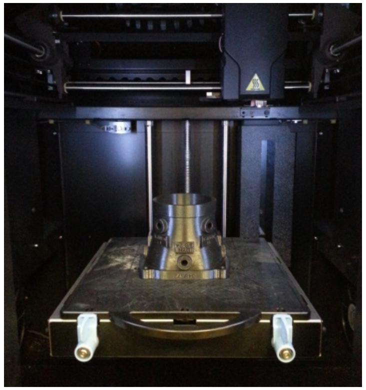
#### Dimension SST 1200es 3D Printer

- Fused Deposition Modeling (FDM) Technology

  *"FDM uses two materials to execute a print job: modeling material, which constitutes the finished piece, and support material, which acts as scaffolding. Material filaments are fed from the 3D printer's material bays to the print head, which moves in X and Y coordinates, depositing material to complete each layer before the base moves down the Z axis and the next layer begins"* – Stratasys.com
- ABS*plus* Thermoplastic (resolution up to 0.010")
- Water soluble support structure
- Print times average between 2 hours for a small model to 30+ hours for a large model

**CAD Model**

**FDM Printer**



**FDM Part Printing**

**Finished FDM Part**

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# Additive Manufacturing
## Plastic Substrates

### Applications

- Design Models
  - Fit, Form, Function
  - Design Confirmation after CAD
- Demonstration / Customer Models
  - Cutaways
  - Lightweight Assemblies
- Packaging Studies
  - Fit, Form, Function
- Test Components
  - Rapid turnaround vs. traditional machining
  - Near infinite flexibility in geometry
  - Must work within material constraints

**Design Confirmation Model**

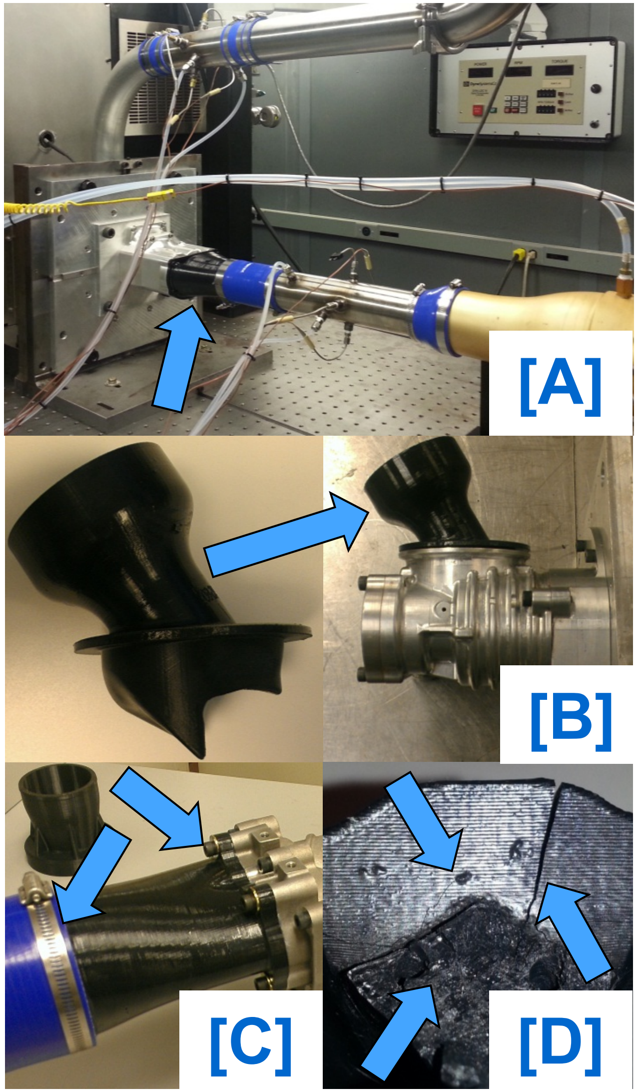
**Demonstration Model**

**Test Component**

# Additive Manufacturing
## Plastic Substrates

### Testing with FDM ABS

- Test Components [A] [B]
  - Can be test ready in under a day
  - Ideal for quick geometry changes
  - Painted with thin, solvent based cement to improve porosity and mechanical strength
- Mechanical Stress [C]
  - Accepts thread inserts
  - Reasonable clamping/compression loads
  - Print orientation is significant to part strength
- Pressure
  - Tested up to 2.3 bar with ~4mm wall thickness
- Temperature
  - Maximum working temperature of 115°C
- Failure Modes [D]
  - Cracking (stress)
  - Brittleness (temp)
  - Blistering (temp)

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# Additive Manufacturing
## Plastic Substrates

### Low Volume Manufacturing

- Customer Engineering Samples
  - Printed and assembled same day
  - Immediate part revisions
  - Limited durability
  - Limited material selection

- Low Volume Manufacturing
  - Print as needed (JIT)
  - Balance Rate of Sale vs. Print Time
  - Balance Cost vs. Production Volume
  - Inverse relationship between Additive Manufacturing and Traditional Manufacturing

| 3D Printing (Plastic) | | Injection Molding (Plastic) | |
|---|---|---|---|
| Intial Cost | O | Initial Cost | X |
| Part Cost | X | Part Cost | O |
| Lead Time | O | Lead Time | X |
| Manufacturing Time | X | Manufacturing Time | O |

**Plastic FDM Electronics Housing (Engineering Sample)**

**Plastic FDM NVH Resonator (Low Volume Production)**

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# Additive Manufacturing
## Metallic Substrates

### Supplier Techniques

- Direct Metal Laser Sintering (DMLS)
  - Laser fused powdered metal
  - Geometry capability beyond any traditional manufacturing method
  - Common alloys available (Stainless Steel, Titanium, Aluminum, Inconel, etc.)
  - Extremely quick turnaround
  - Competitive pricing compared to billet
  - Requires additional machining (tolerances up to +/-0.005”)
- Rapid Casting
  - Lost wax investment casting utilizing an SLS fabricated disposable pattern
  - Quick lead time compared to traditional casting
  - Turnaround time on par with billet
  - Requires additional machining

**Aluminum SLS Part**

**Aluminum SLS Surface Finish**

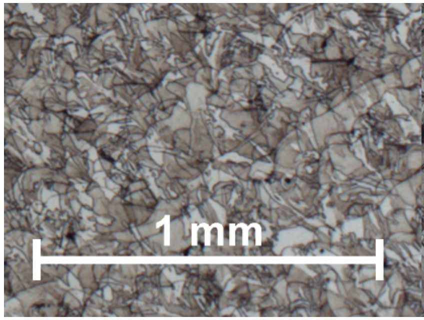
**Aluminum SLS Part Post Machining**

# Additive Manufacturing
## Metallic Substrates

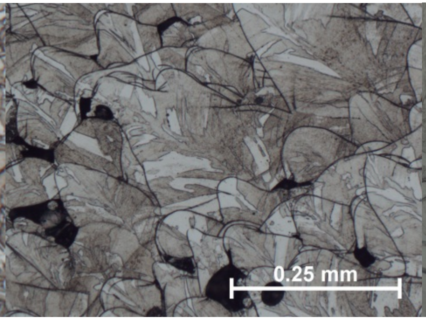

316 Stainless SLS Part

## Testing & Observations

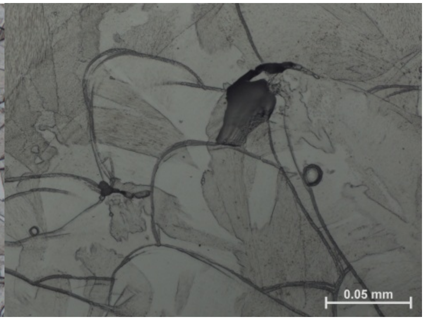
- DMLS 316 Stainless Steel
  - Unique, defined grain structure
  - Porosity of 1.0 - 2.5%
  - Unconfirmed structural properties



316 Micro Structure 25x

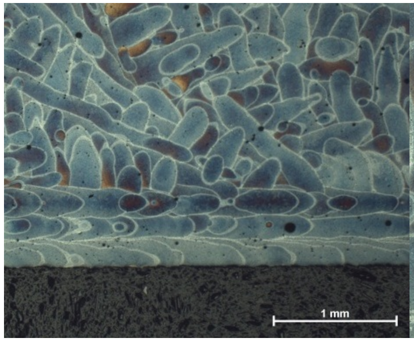


316 Micro Structure 100x

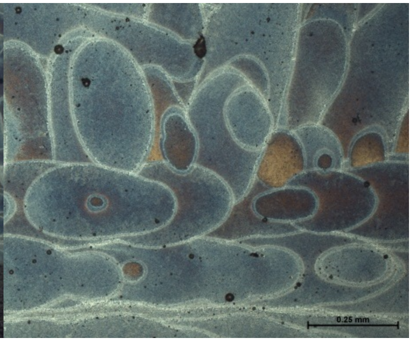


316 Micro Structure 500x

- DMLS 6061 T6 Aluminum
  - Unique surface structure orientation
  - Porosity of 4.0 - 5.0%
  - Unconfirmed structural properties
  - Component testing underway

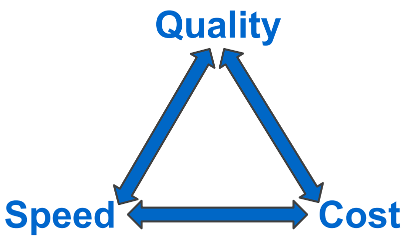


6061 Micro Structure 25x


6061 Micro Structure 100x

# Additive Manufacturing
## Value Proposition

- Considerations
  - Application / Material Properties
  - Part Quality
  - Lead Time
  - Production Volume / Quantity
  - Part Cost
  - Tooling Cost




| **FDM** | **SLS** | **Rapid Cast** | **Billet** | **Production Cast** |
|---|---|---|---|---|
| Lead Time - 8 hours | Lead Time - 3 Days | Lead Time - 4 weeks | Lead Time - 4 weeks | Lead Time - 2 Months |
| Cost - $50 | Cost - $2500 | Cost - $2000 | Cost - $1500 | Cost - $5 |

Lead Time

Cost

# Additive Manufacturing
## Research & Development

# Q & A

**AC Tech – rapidcastings.com**

**Fisher / Unitech – funtech.com**

**Fineline Prototyping – finelineprototyping.com**

**Stratsys – stratasys.com**

**Synergeering Group – synergeering.com**

**CAM Logic – camlogic.com**

**Additive Manufacturing LLC – lasersintering.com**

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# Nuvera Perspectives on Additive Manufacturing

# Hydrogen Ejector for PFC Developed using DMLS

(Direct Metal Laser Sintering)

Benjamin S. Lunt

Nuvera Fuel Cells, Inc.

Presented To: DOE

2/3/2014

# *Abstract*


- Review of a development project using DMLS (Direct Metal Laser Sintering). Anode recirculation ejectors were prototyped and tested for use in PEM fuel cell systems. Process was selected for its relatively short lead time, and low cost relative to machining or molding to achieve desired designs.

# Outline

- Complex Shapes
- Design Innovations
- Weight Reduction
- Multiple Design Variations in a Single Build
- Product Development – Component Integration

# *Complex Shapes*

- DMLS additive fabrication allows for the creation of complex geometry not possible with conventional machining
- This ejector nozzle, throat, and diffuser where built in one piece. Previous part was machined in two or more pieces and welded together.
- Additive machining also allows for parts of lower mass. Material is added only where needed, as opposed to conventional machining where removing all unnecessary material would not be economical or even possible.

NUVERA
Making hydrogen make sense.

## *Design Innovations*

- DMLS was used to prove out a concept for a fully integrated ejector and anode flow valve. The flow valve is controlled by anode pressure acting on a piston.
- The complete assembly was made from 3 pieces, and designed to twist lock, eliminating the need for tools and hardware to assemble.
- This would have been difficult and expensive to machine.
- DMLS is a cost effective way to prove the concept, MIM is envisioned for higher volumes.

## *Weight Reduction*

- An example of weight reduction is shown below. This first design on the right had ports through a solid body. The body was intended to be hollow, but removal of un sintered build material would have been difficult, so the body was built solid. The second design eliminated the face and replaced it with thin spokes, allowing for a hollow build.

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# *Multiple Design Variations in a Single Build*

- Design optimization can be achieved by testing of certain variable that are sensitive to performance.
- In this case, multiple parts where made in a single build. This can be done economically as long as all of the parts being build can fit onto the build table of the DMLS machine being used.
- This build was done to come up with a family of similar designs which would satisfy a wide range of fuel cell systems. In this case, how many different size ejectors would be required to meet the performance targets for systems varying from about 10-90kw gross.

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## *Product Development – Component Integration*

- DMLS was used again to test another variation of a similar part.
- Here, a manifold is added to integrate a solenoid valve directly to the hydrogen inlet of the ejector.

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# Conclusions

- DMLS was used to achieve an optimized ejector design with several iterations. Even with several iterations of the design, this was accomplished with only a few builds.
- The final designs are now optimized, and with a high level of confidence, tooling could now be created for high volume manufacturing.


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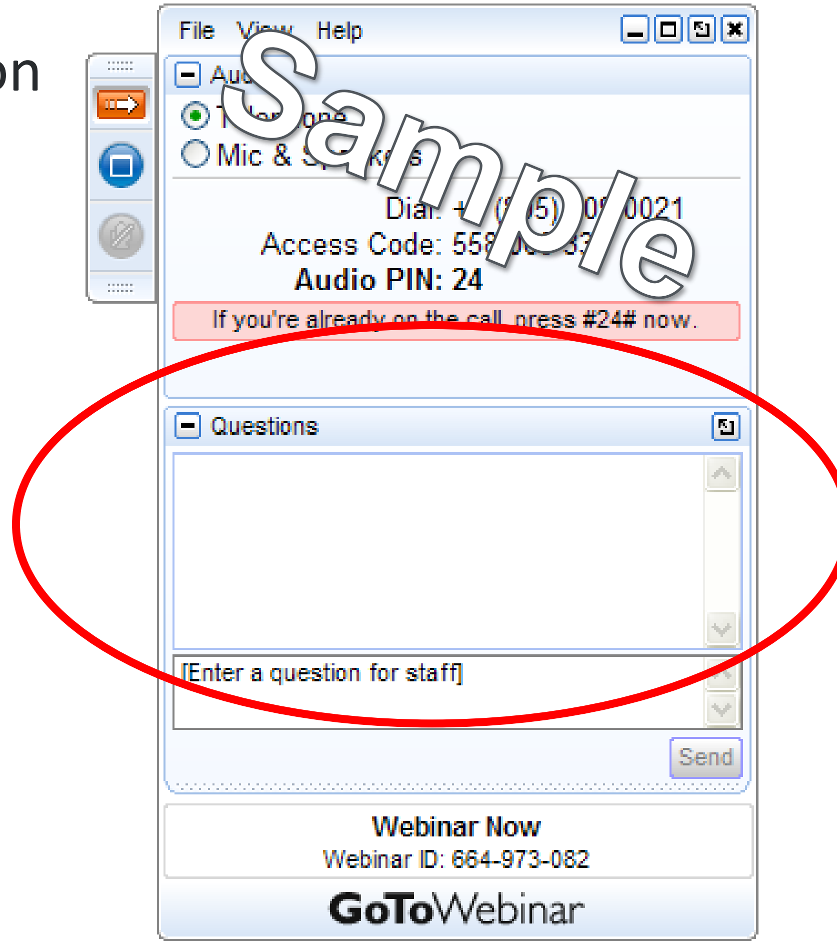
# Question and Answer

- Please type your question into the question box

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# Thank You

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