Developers & Practitioners of Advanced Manufacturing Technology:
Perspectives from an Additive Manufacturing Demonstration Facility

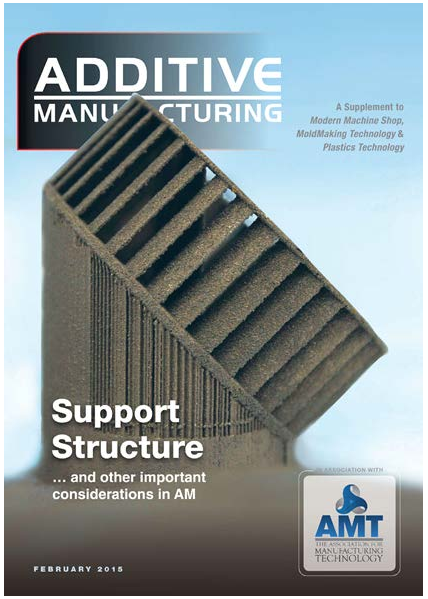
Timothy W. Simpson, Ph.D.
Professor of Mechanical & Industrial Engineering, Penn State University, and Co-Director,
Center for Innovative Materials Processing through Direct Digital Deposition (CIMP-3D)

Acknowledge significant contributions from Rich Martukanitz, Ted Reutzel, Todd Palmer, Griffin Jones, and Corey Dickman of the Applied Research Lab and Karen Thole, Jacob Snyder, Andrew Coward, Curtis Stimpson, and David Saint John from Penn State

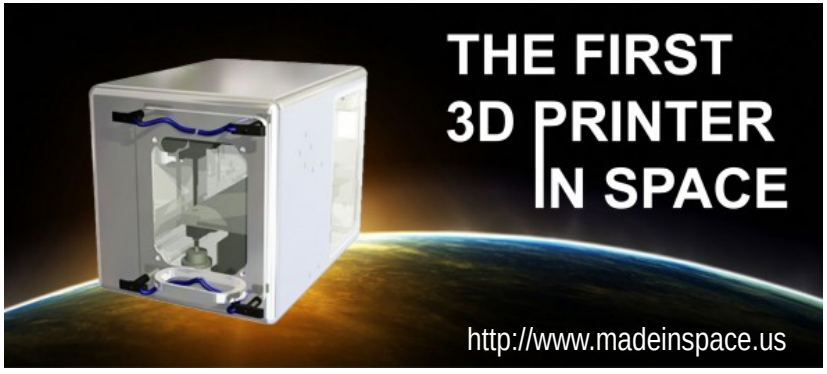
Hype for Additive Manufacturing (AM)

“20% of output of 3D printers is now final products, rather than prototypes. By 2020 it may be 50%.”
– The Economist (2011)

http://www.wired.com

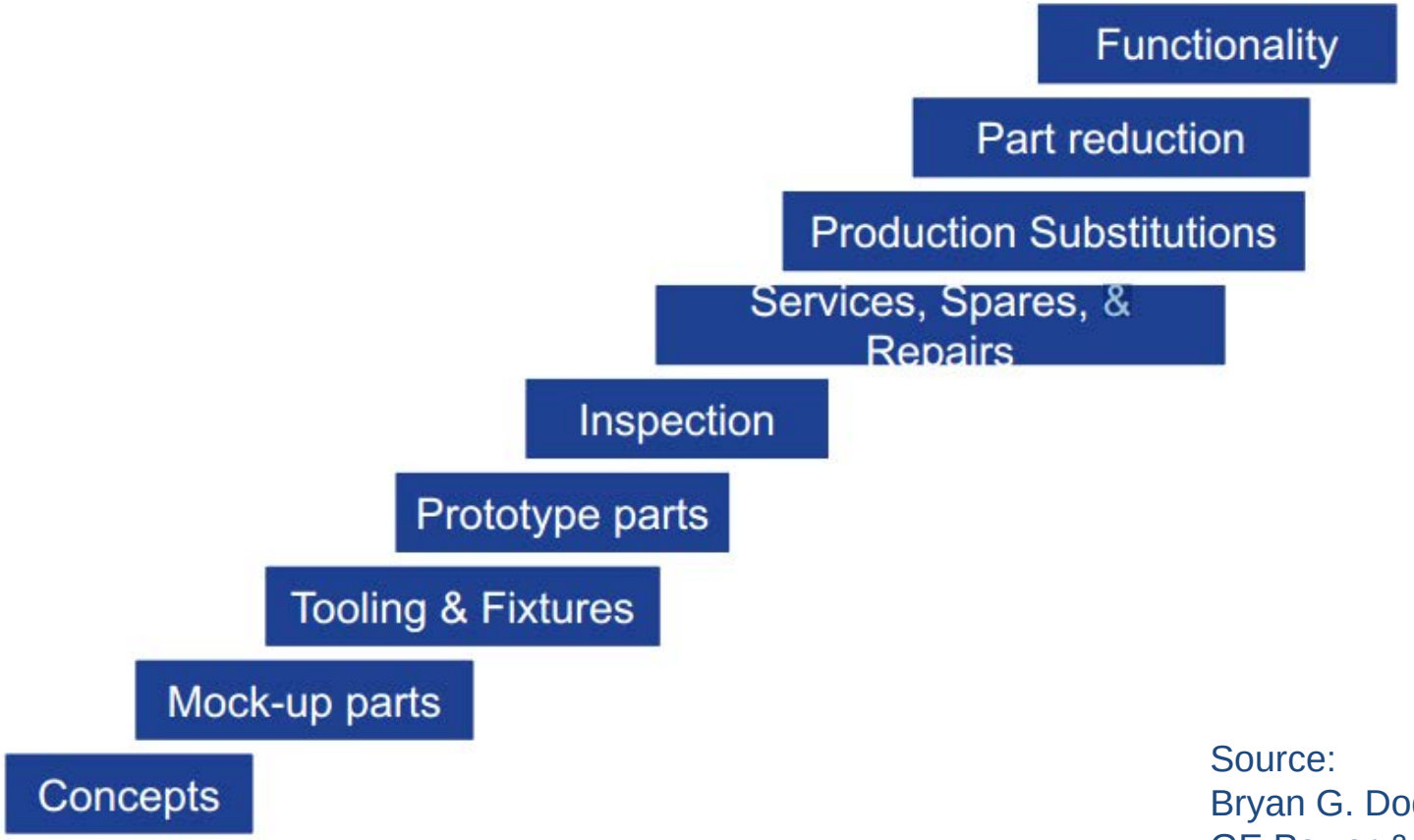


http://www.additivemanufacturinginsight.com



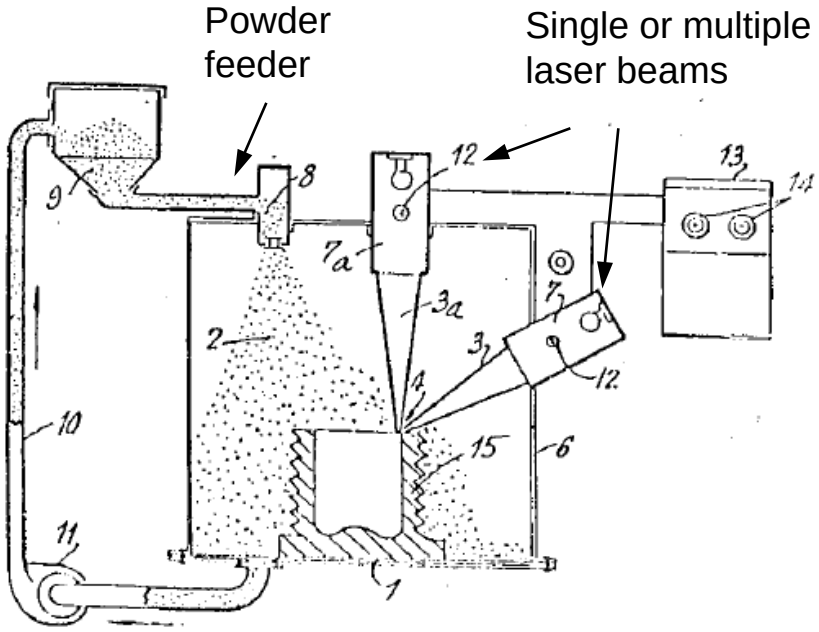
Progression of AM Applications

Change DFM paradigm… "make what we can design"

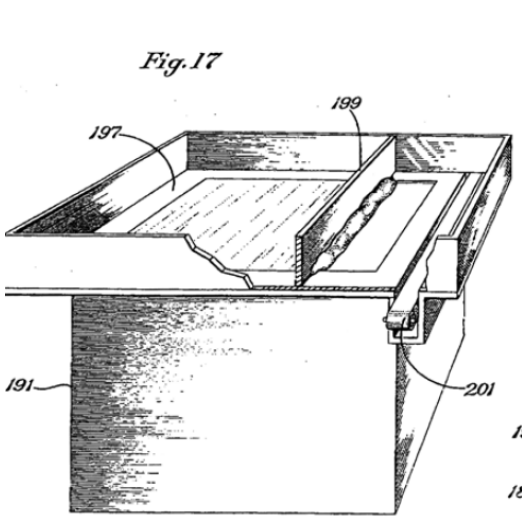


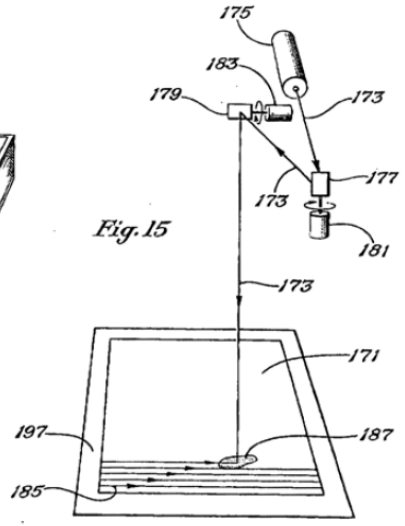
Source:
Bryan G. Dods
GE Power & Water
NSF AM Workshop
12 July 2013

Early AM Inventions



Powder-feed AM process
Proposed by Ciraud in 1971

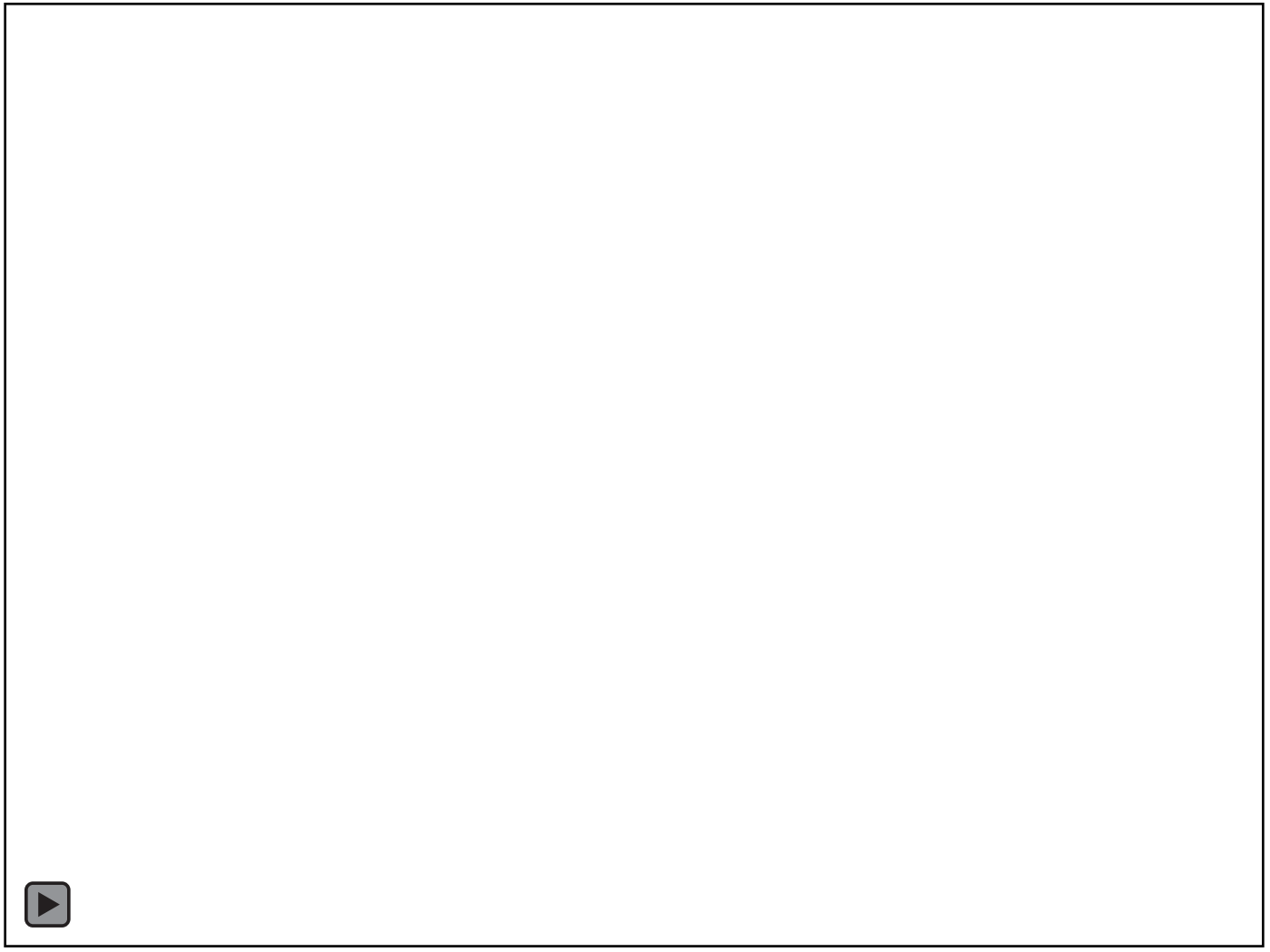




U.S. Patent Jan. 27, 1981 Sheet 6 of 6 4,247,508

Powder-bed AM process
Patented by Housholder in 1979

EOS Powder Bed Fusion (Laser)



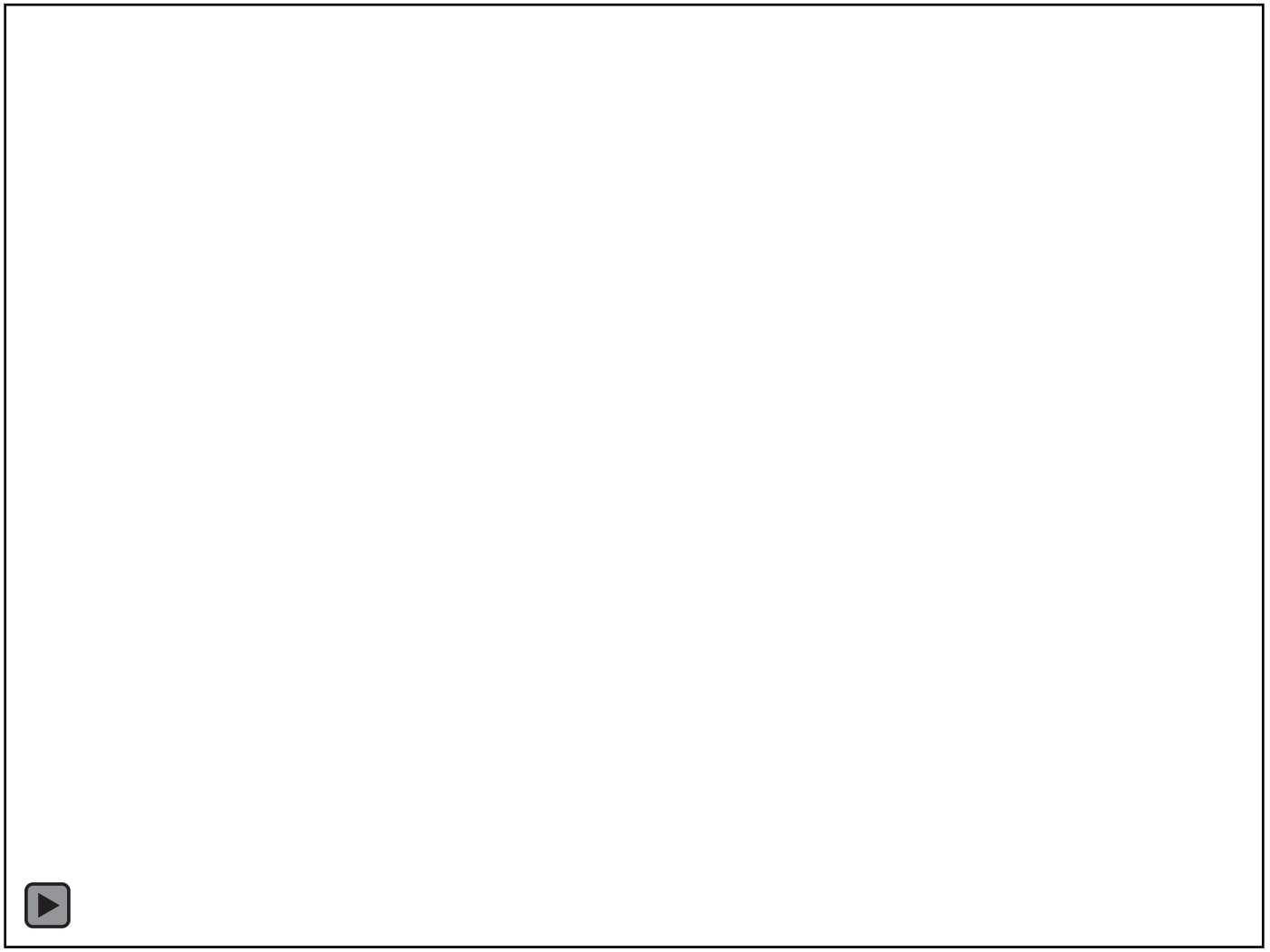
View at: http://youtu.be/RnI6qYYs3c4

Part Consolidation

GE's laser-printed fuel nozzles for their next-generation LEAP engines, which are 25 percent lighter than the current alternative that's welded from 18 different parts.

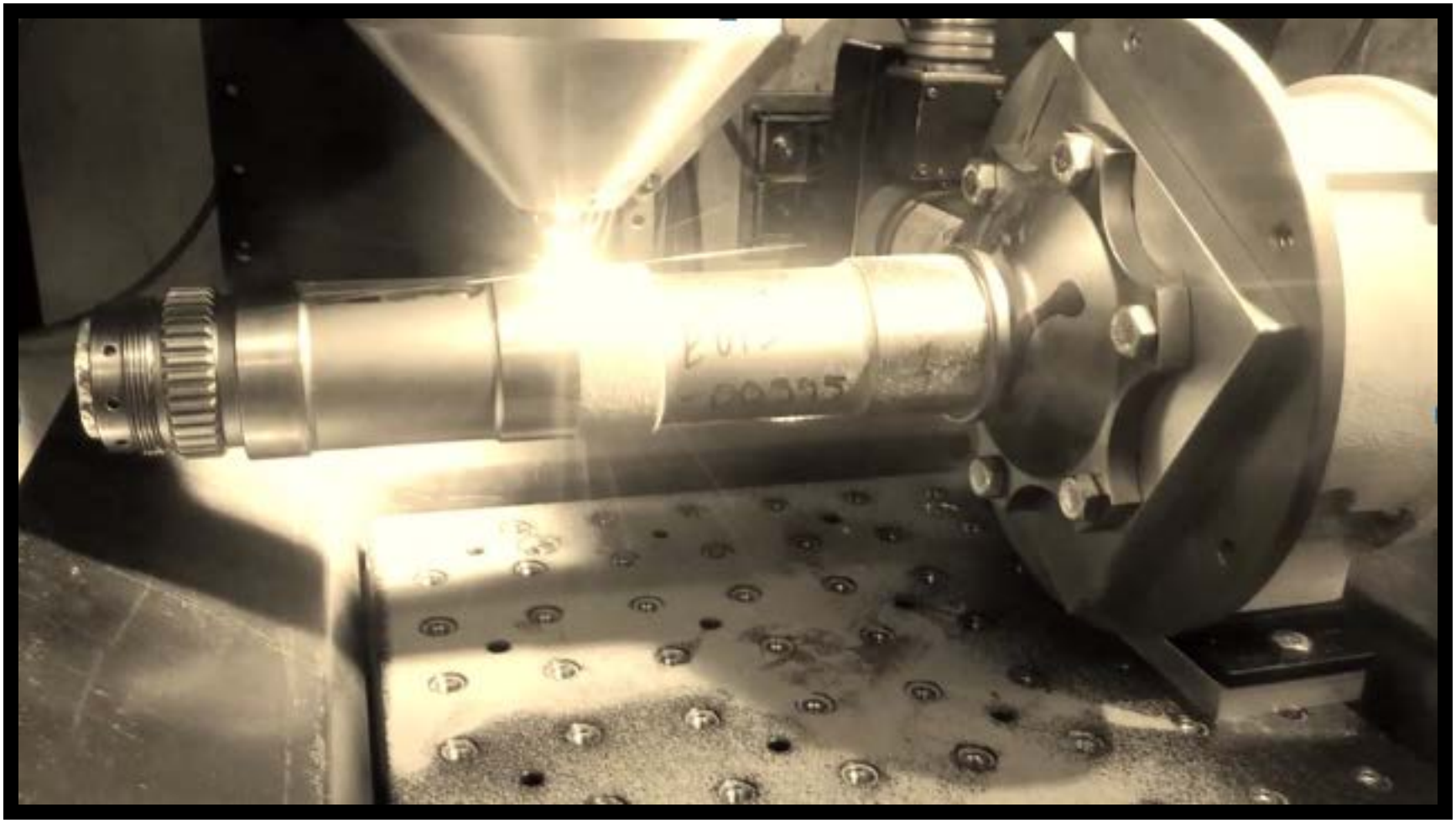
Source: https://www.ge.com/stories/additive-manufacturing

Optomec LENS Build Example



View at: http://youtu.be/yNOdvDJEY1g

Optomec LENS Repair Example

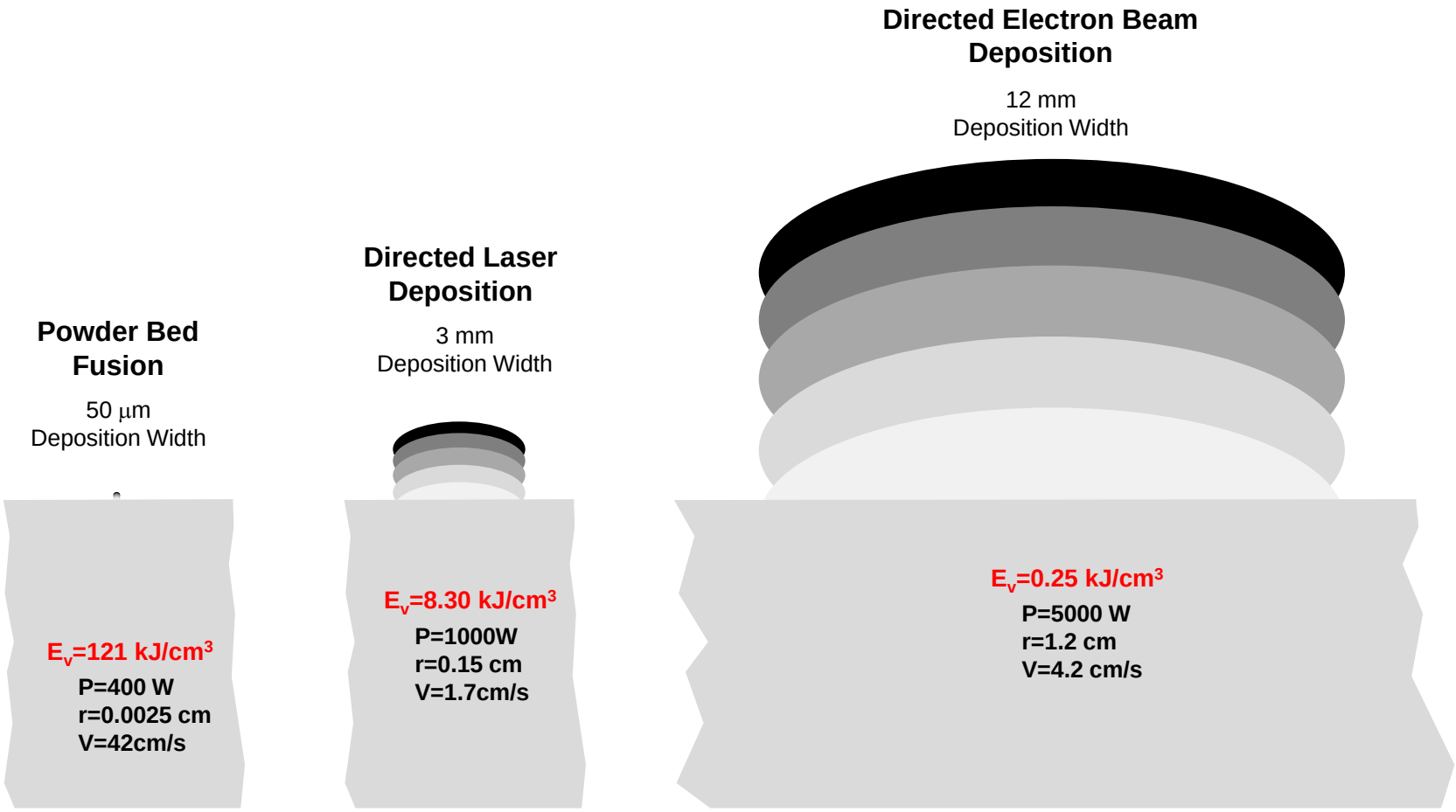


View at: http://youtu.be/c_UVUI296B0

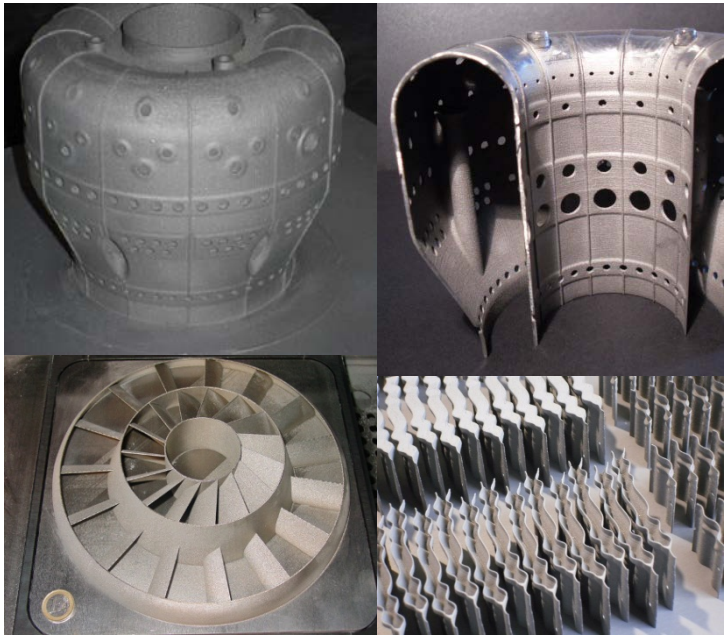
PennState

Inside Sciaky's NG1 EBAM System

Relative Scale of Metal 3D Printers



New Design Freedoms



Phenix Laser / 3D Systems

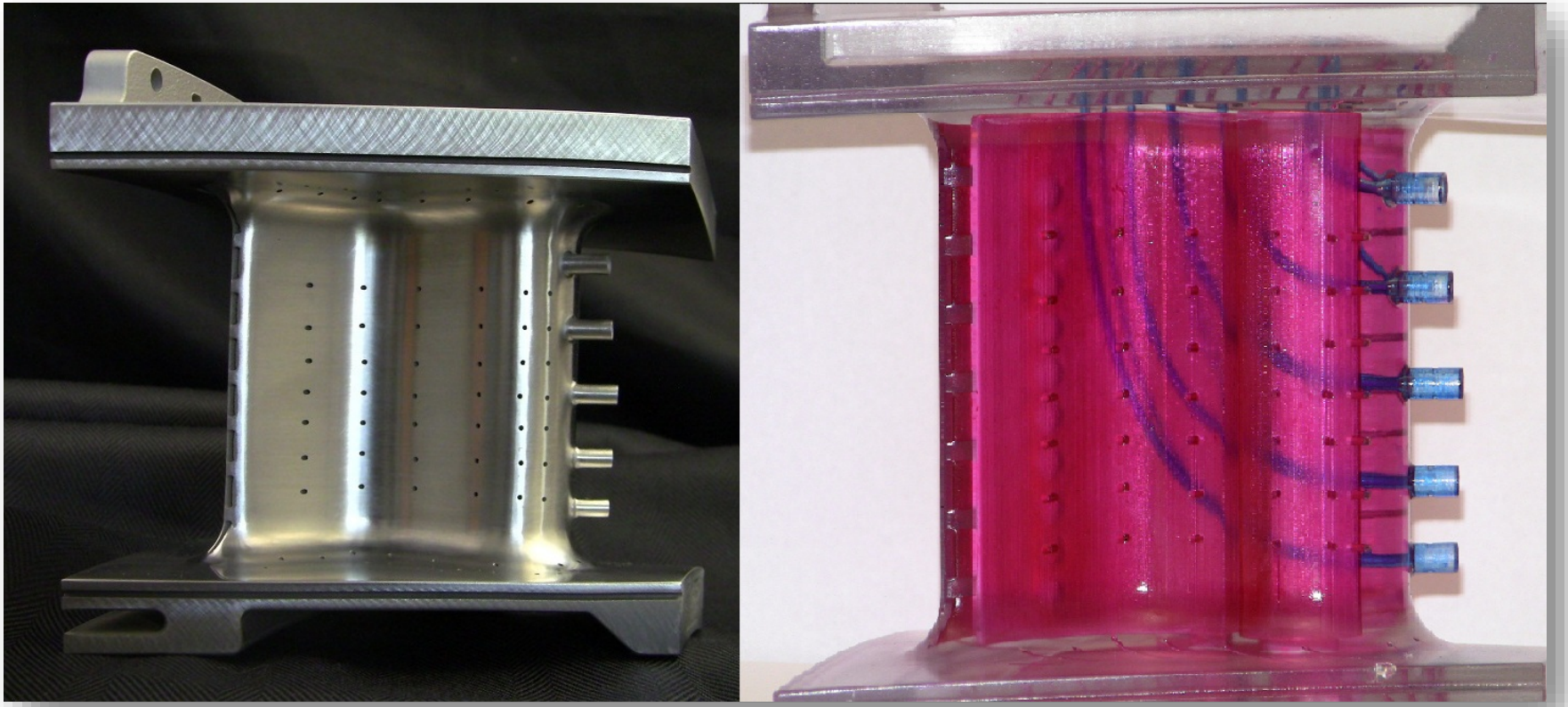
Renishaw

Concept Laser website

Designs are limited by your imagination, not by conventional fabrication

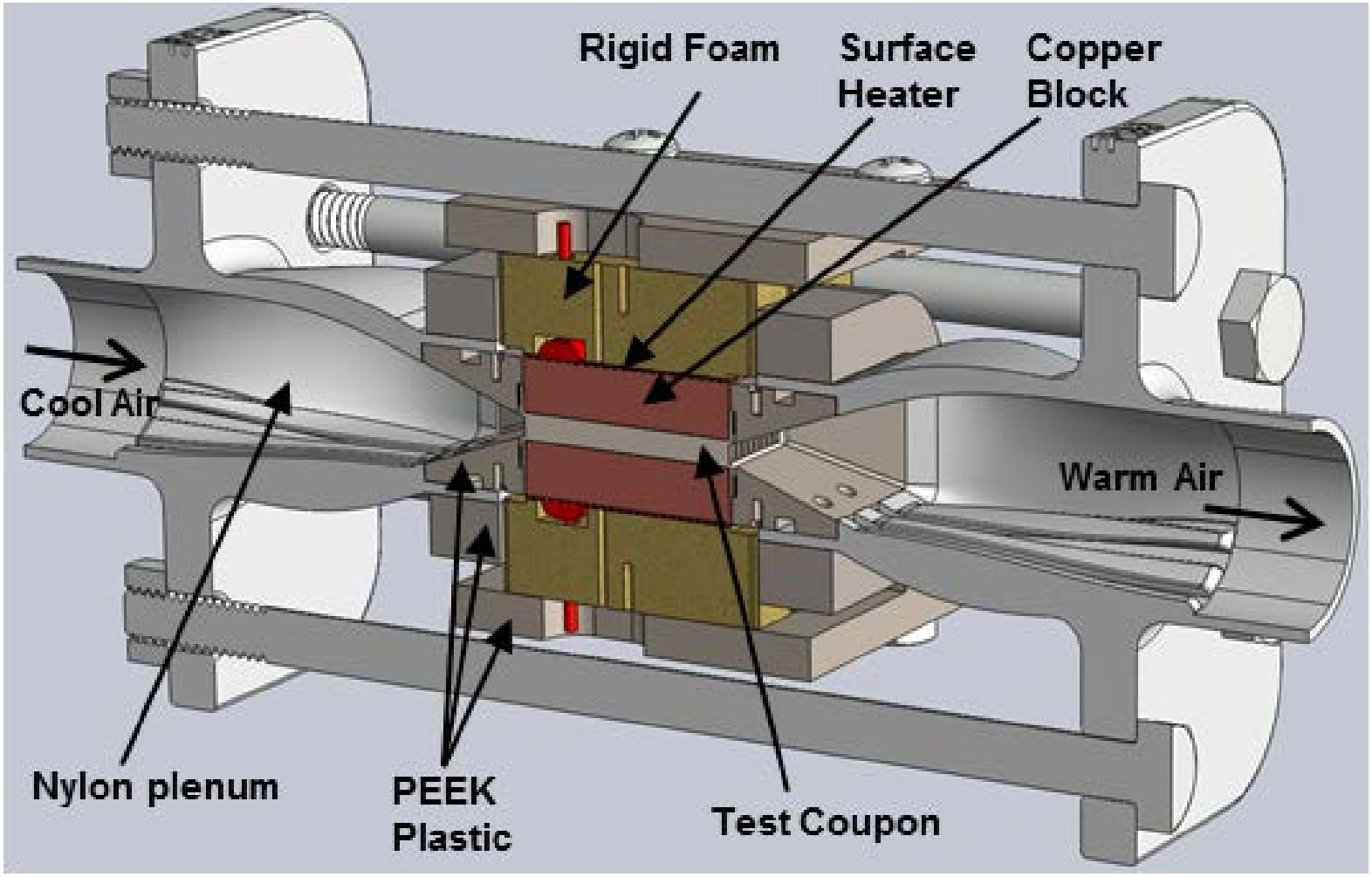
"3D Printing is moving from a nicety to a necessity" – Boeing Engineer, 2014

Novel Internal Geometries



Source: Morris Technologies

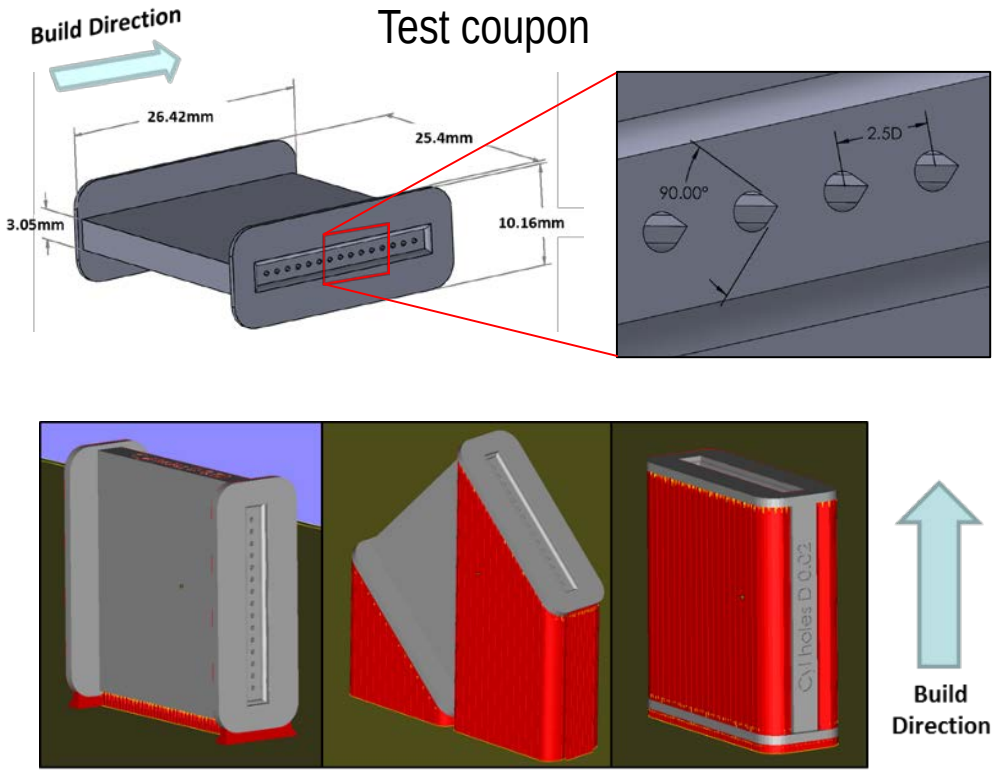
START Gas Turbine Lab at Penn State



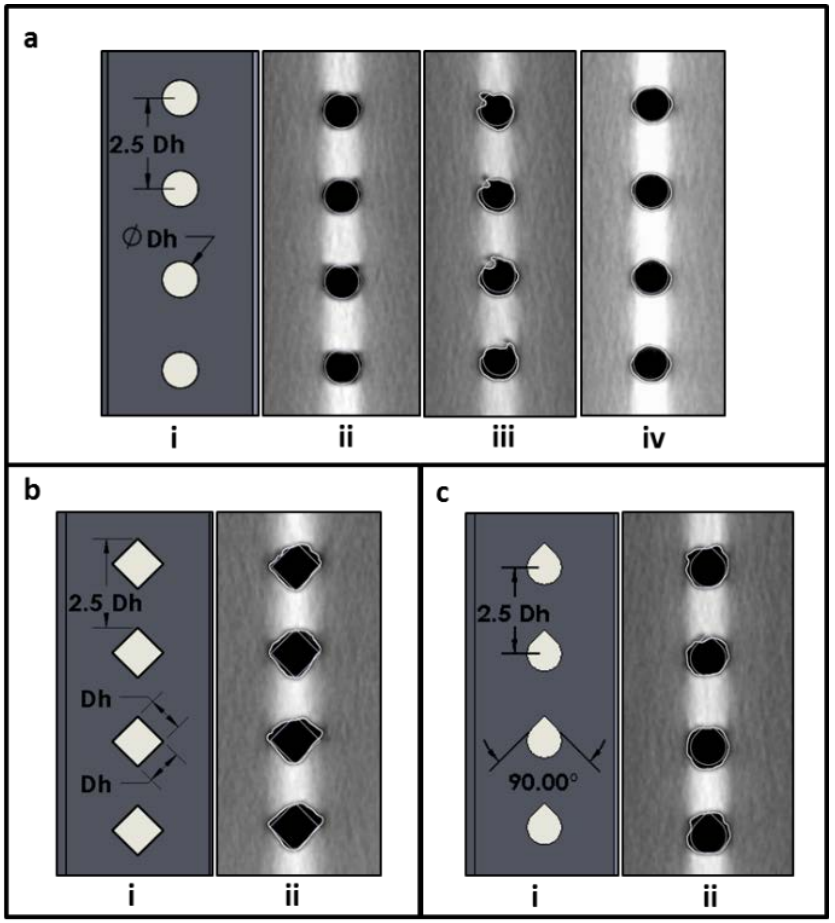
Courtesy: Jacob Snyder, Curtis Stimpson, and Karen Thole (PSU) & Dominic Mongillo (P&W)

Novel Internal Geometries

Working with PSU START Lab to evaluate internal channels for gas turbines



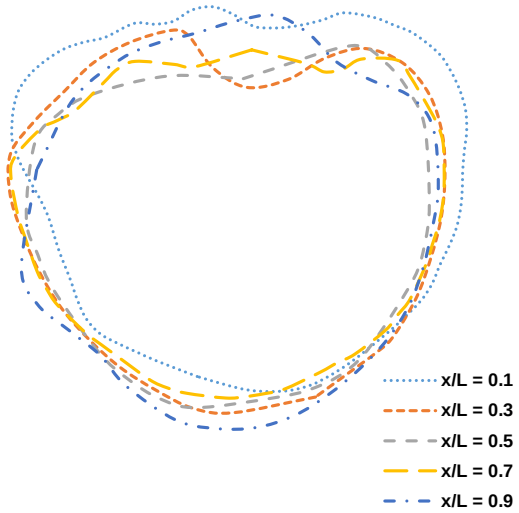
Courtesy: Jacob Snyder, Curtis Stimpson, and Karen Thole (PSU) & Dominic Mongillo (P&W)



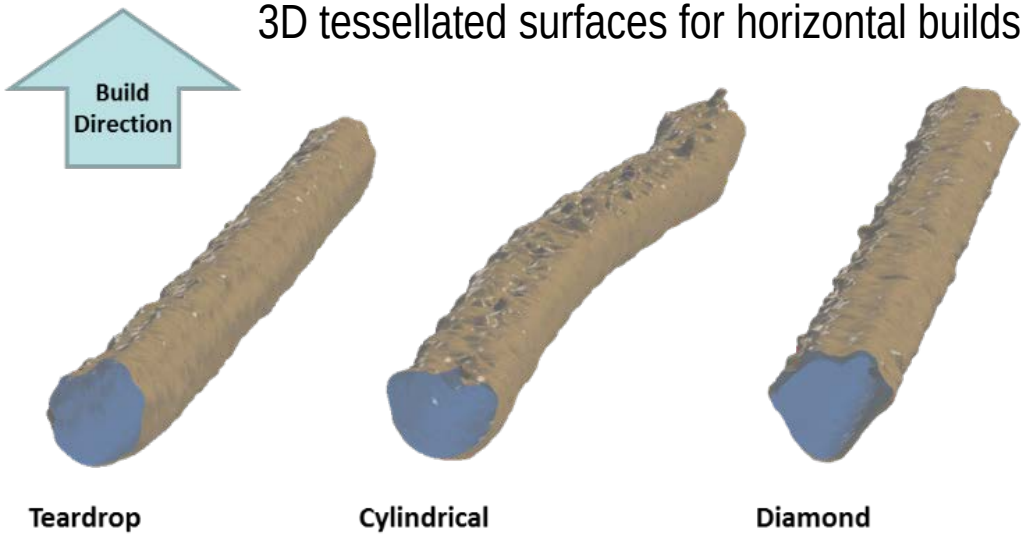
Different hole geometries: designed vs. built

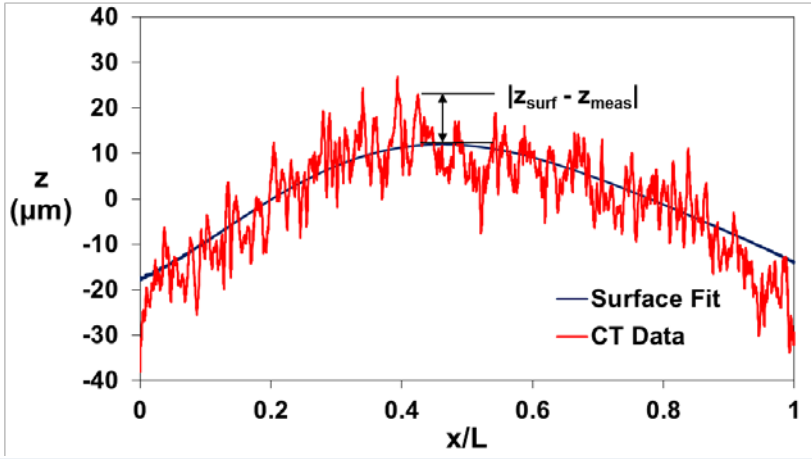
Build Results

Axial slices of cylindrical channel – horizontal build



3D tessellated surfaces for horizontal builds





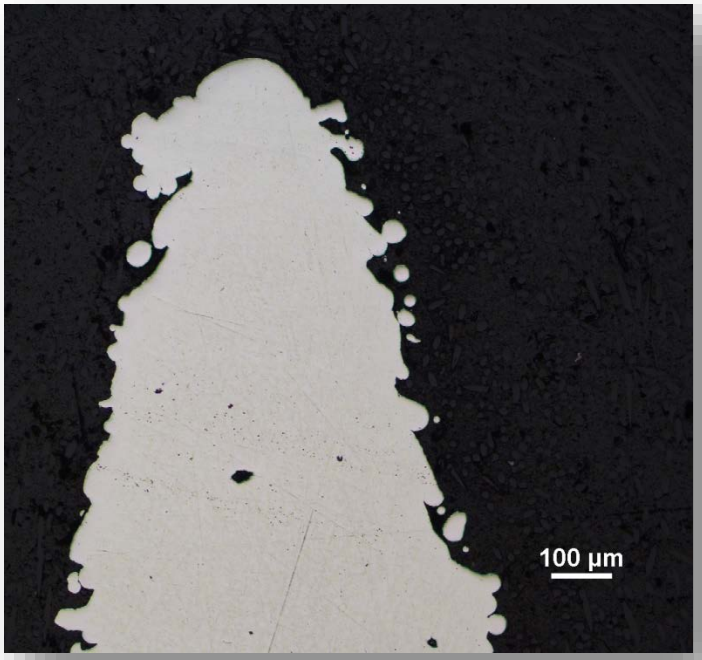
Surface roughness of a slice through cylindrical channel of a vertical build

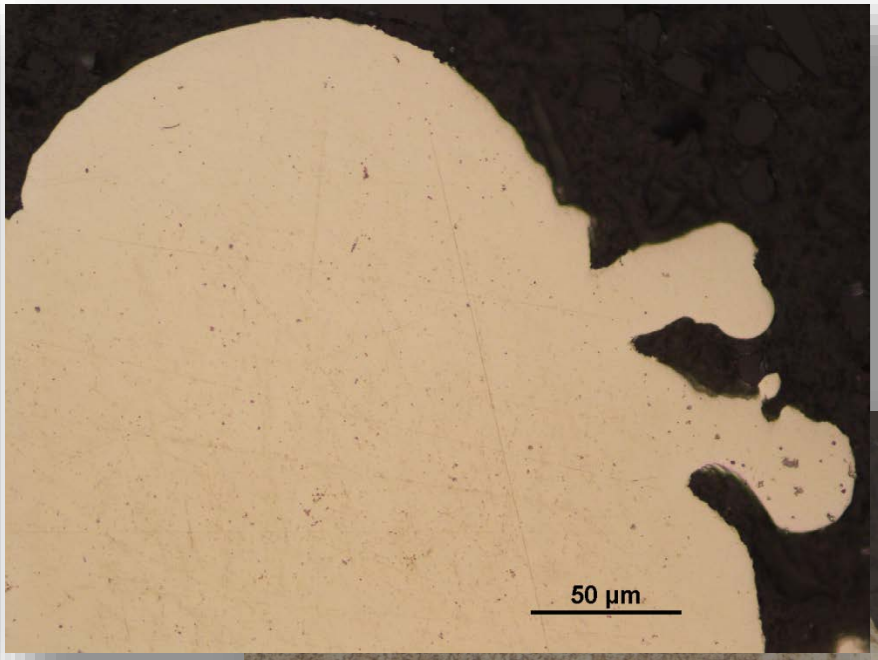
Build geometry and build orientation interaction is significant in many cases

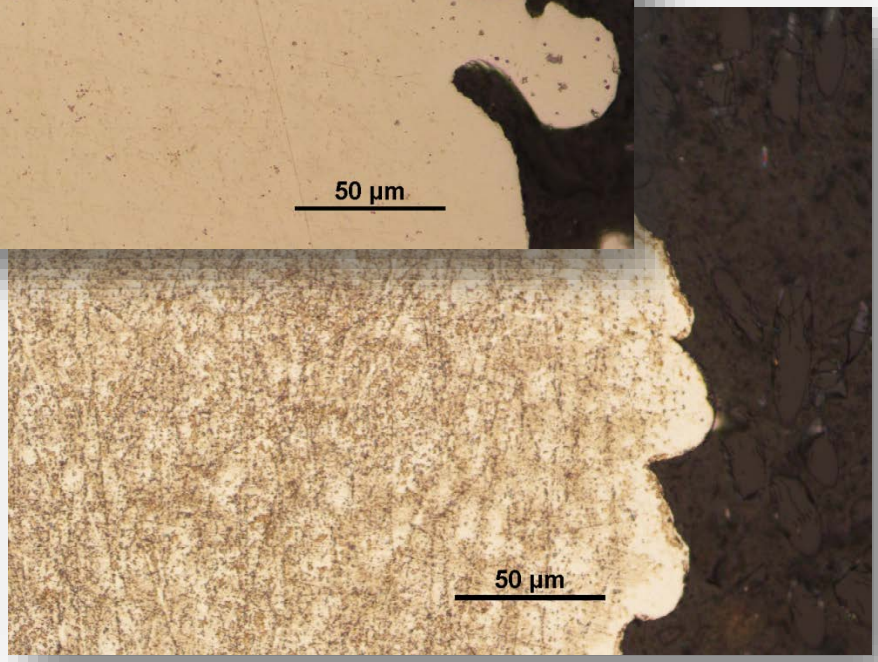
Courtesy: Jacob Snyder, Curtis Stimpson, and Karen Thole (PSU) & Dominic Mongillo (P&W)

Partially Fused Feedstock

EOS Aluminum - AlSi10Mg

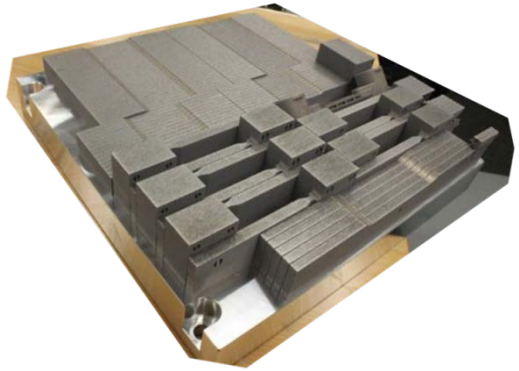






Microscopy from
CIMP-3D and
ARL Penn State

Cost Considerations



Total Cost includes:

- Design-for-Manufacturing
  + Build Time
    + Material (Build Platform + Powder + Gas + Other Consumables)
      + Stress Relief / HIP
        + Removal from Build Plate (Wire EDM, Powder Removal)
          + Heat Treat
            + Finishing (Shot Peen, Harperize, Electropolish, MMP, Abrasive Flow Machining)
              + Final Machining
                + Quality Assurance (Calibration Builds, NDE, Witness Coupon Testing, etc.)
                  + Build Documentation

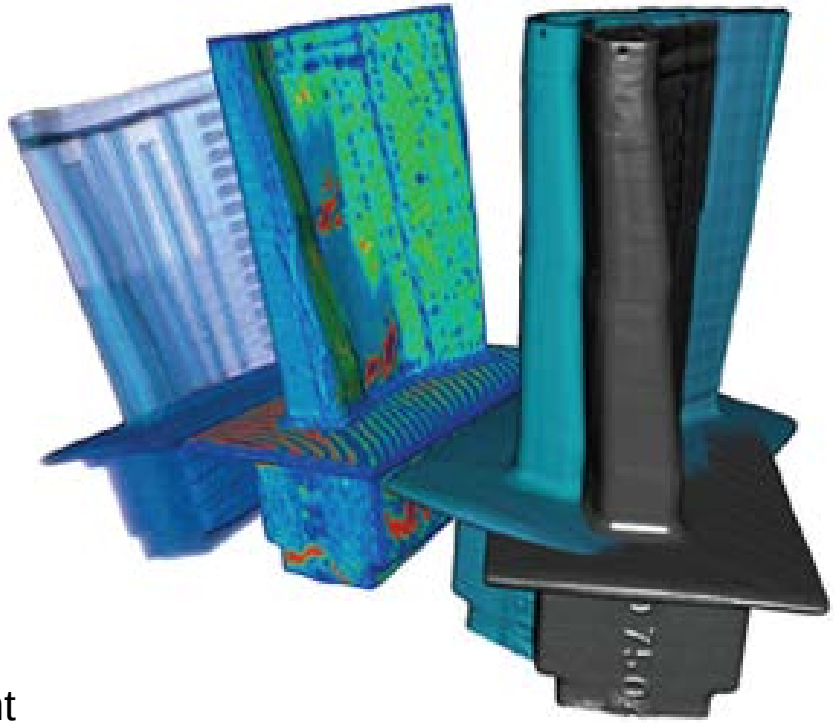
- Build Time considerations:
  - Supports
  - Build Height (Orientation, Recoater Time)
  - Build Density (Exposure Time)

- Material considerations:
  - Build Height
    - 6 inch of Ti6Al4V requires ~$40k powder!
  - Recyclability?
  - Alternate Powder Source?`

Non-Destructive Inspection

- **Computed Tomography (CT) scanning has potential to reduce cost and time in quality evaluation and part validation**

General Electric Company
(http://www.ge-mcs.com)



General Electric Company
(http://www.ge-mcs.com)

Computed Tomography

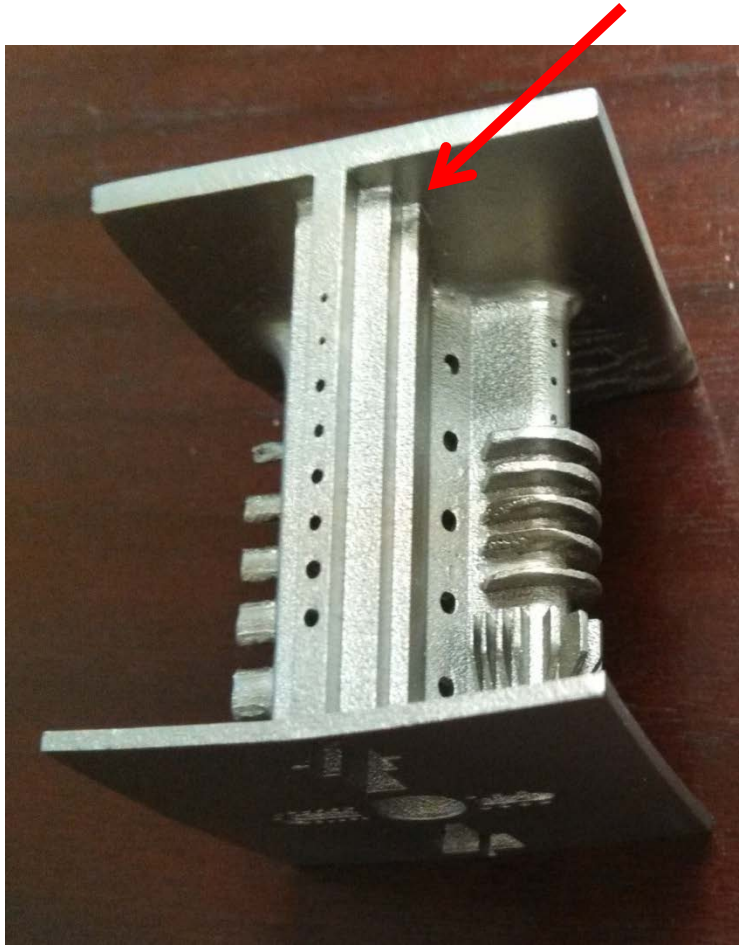
- < 1 micron resolution
- Samples: 360 mm diameter x 600 mm height
- (3D scanning: 390 mm diameter x 400 mm)
- 3D metrology report in an hour

Test Part

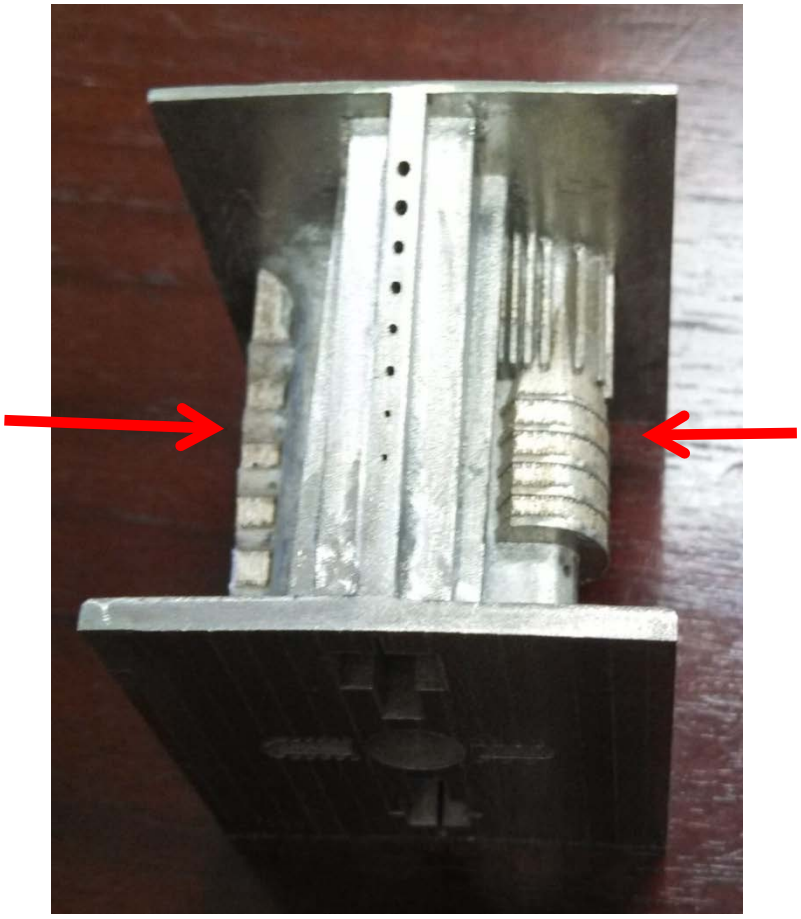
A test block model developed by Andrew Coward[1] at Penn State was provided to different job shops using EOS M270 system to serve their customers. They all received the same CAD file…

[1] In collaboration with Karen Thole, MNE, http://www2.mne.psu.edu/psuturbine/

Same Design – Very Different Results

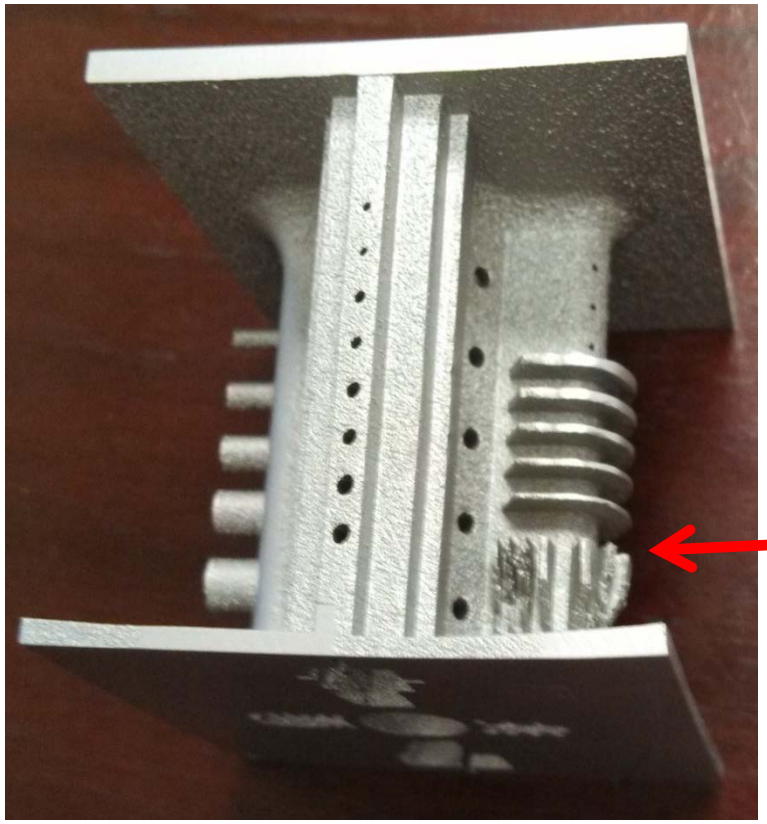


#1: Test part with defect layer

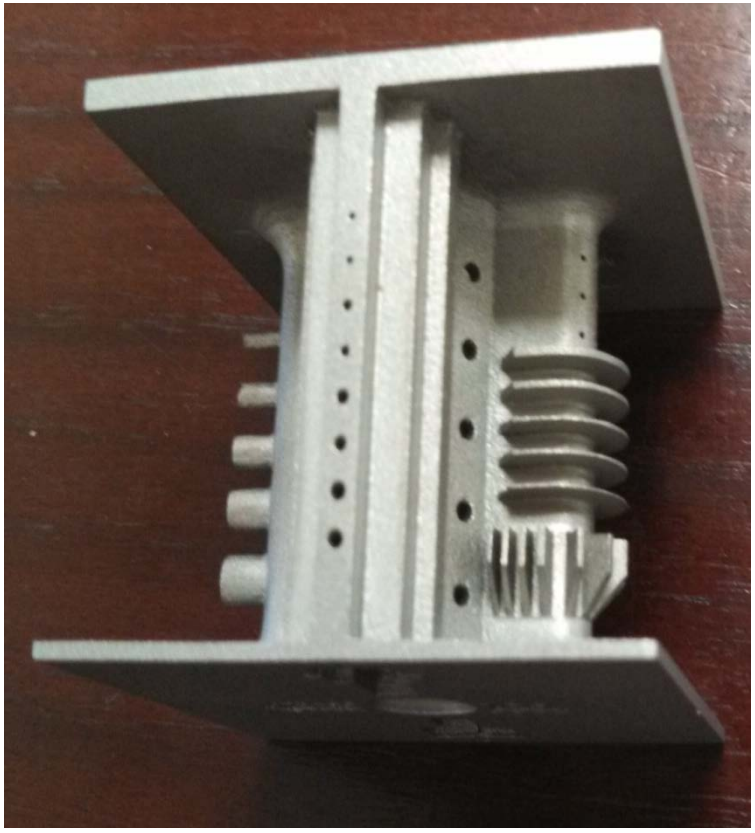


#2: Test part with supports

Different Vendors Build Different Parts

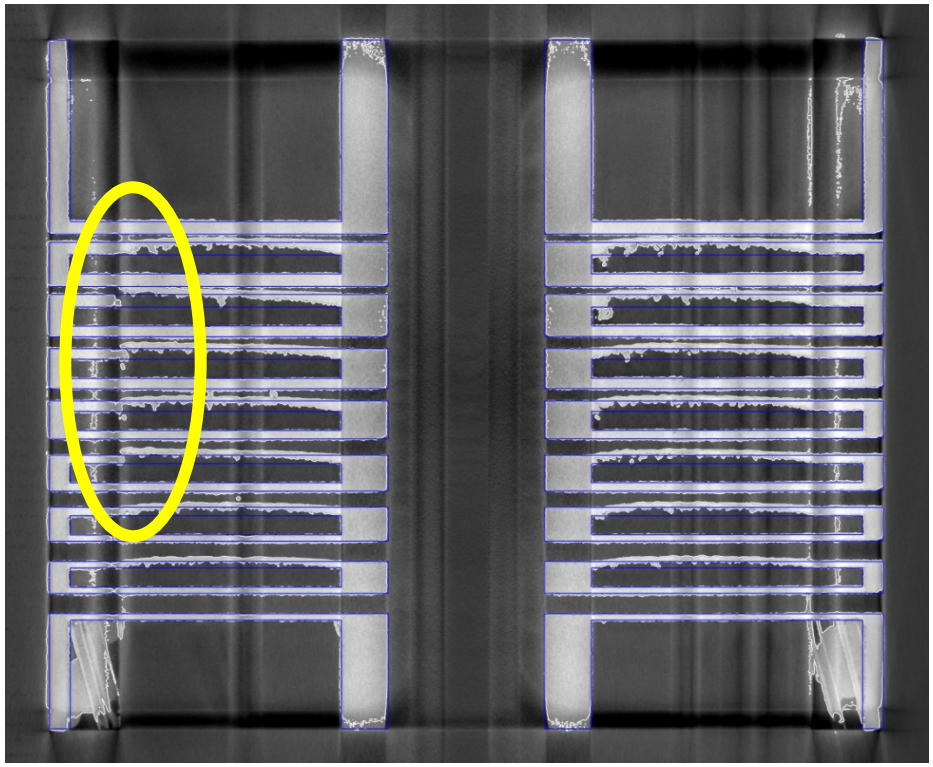


#3: Test part with malformed fins



#4 Test part with broken piping (least amount of warping)

CT Scan of Internal Features



Internal features, while problematic for laser or photo-based 3D scanning, can be obtained and compared directly using tomography absorption data

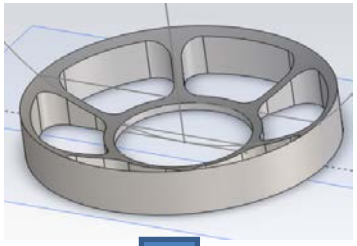
- **CIMP-3D is a world-class facility for developing and implementing additive manufacturing technology for critical metallic components**

- **Mission**
  1. Advance enabling technologies required to successfully implement AM technology for critical metallic components and structures
  2. Provide technical assistance to industry through selection, demonstration, and validation of AM technology as an "honest broker"
  3. Promote the potential of AM technology through training, education, and dissemination of information

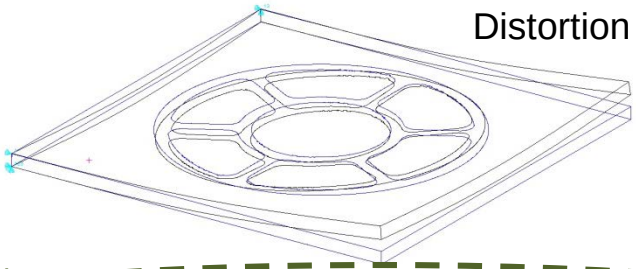
- **CIMP-3D serves as the DARPA Open Manufacturing Program's Manufacturing Demonstration Facility for Additive Manufacturing**

Integrated Research for AM

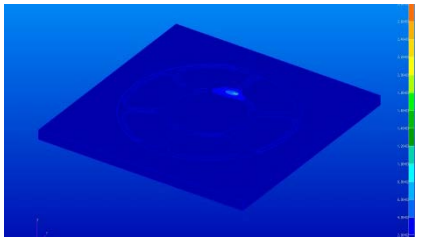
CAD



Distortion

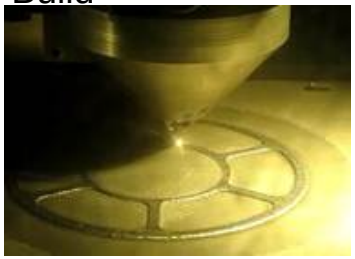


Residual Stresses

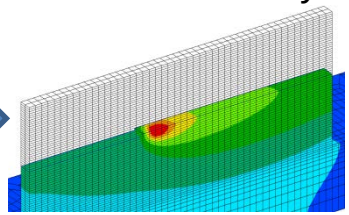


Analysis & Modeling

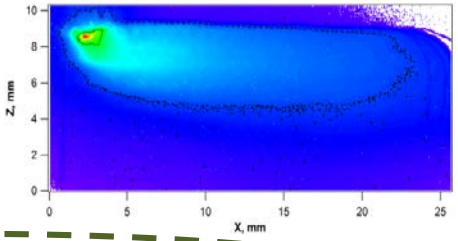
Build

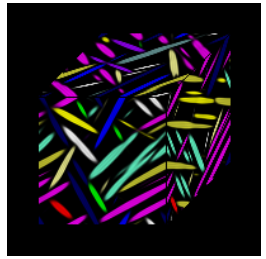


Thermal History



Thermal Imaging



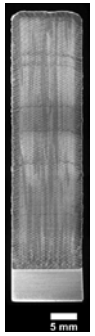


Microstructural Modeling

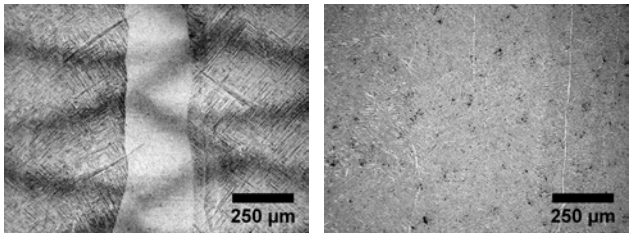
Experimental Validation

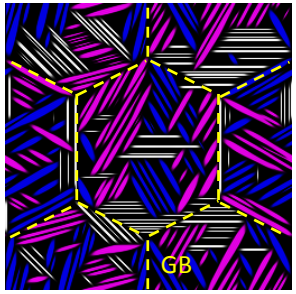
Part

Test Specimens



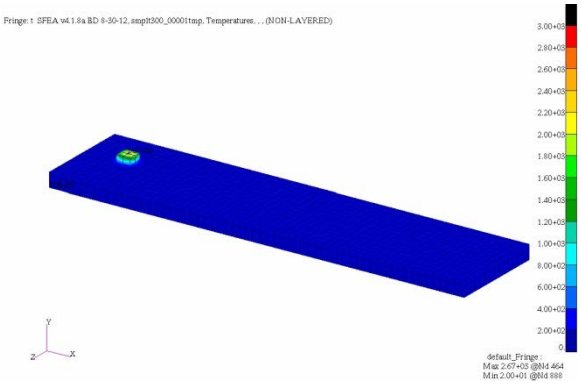
Microstructural Characterization

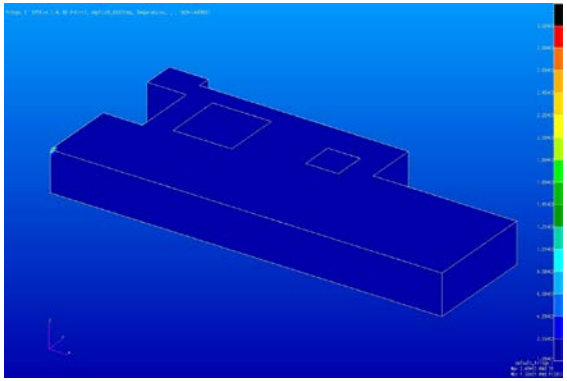


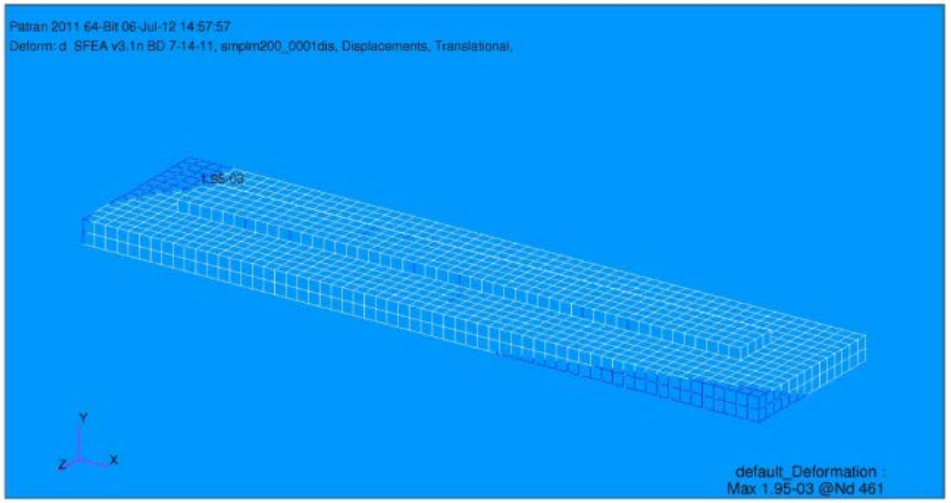


Thermal-Mechanical Modeling

- **Thermal-mechanical modeling and simulation can be used to predict resulting distortion and residual stresses for each AM process**







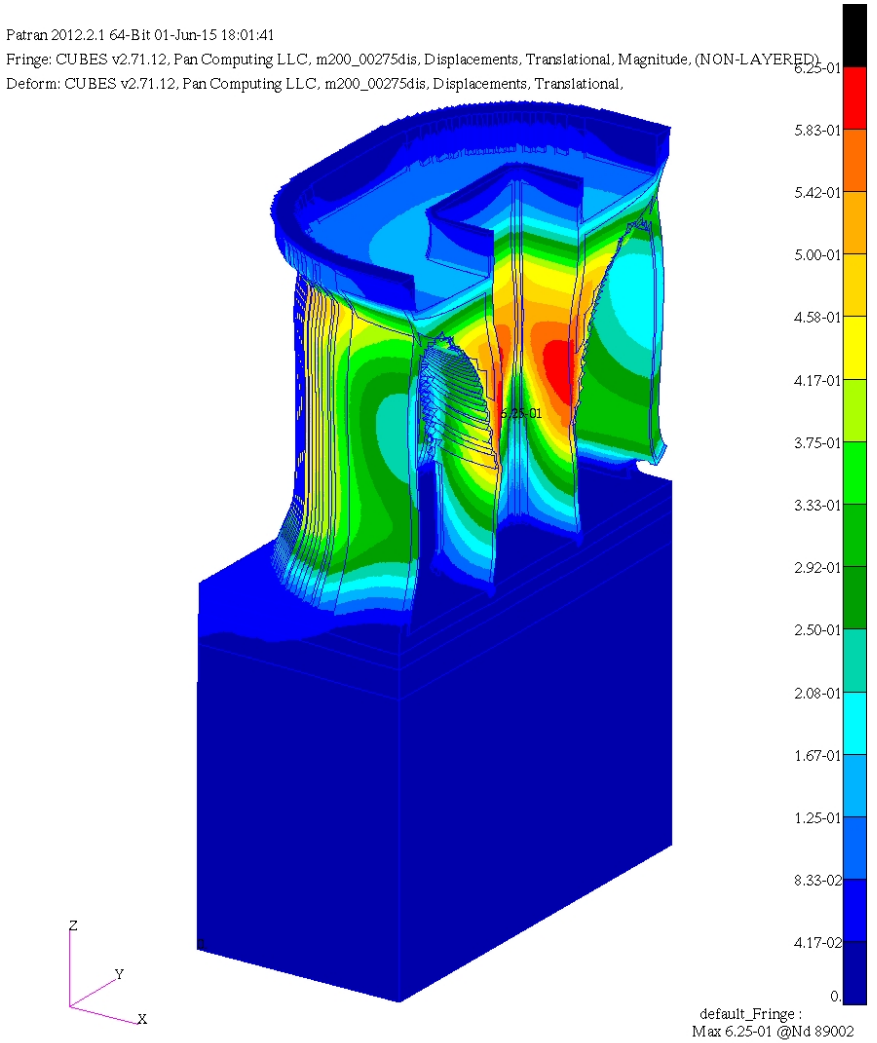
Software available through Pan Computing, LLC (http://www.pancomputing.com)

Videos available at: http://www.me.psu.edu/michaleris/research/DDM/ddm12.html

CUBES® Part-Scale Modeling

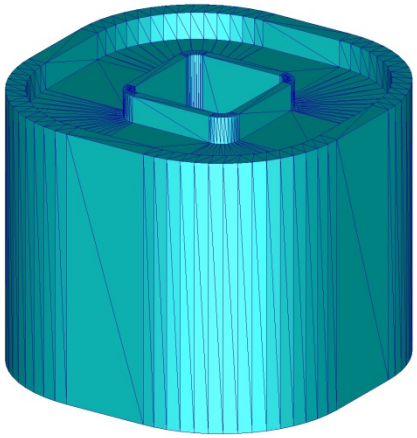
- Multi-scale approach using fine- and part-scale models
- Geometry imported from STL file
- Substrate is added
- Mesh is auto generated
- Mesh fine in active layer
- Mesh coarsens below activated layer to reduce computation time

(Denlinger & Michaleris, 2015)

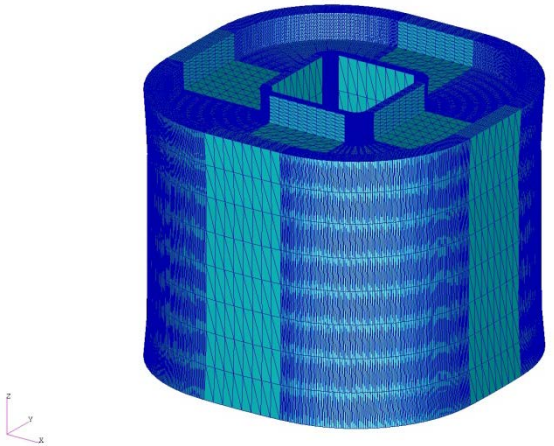


Final part distortion (mm, X5)

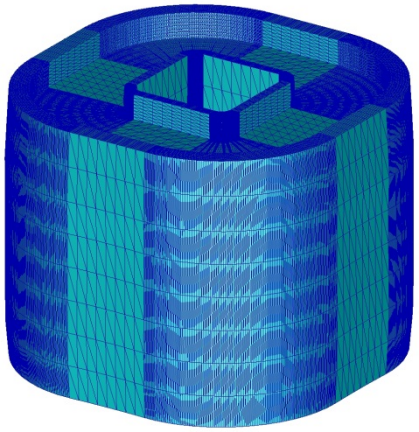
Distortion Compensation
(Denlinger & Michaleris, 2015)



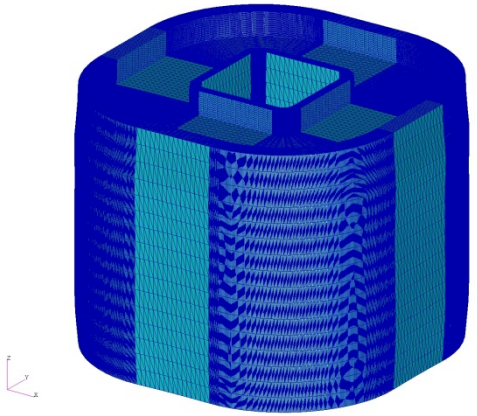
Desired STL geometry



Distorted STL geometry



Compensated STL geometry



Compensated STL geometry
High Resolution

Closing Thoughts

- **Additive manufacturing removes many of our design constraints**
  - Design for manufacturing → manufacturing for design
- **Lots of excitement in many industries**
  - Aerospace: light weight components, improve buy-to-fly ratio
  - Medical: custom devices and implants, improved recovery
  - Energy: novel internal geometries to improve cooling
  - Oil and gas: multi-material applications to improve tool life
- **Gas turbine industry can benefit significantly from AM**
  - Novel part geometries for improved performance
  - Functionally-graded materials and multi-material options
  - Embedded sensors for structural health monitoring and prognostics
- **Significant challenges exist but coordinated modeling, simulation, and validation efforts will help us overcome them – we need to collaborate!**

- **To learn more about CIMP-3D and our Technology Exchanges, visit:**

http://www.cimp-3d.org/

or contact us at:

CIMP-3D Director	Co-Director	Co-Director
Rich Martukanitz Head, Laser Processing Division, Applied Research Laboratory	**Timothy W. Simpson** Professor of Mechanical & Industrial Engineering, Penn State University	**Gary Messing** Distinguished Professor and Head, Material Science & Engineering, Penn State University
rxm44@arl.psu.edu	tws8@engr.psu.edu	messing@ems.psu.edu

Other AM Resources