Presented to

DOE Advanced Manufacturing Office
2015 Peer Review

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Washington, DC

This presentation does not contain any proprietary, confidential, or otherwise restricted information.

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OAK RIDGE National Laboratory | MANUFACTURING DEMONSTRATION FACILITY

Outline

- Manufacturing Demonstration Facility Overview
- Development and Deployment of Advanced Manufacturing Technology
  - Technology Development
  - Deployment to Industry
- Outreach/Community Engagement
  - Industry (workshops, exec. summits)
  - Internships
  - Workforce Development
- Summary

MDF supports AMO's mission

DOE-AMO Mission

- **Develop and demonstrate new, energy-efficient processing and materials**
  - broadly applicable
  - improved products and reduced lifecycle energy consumption
- **Technical assistance to**
  - promote use of advanced technologies
  - capture U.S. competitive advantage in clean energy manufacturing

Manufacturing Matters

- **12.5% of U.S. GDP**
- **12 million U.S. jobs**
- **70% of U.S. engineering and science jobs**
- **75% of U.S. Exports**
- **17% of the world's manufacturing output**
- **25% of US energy use**

Manufacturing Demonstration Facility

A public-private partnership to engage industry with national labs

Core Research and Development	Industry Collaborations	Education and Training
• R&D in materials, systems, and computational applications to develop broad dissemination of additive manufacturing	• Cooperative research to develop and demonstrate advanced manufacturing to industry in energy related fields	• Internships, academic collaborations, workshops, training programs, and course curriculum for universities and community colleges.

Leveraging ORNL's Science and Manufacturing Capabilities

Neutron scattering: SNS and HFIR

- World's most intense pulsed neutron beams
- World's highest flux reactor-based neutron source

Leadership-class computing: Titan

- Nation's most powerful open science supercomputer

Advanced materials

- DOE lead lab for basic to applied materials R&D
- Technology transfer: Billion dollar impacts

Advanced manufacturing

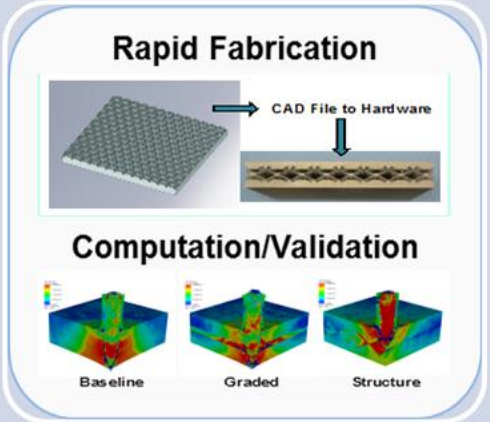
- Novel materials
- Advanced processing

Understanding Additive Manufacturing

Mainstream applications and beyond

Direct Fabrication

- Complex shapes or designs only possible from additive manufacturing
- High yields for specialty materials
- Improved production time



Prototyping and ICME

- Using additive and computation to simulate and experimentally validate design
- Can provide structural or functional data rapidly
- Final part may be conventionally fabricated

Tooling & Indirect Fabrication

- 37% of tool and die business closed within the last decade
- Long lead times for tooling and dies
- Costly and timely repair or refabrication of tooling

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Transition to Mainstream Manufacturing

The global manufacturing R&D community is moving rapidly forward on a broad front to develop AM and realize its economic benefits.

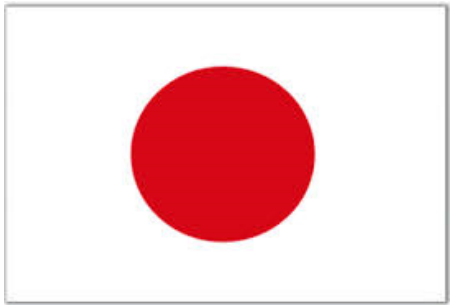
Europe *2007-2013: >60 projects on AM technologies, total budget of* ***~€225 million****.*

Source: Report from the EC Workshop on Additive Manufacturing, 18 June 2014

China *Next 7 years: 1.5 billion yuan (****$245 million****) project to boost development of additive manufacturing.*

Source: Wohlers Report

Japan 2014: 4 billion yen (**$38.6 million**) in funding 3D printing projects.



Source: IHS Market Insight Report. "Asia investing heavily in 3D printing technology" Alex Chausovsky. July 14, 2014.

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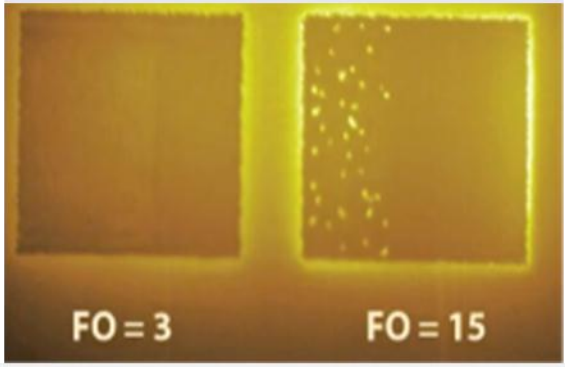
AM is an exciting, high-potential technology that is in the embryonic stage of development

Warping in Conventional Materials

Columnar Grain Growth

Porosity Due to Focus Offset Values



Challenges with additive manufacturing technologies and deployment include

Materials

- Costly Material Feedstocks
- Limited Materials
- No AM Developed Materials
- Required Materials Specifications & Practices

Process Limits

- Limited Sensor Employment
- No Closed Loop Control
- Slow Processing
- Limitations in Build Volumes
- Post-Processing Required

Reliability

- High Variability
- Lack of Understanding On How Local Microstructure Impacts Properties
- Warping
- Anisotropic Properties

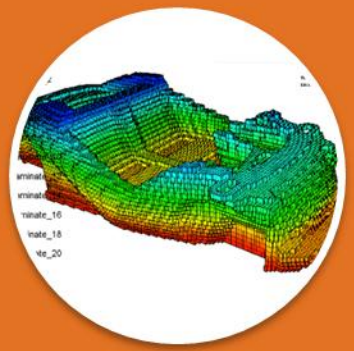
Most companies do not have the background and resources required to mature the technologies or commercialize additive manufactured components.

R&D to enable broader AM application

ORNL is working to understand challenges and accelerate technology implementation

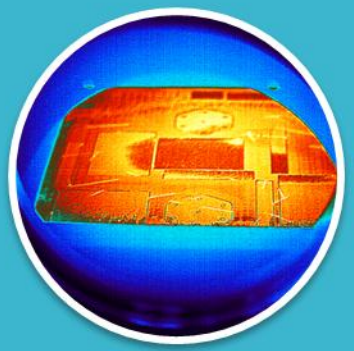
Improved and AM-Specific Materials Development

- High Temperature Applications
- Light Weighting
- Bio Derived Materials
- Functional Materials



AM Process Science

- Material Property Dependency on Process Inputs
- Computational Framework for Data Visualization and Analytics
- Topology optimization for AM



Process Characterization for Qualification

- In-Situ Non-Destructive Evaluation
- Neutron Diffraction and Imaging
- Coupling to National Laboratory Network

Exploring Next-Generation Systems

- Bigger, Faster, Cheaper, & Better
- Integrating the Supply Chain
- Working with Current and Future Equipment Developers

Integrated Process and Material Understanding

Supporting Industry and R&D with a Wide Range of AM Capabilities

Electron Beam Melting

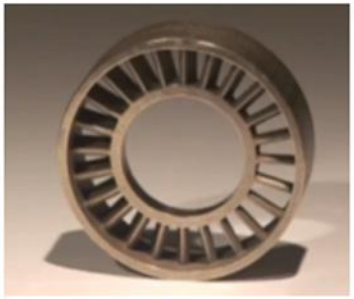
CAD TO METAL
Arcam AB

Laser Sintering

RENISHAW

Laser Blown Powder Deposition

Binder Jetting



ExOne
DIGITAL PART MATERIALIZATION

Fused Deposition Modeling

Solidoodle
MakerBot
Cubify

Multi-head Photopolymer

OBJET
Stratasys
FOR A 3D WORLD

Large-Scale Polymer Deposition

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CINCINNATI
CINCINNATI INCORPORATED

Future Systems

CONCEPTLASER
hofmann innovation group

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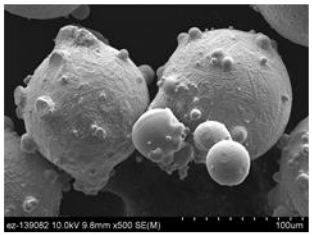
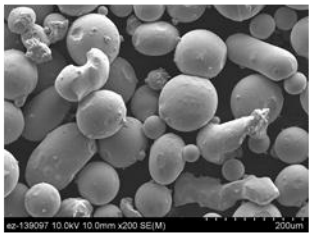
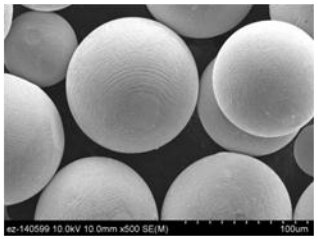
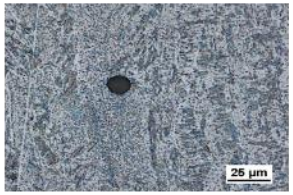
Developing the Powder Characteristics Required for Powder Bed Technologies



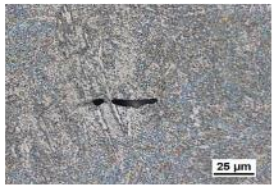


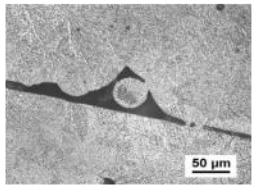


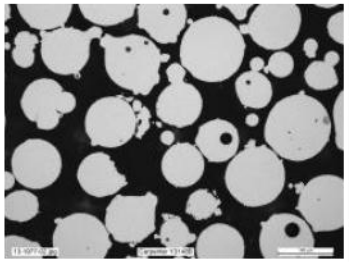
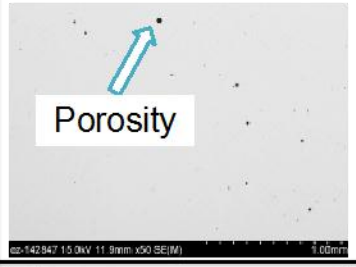
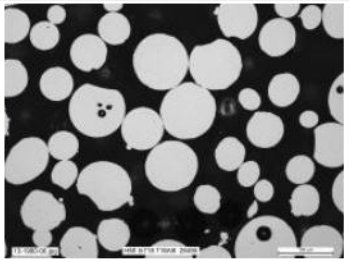
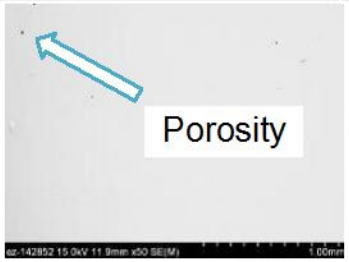
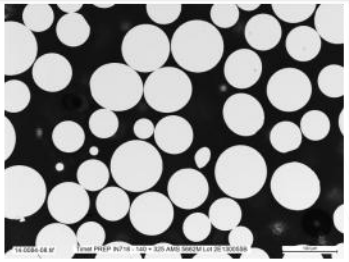
Powder Induced Porosity



Process Induced Defects





	Powder	As Deposited	
Gas Atomized			Porosity in Powder = 0.873% Porosity in Deposit = 0.117%
Rotary Atomized			Porosity in Powder = 0.491% Porosity in Deposit = 0.037%
Plasma Rotated Electrode			Porosity in Powder = 0.000% Porosity in Deposit = 0.000%

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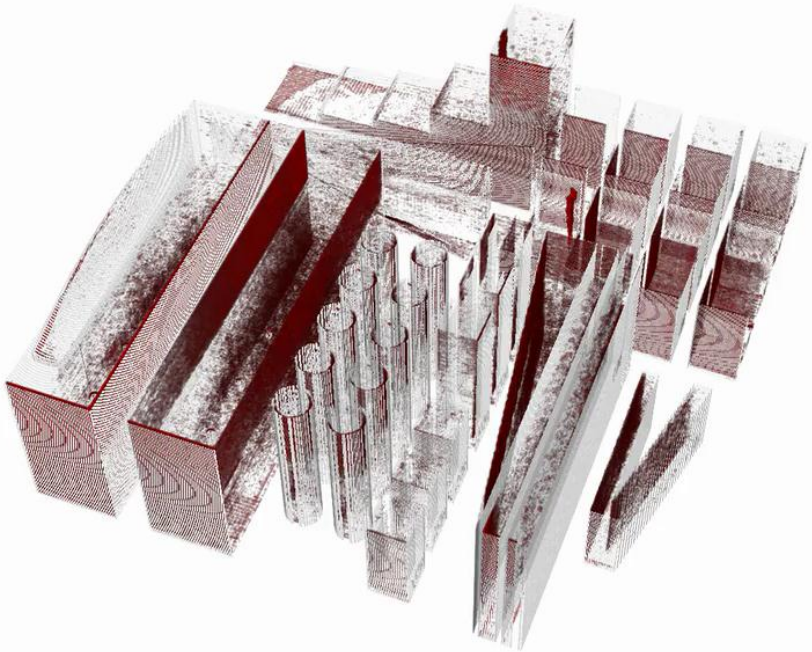
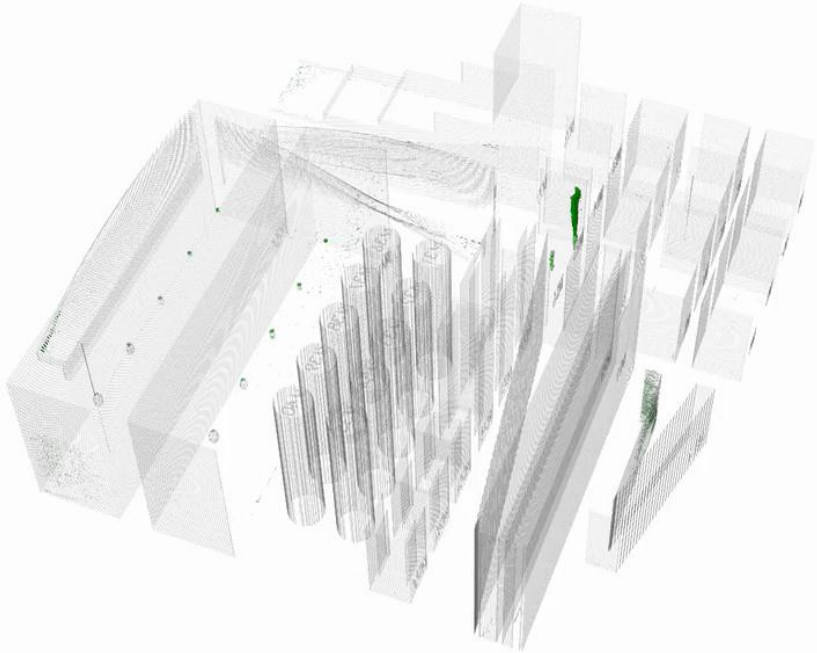
Improved Porosity Detection in Electron Beam Deposition

- ORNL developed graphical user interface working with Arcam Layer CAM
  - Edge detection significantly improves results for porosity detection
  - ORNL software will be publically available
- Developments in Continuous In-Situ NDE Using Infrared
  - Both porosity and temperature measurements

Shutter system inside chamber to eliminate metallization build up during processing



Initial algorithm with no edge detection



Now algorithm WITH ORNL edge detection

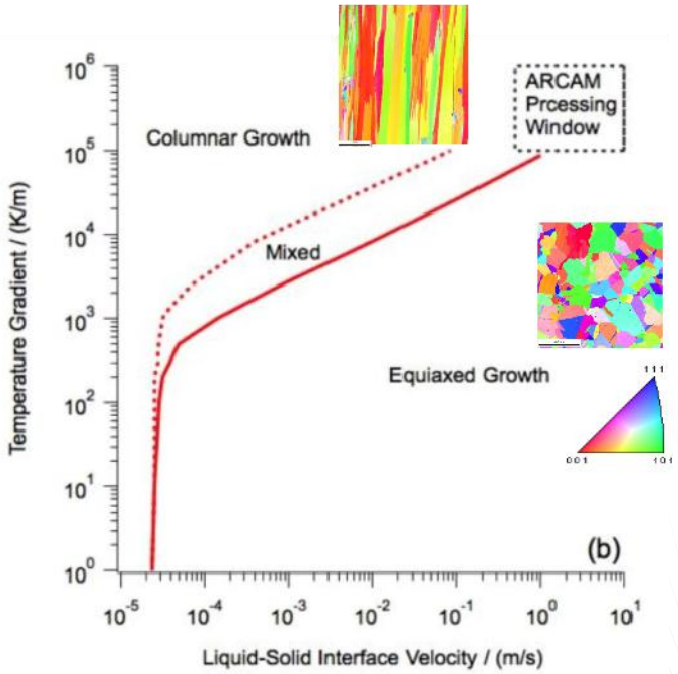
ORNL research reveals unique capabilities of 3D printing

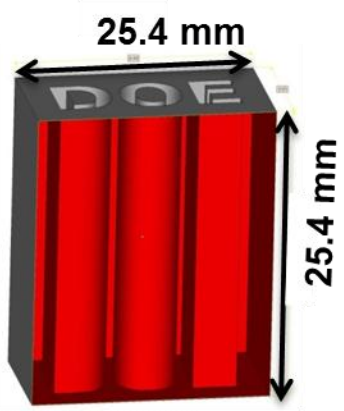
"ORNL's EBM Discovery 'Potentially the Most Important Development in Metal Additive Manufacturing' to Date."

-Brian Krassenstein, 3dprint.com Oct. 2014

Most Highly Read Article in MS&T Last 3 Months

Downloaded Over 1,100 Times





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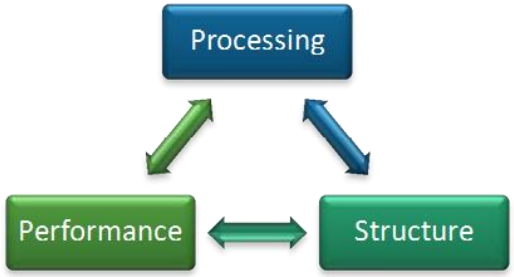
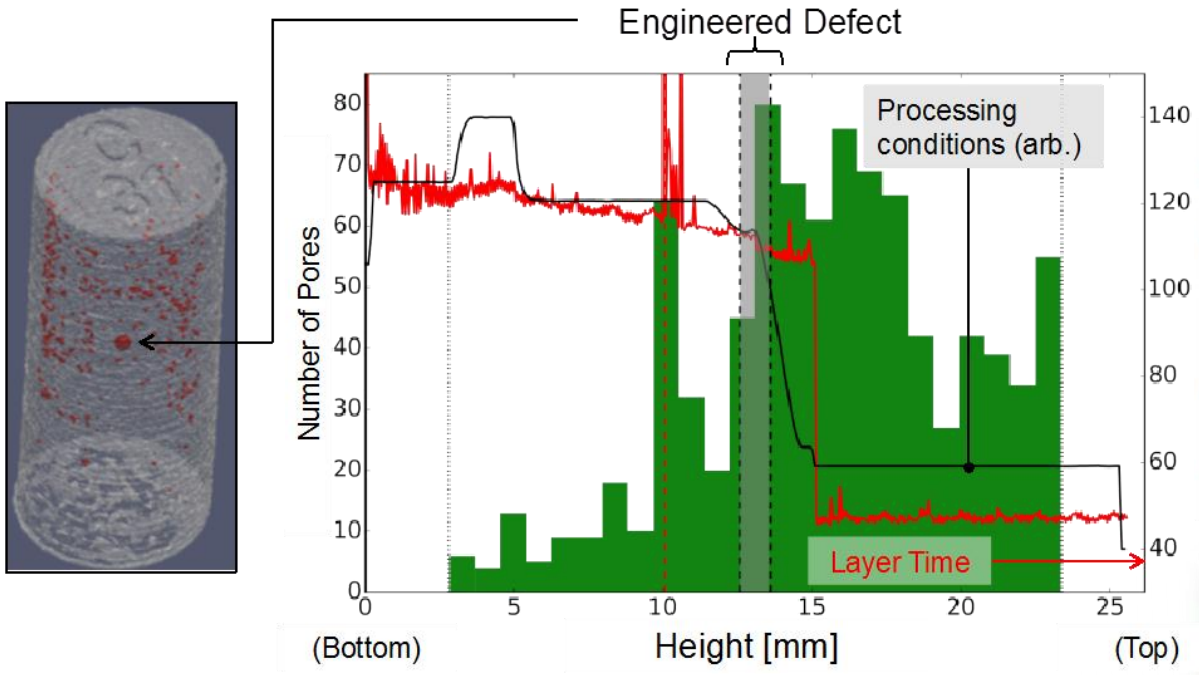
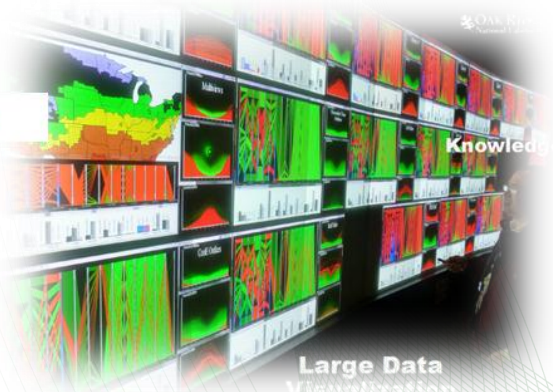
Large data analysis is path to AM process qualification



Collaboration with AFRL to develop certification methodology for AM components



Anomaly/interruption: Execution ↔ Outcome correlation
Late stage porosity: Planning ↔ Outcome



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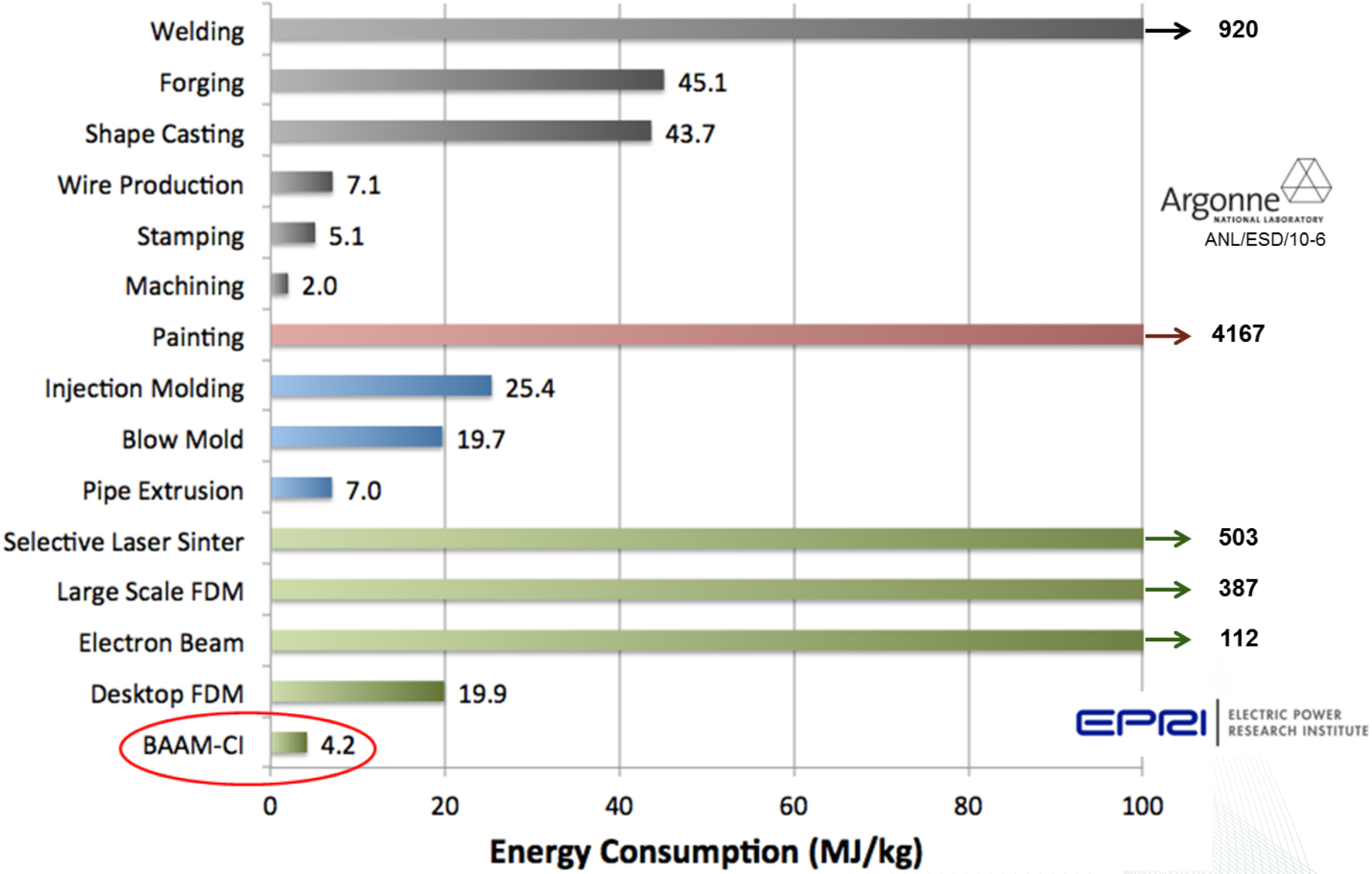
Big Area Additive Manufacturing (BAAM)

Bigger, Faster, Cheaper, Better

- **Large Scale Printers**
  - Prototype system 8'x8'x8' build volume
  - Cincinnati System 6'x12'x1.5' build volume
  - The New System 8'x20'x6'
- **Fast Deposition Rates** (~10 to 80 lbs/hr)
  - 100X to 1000X commercial systems
  - FDM is 1 to 4 ci/hr vs. BAAM up to 1,000 ci/hr
  - Extruder continuously evolving
- **Cheaper Feedstocks: Pellet-to-Part**
  - Pelletized feed replaces filament to enable 50x reduction in material cost
- **Better Materials: Carbon or Glass Fiber Reinforced Polymers**
  - Ever growing selection of materials (i.e., ABS, Ultem, PEEK, PEKK, PLA, PPS, etc.)
  - Growing assortment of reinforcing materials

Energy Intensity of Manufacturing



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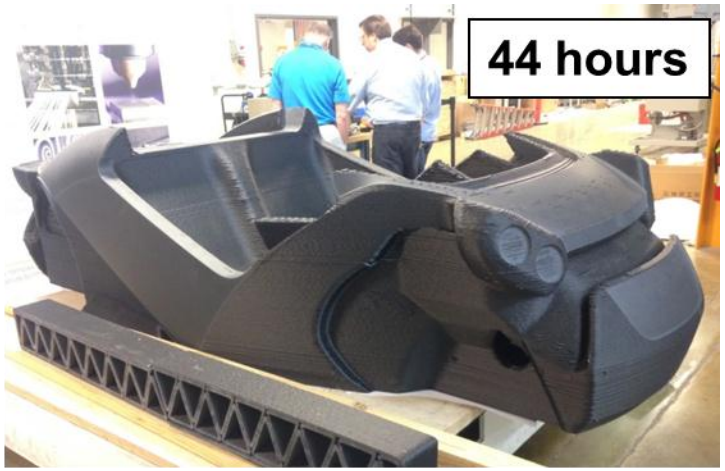
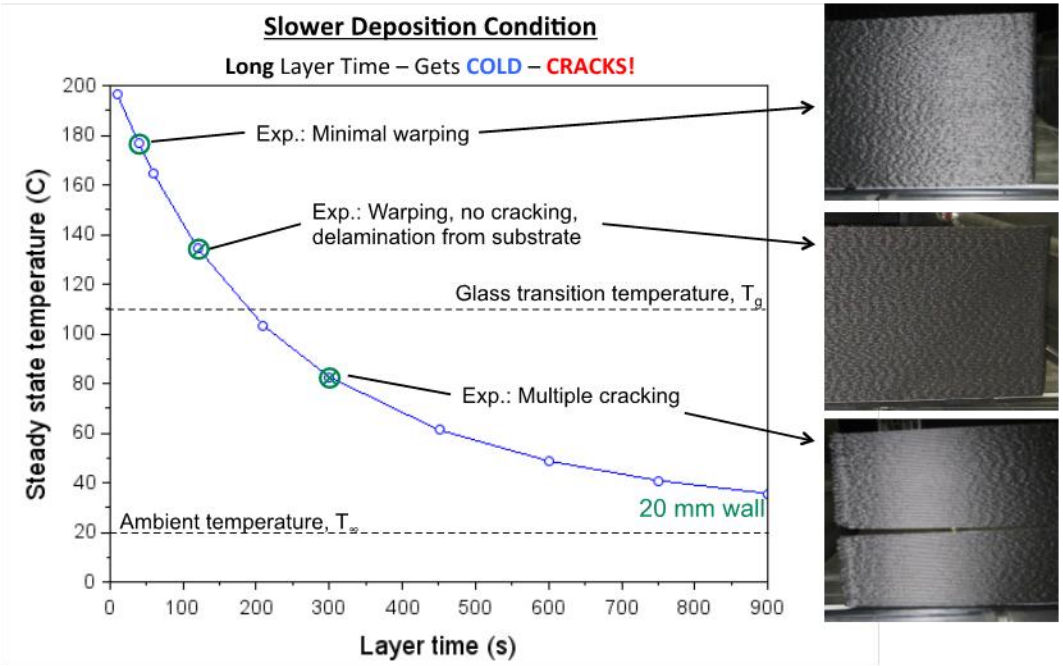
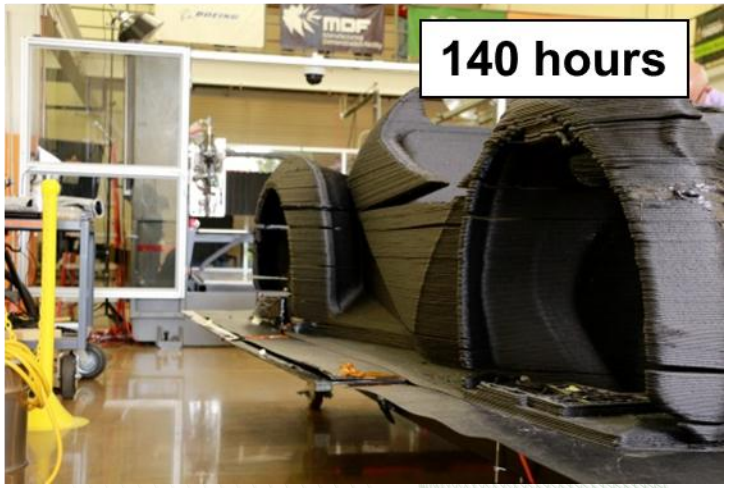
Computation and Technology Advances to Enable Printing

45.2 lb/hr





15.9 lb/hr



U.S. DEPARTMENT OF ENERGY | Advanced Manufacturing

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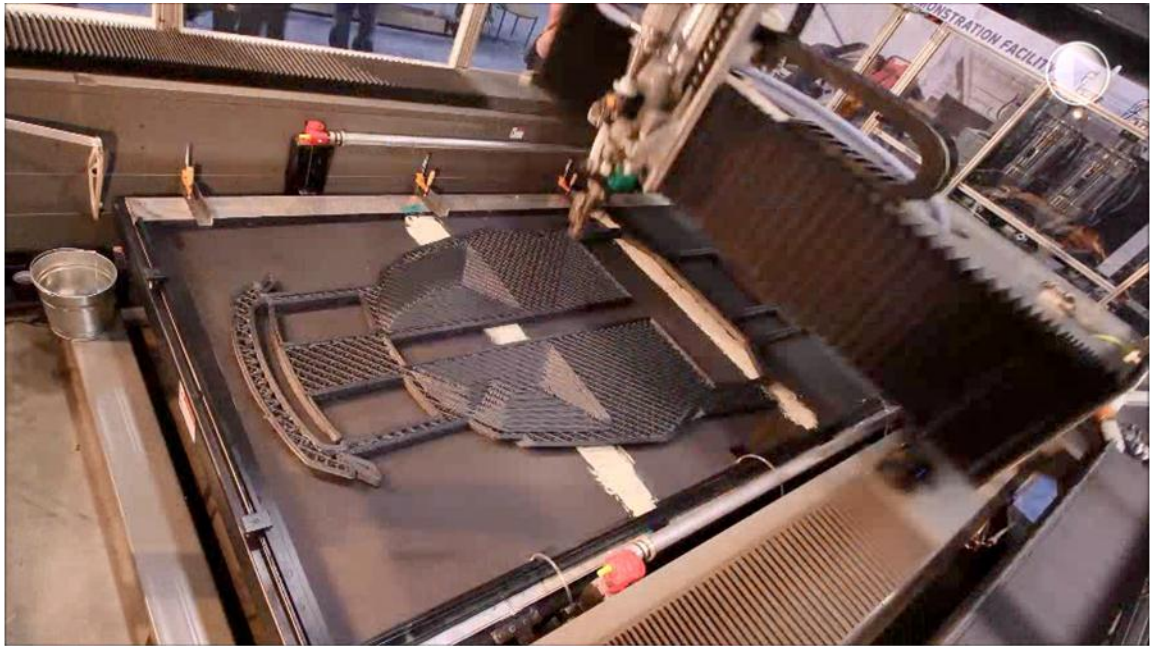
End Result: First 3D Printed Car Built in Less Than a Week



IMTS 2014

114,000 attendees

CINCINNATI
CINCINNATI INCORPORATED

LM
LOCAL MOTORS

Print time = 44 hrs

Print rate = ~35 lbs/h

Print weight = ~1600 lbs

Total weight = ~2000 lbs

U.S. DEPARTMENT OF ENERGY | Advanced Manufacturing

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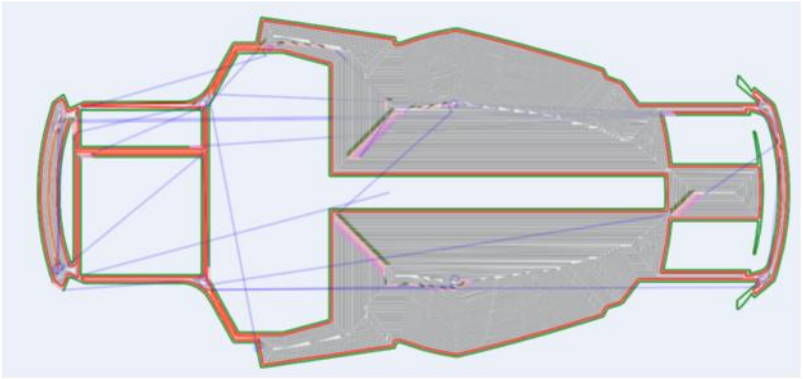
3D Finite Element Model

Big Area Additive Manufacturing

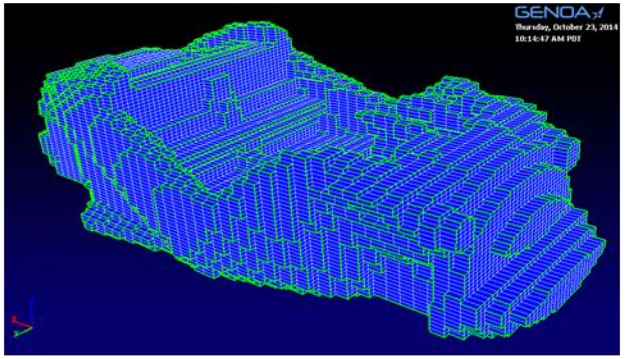
3D Model

BAAM Print Parameters

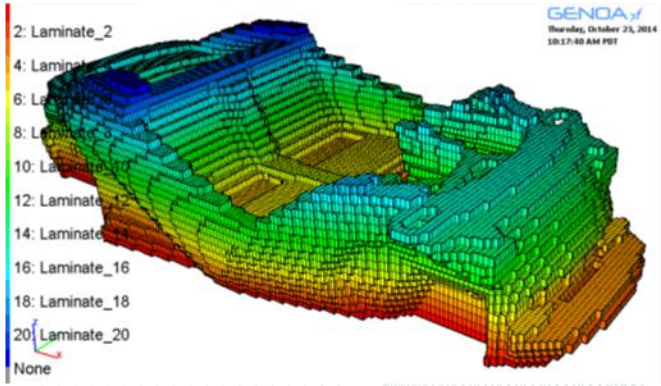


Tool Path Generation

Automated
Finite Element Mesh



Process &
Damage Analysis



AlphaSTAR

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Ever Growing Partnerships: Integrating the AM Supply Chain

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Arcam collaboration has yielded measurable outcomes

CAD TO METAL
Arcam AB®

July 2012

ORNL, Arcam sign CRADA

to improve process reliability, develop in-situ process monitoring and closed loop control, expand materials systems, increase deposition rate, and increase build volume of the Electron Beam Melting (EBM) technology

Feb 2013

Arcam and DiSanto Technology (Shelton, CT) sign Strategic Alliance

to accelerate market adoption and penetration of commercially manufactured, finished EBM-based implants and components.

June 2014

Arcam launches Nickel Base Superalloy process for 3D printing

The Inconel process is "initially" available for its A2X platform. Arcam's A2X is highly suited for processing high temperature materials and is used for aerospace applications.

June 2015

50% Arcam employees now in North America

- *Recent acquisition of DiSanto and AP&C*
- *North American technical lead resident at MDF*
- *Dramatic expansion of installed EBM systems at aerospace, NNSA and medical device companies*

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The Strati

World's First 3D Printed Car

LOCAL MOTORS™

Dec 2013

ORNL, Local Motors sign CRADA
to produce the world's first production 3D printed vehicle

June 2014

Local Motors opens location in Knoxville, TN

Sept 2014

Strati car printed live at IMTS Show
on BAAM system

Jan 2015

Local Motors announces two micro-factories at Detroit Auto Show
to be located in Knoxville, TN and National Harbor, DC

May 2015

Local Motors breaks ground on Knoxville micro-factory
co-locates with MDF

Media Mentions

for Aug 29-Sept 12, 2014

- 227 articles
- 77 online
- 100 social media
- 50 broadcast

National and International coverage!

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BAAM
World's Largest 3D Printer

CINCINNATI®
CINCINNATI INCORPORATED

BAAMCI
BIG AREA ADDITIVE MANUFACTURING

Feb 2014

ORNL, Cincinnati sign CRADA
to develop commercial large-scale additive manufacturing (BAAM) system

Sept 2014

- **Strati car printed live at IMTS Show**
  on BAAM system

- **CINCINNATI sells first BAAM beta system**

Mar 2015

Cincinnati delivers next-generation BAAM system to MDF

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ORNL prints iconic Shelby Cobra

50th Anniversary | 3D Printed, All-Electric

Nov 2014

ORNL drives innovation

to design, print, build, and finish a fully functional car in only 6 weeks!

Jan 2015

President Obama and VP Biden briefed on printed Shelby Cobra

at Techmer in Clinton, TN during the Composites Institute announcement

Next day, arrives for Detroit Auto Show

NORTH AMERICAN INTERNATIONAL AUTO SHOW

Feb 2015

Shelby goes on the road; receives impressive demand

Apr 2015

Energy Secretary Moniz takes Shelby for spin in DC

Media Mentions

for January 8-22, 2015

- **15** TV News clips
- **425** direct mentions
- **205,628** YouTube views since January

National and International coverage!

Quick Facts

- **29** stops confirmed so far
- **$62,000** transportation costs paid by companies for car appearances
- **>56** requests, to date

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Technical Collaborations Program

The MDF Model

Explore

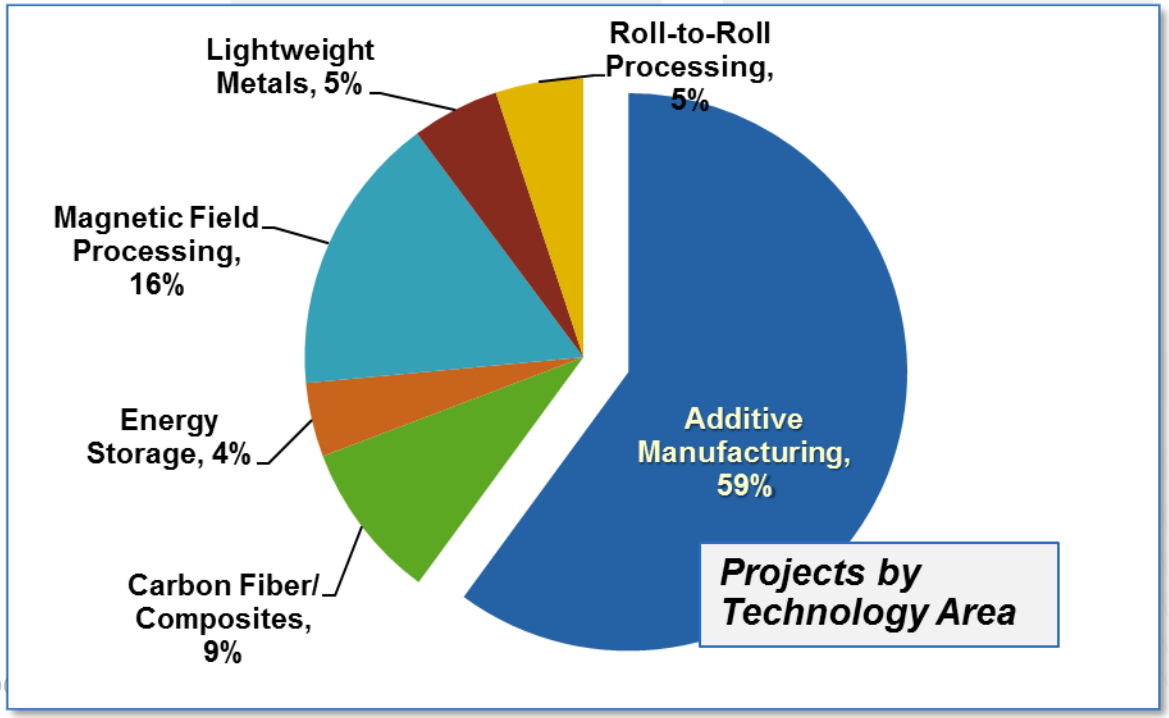
- Opportunity for industry to discover and apply new manufacturing technologies

Engage

- Work with MDF staff to develop scope of work

Execute

- Simplified on-line application
- Phase 1 $40K, Phase 2 $200K
- 1:1 Cost Match
- ~90-day cycle time from review to a signed agreement



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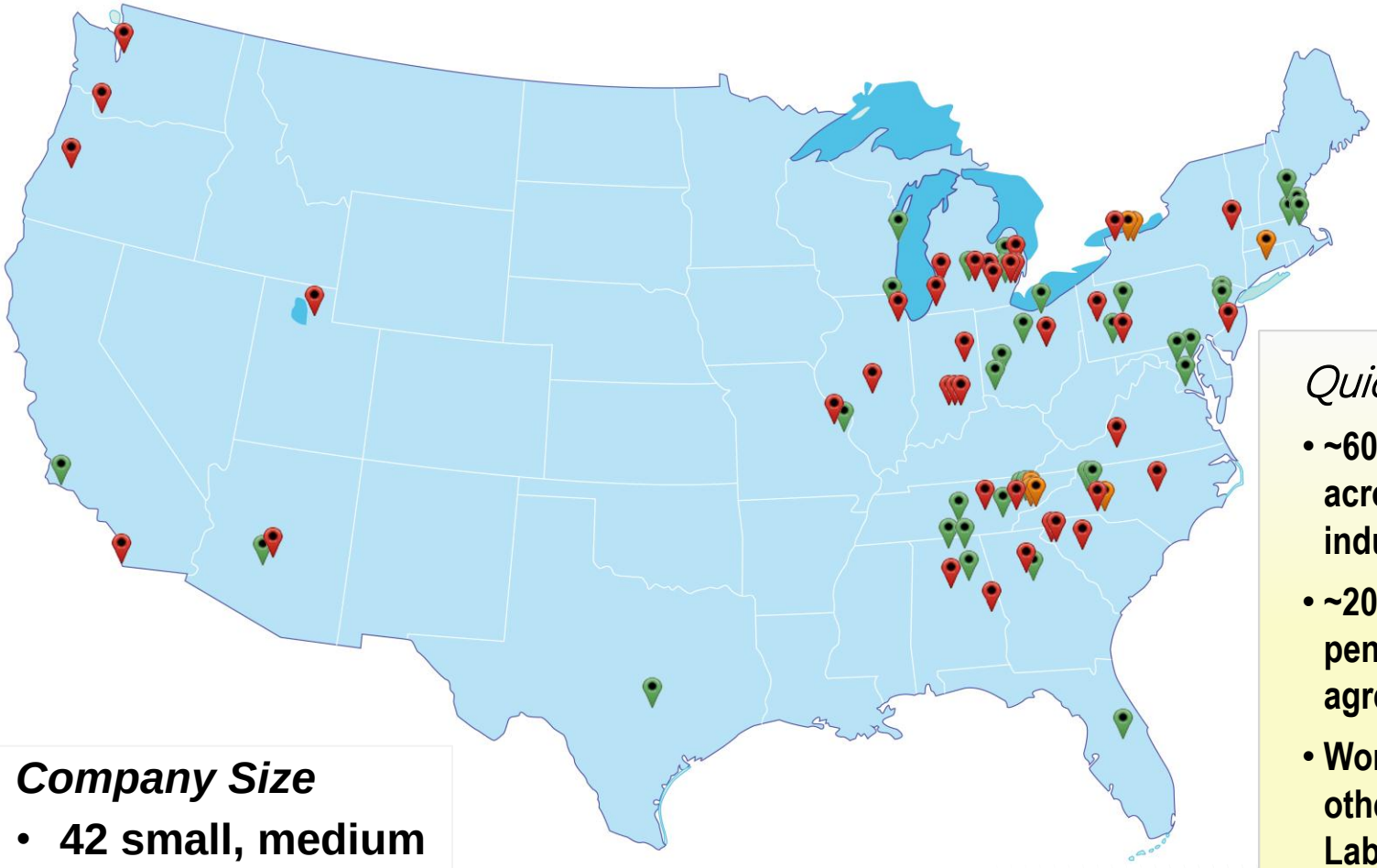
Engaging with industry across the nation



Company Size

- **42 small, medium**
- **24 large**

Quick Facts

- **~60 active projects across 24+ industry sectors**
- **~20 proposals pending agreement**
- **Working with other National Labs**

Working with Industry

>8000 Visitors
>1400 Organizations

41 WFO
Work for Others

129 NDAs
Non-Disclosure Agreement

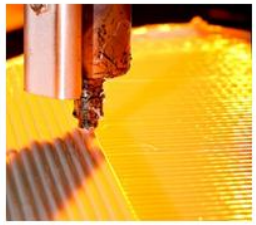
We partner extensively with industry to enable demonstration of next-generation materials and manufacturing technologies for advancing the US industrial economy.

>38 CRADAs
Cooperative Research & Development Agreement

27 MOUs
Memorandum of Understanding

17 UFAs
User Facility Agreement

13 MTAs
Material Transfer Agreement



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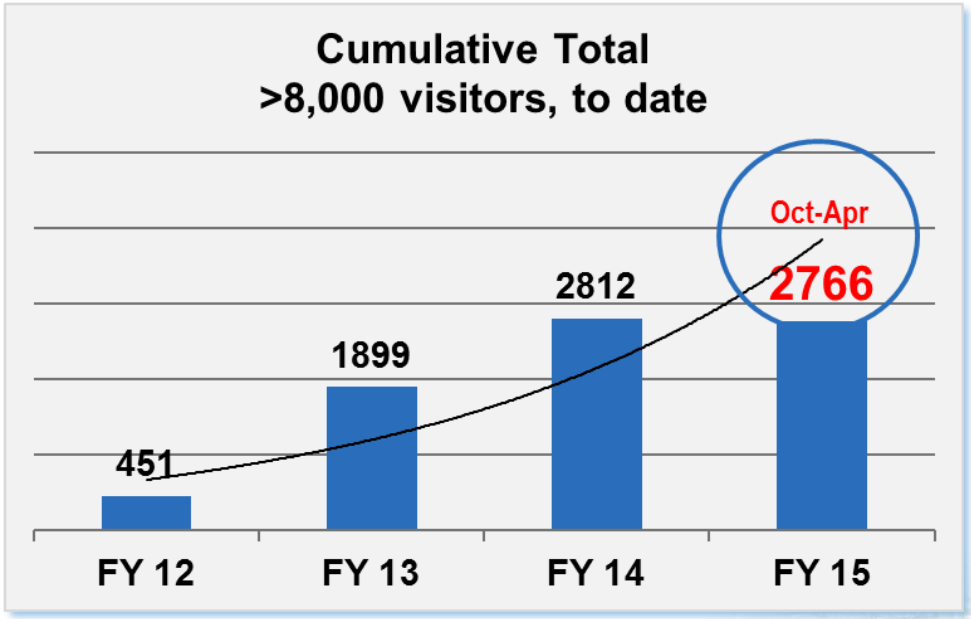
Interest in the MDF continues to grow!



Building Envelopes Workshop

NASA

Cummins

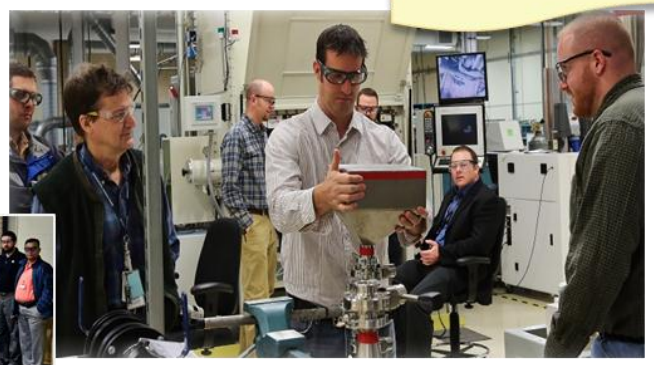
Society of Women Engineers

Training and Education for Industry

FY15 Activities

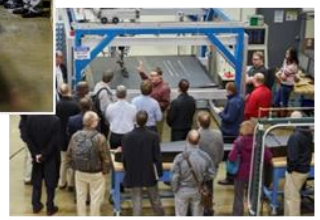
Industrial Executive Meetings

- **Cummins** Annual Technical Meeting
- **Honda** Global Cooperative Summit



MDF Workshops

- NASA AM Meeting
- Advanced Simulation for AM
- Army Additive Manufacturing
- **EWI** AM Consortium 2015
- Fuel Cell and Building Technologies for AM
- Neutron Characterization for AM
- AM for Small Modular Hydropower, planned for August



Corporate Training

- **Boeing** pilots training program at MDF (Dec 2014, May 2015)
- **Deloitte** Free Online Class in AM for business leaders

OAK RIDGE National Laboratory

Industry Fellows and Interns

Engaging Industry, Academia and National Labs

David Dietrich

BOEING

Jonaaron Jones

BOEING

Frank Medina

CAD TO METAL

Arcam AB

Roger England

Cummins

James Earle

LOCAL MOTORS

David Riha

LOCAL MOTORS

Kurtis Hodge

LOCAL MOTORS

Sid Palas

LOCKHEED MARTIN

Sergey Mironets

United Technologies

Bradley Jared

Sandia National Laboratories

Eddie Schwalbach

AIR FORCE RESEARCH LABORATORY

Kelly Thompson

AIR FORCE RESEARCH LABORATORY

Lance Hall

AMRDEC

(20)
The University of Tennessee

(12)
High School

RAMP-UP

Research for Additive Manufacturing Program – University Partnerships

New!
April 2015

FedBizOps

solicitation#
ORNL-MDF-2015-3

- **Up to 10 awards for university professors and student support**
- **Aligned with MDF core research in additive manufacturing**
- **15 applications from 9 universities rec'd in first 2 weeks of announcement**

OAK RIDGE National Laboratory

STEM

Science, Technology, Engineering & Mathematics

FY15 Activities

- **2015 FIRST Robotics, Lego League student teams**
  - **>750 students, 26 teams FRC**
  - **30 students, 3 teams FLL**
- **80 students for summer 2015**
  - **50 Students Summer of 2014**
  - **Teams of 5 Take on Projects**
  - **High School to Graduate Students**
  - **Projects Include Prosthetics, Robotic Design, Software for AM, Efficient Propeller Design, etc.**

FRC FIRST® Robotics Competition

FLL FIRST® LEGO® League

OAK RIDGE National Laboratory

MDF hosts EERE Advanced Manufacturing Internship

Pellissippi State Community College | ORAU | U.S. Department of Energy | Advanced Manufacturing

- Six week program with classroom and laboratory training
- Core competencies: introduction to materials, design for advanced manufacturing, printers and fabrication, titanium and ABS Plastics, and carbon fiber

Pilot launch: 120 inquiries, 73 applications, 25 internships

15 Army, Navy, or Marine veterans, 3 active duty personnel, 2 reservists, 3 FIRST Robotics students, and 2 undergraduate engineering students

outcome
18 job offers extended from 5 companies

Making News

727 direct media mentions, so far in FY15

Washington Business Journal

"…besides being a cool car, it's a great example of how a hub like this operates."-*President Obama, January 9, 2015*

BBC

"The result is stunning and difficult to tell from a car in a more convention way from formed steel body panels…" - BBC, *The dawn of the plastic car?*

BAAM CI @BAAM_CINCINNATI · Apr 13

Awesome @ORNL video of the team of @ORNLMDF and @CINCINNATI_INC creating BAAM 3D Printer. youtu.be/3ijVbjgxCLY

POPULAR SCIENCE

SCIENTIFIC AMERICAN™

THE HUFFINGTON POST

MarketWatch
THE WALL STREET JOURNAL

The New York Times

YAHOO!

sci science

Science Channel @ScienceChannel · Apr 14

Learn why the Department of Energy is making 3D printed cars like this Shelby Cobra. Is manufacturing change forever? ow.ly/LAXER

Harvard Business Review

MAKE BETTER DECISIONS

How to outsmart your biases and broaden your thinking PAGE 51

Knoxville NEWS SENTINEL
KnoxNews.com

Business Wire

R&D 100

npr

"The best way to see the future is to peek over the balcony above the entrance of a manufacturing floor." - NPR, JOE PALCA

Detroit Free Press

USA TODAY

ORNL Manufacturing retweeted

Jonathan P Scott @jonathanpscott · Apr 29

@SSYS_Milwaukee You should have seen the presentation from @ChadDuty1 of #ORNL at #COE2015. His topics were game-changers in additive mfg.

AMC Meeting at Oak Ridge National Laboratory – Time Well Spent

By Jesse Bonfeld on Wednesday, February 25th, 2015

Engagement in the National Manufacturing Institutes

Additive Manufacturing

America Makes
National Additive Manufacturing Innovation Institute

- Gold Member
- Proposal development and collaborations with members
- Portal for DOE Nat'l Labs
- Attendance at all review Meetings
- Joint initiatives (e.g., 3D printers for FIRST)

Lightweight Metals

LIFT
LIGHTWEIGHT INNOVATIONS FOR TOMORROW

- Powder pillar technology lead
- Joint Faculty Appointment with the University of Tennessee
- Potential for collaboration with other DOE Nat'l Labs

Composites

iacmi

- Founding Member
- Tennessee Composite Materials & Process Technology Lead
- Shared space and capabilities

Developing an AM Ecosystem

MVP Magnum Venus Products

LOCAL MOTORS

TECHMERES ENGINEERED SOLUTIONS

Looking ahead

- AM is an exciting, high-potential technology that is in the embryonic stage of development
- To date the MDF has effectively demonstrated the potential of AM and is beginning to develop process and materials capabilities.
- Much work remains to transform AM into a viable manufacturing technology. The global manufacturing R&D community is moving rapidly forward on a broad front to develop AM and realize its economic benefits.