Manufacturing Demonstration Facility Overview

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ORNL is managed by UT-Battelle, LLC for the US Department of Energy
Leveraging ORNL’s Capabilities to Advance Mfg.

Neutron Scattering: SNS & 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
- Application development, software & hardware technology, Exascale systems

Nuclear Research & Advanced Mfg.
- Manhattan Project, 75 years of nuclear research
- Radioisotope projection, fusion and fission

Advanced Materials
- DOE lead lab for basic to applied materials R&D
- Technology transfer; billion dollar impacts
ORNL’s Advanced Manufacturing Program

Facilities
• Carbon Fiber Technology Facility
• Manufacturing Demonstration Facility
• Roll to Roll Processing / Battery Manufacturing Facility

Projects
• DOE-AMO Lab Led Projects
• DOE-AMO Industry Led Projects
• Combined heat and power
• Strategic Partnership Program Projects
  • Other Federal Agencies
  • Private Business

Multi-party consortiums
• Critical Materials Institute
• Roll to Roll Consortium
• CEMI and NNMI Institutes, Hubs, MDFs and Initiatives
• Research Projects Between Labs
• Mission Innovation

Tech to market
• MDF Technical Collaborations
• Small business vouchers
• Innovation Crossroads
• TN REV program
• Technologists in residence
• Better Plants & Technical Assistance

Partnering with industry, small business, universities and others to:
• Develop and commercialize targeted technologies
• Reduce life-cycle energy consumption of next generation products
• Encourage continuous improvement in corporate energy management
• Enhance US competitiveness
Building on a strong base of materials and manufacturing capabilities

<table>
<thead>
<tr>
<th>Novel materials</th>
<th>Advanced processing</th>
</tr>
</thead>
<tbody>
<tr>
<td>Powder metallurgy</td>
<td>Direct roll compaction</td>
</tr>
<tr>
<td>Casting and computation</td>
<td>Isothermal/shear rolling</td>
</tr>
<tr>
<td>Extrusion/process development</td>
<td>Infrared processing</td>
</tr>
</tbody>
</table>

- **New reduction technologies**
- **Affordable consolidation development**
- **Net shape fabrication**

- **E-beam, arc, induction, plasma**
- **High-strength, low-density component fabrication**
- **Porosity evolution and grain refinement**

- **Piping and tubing**
- **High yield aircraft long forms**
- **Energy-efficient mill product**

- **Low-cost Ti sheet**
- **Composite armor**
- **Heat exchanger plates and desalination**

- **Improved formability of Ti and Mg sheet and plate**
- **Cladding of lightweight metals**
- **Energy-efficient rolling practices**

- **High density**
- **Infrared**
- **Pulse thermal processing**
- **Direct write capability**

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F-35 component forging from powder

Reduced porosity casting control arm

Net shape extrusion

Powder to sheet fabrication

Infrared processing of aluminum turbo chargers
Advanced Manufacturing Facilities: Engaging with Industry

Manufacturing Demonstration Facility
- Public-private partnership engaging industry with national labs
- Focused on AM and composites
- Over 30 adv. mfg. systems

Carbon Fiber Technology Facility
- Capacity of up to 50 tons/yr.
- Low cost feedstock for CF production
- Applications include vehicles, wind, compressed gas, other DOE initiatives

Battery Manufacturing Facility
- Country’s largest open-access battery mfg. R&D center
- Developing low cost mfg. processes
- Establishing domestic supply chain of adv. batteries
The Manufacturing Demonstration Facility

An ORNL User Facility focused on cost-shared early-stage applied R&D in the areas of additive manufacturing and carbon fiber materials research related to energy.

- **Mission driven to reinvigorating US manufacturing**
- **Diversity in various technology areas**
- **Embraces technical & scientific risk**
- **Colocation of staff, industry partners and academia**

**Position**

<table>
<thead>
<tr>
<th>Position</th>
<th>No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Researchers</td>
<td>40</td>
</tr>
<tr>
<td>Technicians</td>
<td>14</td>
</tr>
<tr>
<td>Support Staff</td>
<td>10</td>
</tr>
<tr>
<td>Post Graduates</td>
<td>17</td>
</tr>
<tr>
<td>Students</td>
<td>69</td>
</tr>
<tr>
<td>Guests &amp; Internships</td>
<td>44</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td><strong>194</strong></td>
</tr>
</tbody>
</table>

Staff, intern, student, and industry performing research on over 50 current projects that serve a wide range of energy and manufacturing needs.

**Sponsored by**

ADVANCED MANUFACTURING OFFICE
High Potential, Early-Stage R&D for Advanced Manufacturing

Materials
- Costly material feedstocks
- Limited materials
- No AM-developed materials
- Post-processing required
- Microstructure engineering through precise process control and monitoring

Qualification and Certification
- Limitations in conventional metrology
- Required materials specifications & practices
- Costs in certification
- Variability of process

Modeling and Characterization
- Complex temporal-spatial process
- Lack of understanding on impact of local microstructure
- Warping
- Anisotropic properties

Systems
- Limitations in build volumes
- Slow processing
- Reliability
- Limited sensor employment
- No closed loop control
- Improved reliability

R&D Solutions
- New metallic alloys and polymers designed for AM
- Spatially graded & hybrid materials
- Understanding the role of feedstock

In-situ process monitoring
- Filters and correlative data analysis
- Machine learning and uncertainty quantification
- Integration and deployment of rapid qualification tools

Development, implementation and validation of AM-specific workflow
- Crystallographic & 3D tomographic information
- Physics-based simulations
- In-situ non-destructive evaluation and post-processing metrology techniques

Pick and place/hybrid
- Expansion of materials
- Large-scale/fast rates
Materials for High Performance AM Components

- **High Temperature Nickel Alloys and Refractories**
- **Location Specific Control Over Microstructure**
- **Advanced Steels**
- **Hybrid Materials, Composites, and Graded**

- Over 50 Metal and Metal Matrix Composite Combinations Printed
Big Area Additive Manufacturing
AM of thermoplastics and composites

Over 75 Reinforced Polymer Material Combinations Printed

- Large-scale bio-derived structures
- 3D printed rare earth magnets
- Foams between 0.2 to 0.8 g/cm³
- Room- and high-temperature composites
- Developing Thermosets with MVP Printer
“Born Qualified” Approach on Evaluating AM Components

Qualification Framework for Additive Components

Creation of a 3D data framework for Additive Manufacturing
- Utilizing DREAM3D in collaboration with AFRL
- Independent of size scale, material or deposition technology

Software tool development
- Broad dissemination of tools to help users understand process variables which govern material quality
- Visualization and statistical correlation methodologies

Certification with Industry
- Novel data driven construct for certification of AM processes as opposed to individual parts: Built-certified components

New Software Programs to Visualize AM Data

Ability to log data into a 3D Structure, Temporally and Spatially

Create a Digital Twin of the Component Fabricated to Evaluate Health of the Part

Planning  Modeling  Monitoring  Characterizing
Uniform, Defect-Free Microstructures through AI / Machine Learning

Applying standard processing conditions (scan strategy, energy inputs, etc.) to AM builds of different geometries will result in components with different microstructures, defect structures, and mechanical properties at different locations.

**Current Results**

**Top Horizontal**

**Bottom Horizontal**

**Machine Learning for optimizing process parameters based on desired local property**

- Geometry based-thermal model
- Link Microstructure and Defects to Key Process Parameters

**Outcome:** Significant Reduction in Scatter

**Develop Machine Learning Algorithms for Automated Microstructure Analysis**

**Combine Defect Structure / Porosity / Sensing / etc.**

**Multidimensional data analytics**

**Defect map**

Source: Ross Cunningham et al.
Simulation of the Processes at Various Scales

Model Development and Integration
Localized Control of Mechanical Performance

Location specific control over the microstructure has been demonstrated in AM Components

- New scan strategies are being developed based on physics based modeling of material properties and thermal fields during deposition
- Unprecedented ability to control the microstructure and material properties over conventional processing technologies
- Co-optimization of multiple material properties: tensile, fatigue, creep, corrosion, etc. can be simultaneously optimized
- New design methods and models to effectively take advantage of the new controls
Developing Large-Scale Additive Machines

Cincinnati System
- 8’ x 20’ x 6’ build volume
- Up to 100 lbs./hr.
- Pelletized feed replaces filament reducing cost up to 50%

MVP System
- 16’ x 8’ x 3.5’ build volume
- Prints up to 50’/second depending on material
- 4 axes + coordination with pumping system

Ingersoll System
- 100’ x 40’ x 20’ build volume
- Will print up to 1000 lbs./hr.

Wolf Robotics System
- Fewer limitations
- MIG welding arm with 6 DOF
- Lost-cost feedstocks

America Makes Hybrid System
- Laser powder and wire feedstock system
- Working with advanced materials such as 410ss

GKN Aerospace System
- High-yield parts
- Net-shape titanium fabrication
- In-situ process monitoring

Future Concrete Systems
- Highly Deployable
- Versatile Volume Builds
- Low Cost Materials

Future Metal Additive Systems
- Additive / Subtractive w Machining Capability
- Pick and Place Capability
- Multi-head, multi technology
- Digital Thread for Machine Learning and Automation
Large Scale Metal Additive Manufacturing
AM System for Steel

ORNL is developing Large Scale Metal 3D Printing
- Fast deposition: multi-deposition technologies being developed
- Geometry control: simulation tools and machine controls
- Graded structures: multi-material feed
- Low Cost Feedstocks

Wolf Robotics MIG Wire Additive System

Steel Tooling
Technical Achievements from Partnerships in the Last Year

- Achieved 97% density of H13 injection molded tool with part consolidation within 3% of target geometry.
- 3D printing rare earth magnets with PPS and anisotropic properties to increase strength of magnetic field.
- ORNL and TechmerPM are printing high thermal conductivity polymers and have achieved heat conduction up to 4W/(m·K).
- ChoiceSpine granted FDA clearance for 3D Printed Vertebral Body Replacement Device based on ReVV program.
- Development of thermal mechanical models to predict distortion and thermal history of large-scale steel structures.
- MVP and ORNL co-develop large-scale thermoset printer.
- ORNL and Xzeres Wind make a composite wind blade using an additive mesh core and composite clamshell skin.
- ORNL and industry showcase the ability to additively manufacture, machine and pull parts from 5 dies fabricated over the course of 6 days on the IMTS show floor. Dies were then scanned to ensure tolerances were met.
Rapid Solutions and Innovation

- Rapid Prototyping and Direct Fabrication of Final Components
- Additive Manufacturing of Tooling, Die, Molds, Jigs, Fixtures, etc.
- Over one-third of U.S. tool, die, and mold establishments have gone out of business. *Source: 2012 U.S. Congressional Report*
- AM provides opportunity to fabricate tools at reduced times and costs
ORNL’s Vision for Manufacturing

**Vision:** ORNL’s vision is to integrate additive manufacturing, machine tools, and CF/Composites Manufacturing with Artificial Intelligence, Data Analytics, Robotics, Controls and Automation to enable Manufacturing 4.0.
Smart & Secure Manufacturing

• The factory of the future is:
  – Automated: Extremely efficient, fast, reliable
  – Digital: Machine to machine, factory to factory, consumer to product
  – Intelligent: Optimizes workflow and predicts failure
  – Flexible: design, logistics, adapting to changes in demand
  – Multiple Material Solutions: Enable hybrid, composite, and graded structures with multiple manufacturing technologies
  – Human: Workforce converted from manual, monotonous tasks (low skill/low wage) into supervision and control tasks (high skill/high wage). Synergistic combination of human (cognitive) and machine (labor)
  – “Born Qualified”: Data analytics, machine learning and AI approach to rapid low-cost certification/qualification
  – Security by design and manufacture

• End to End – Concept to product
Education and Training

**Governor’s Chairs in Strategic Areas**
- 50% ORNL & 50% UTK with shared lab space
- ~54 undergrad & graduate students performing R&D in advanced manufacturing
- MAJIC IUCRC (The Ohio State University, Colorado School of Mines, the University of Tennessee, etc.)

**Workforce Development**
- Adv. mfg. internship with Pellissippi pilot launched: FY14 [120 inquiries, 73 applications, 25 internships]
  - 15 Army, Navy, or Marine veterans
- >5 years of volunteer mentorship for FIRST ROBOTICS
- >750 students engaged
- DOE-AMO enabled 400 desktop printers 2014 FIRST Robotics partnering with America Makes.

**Training Our Next Generation**
- >5 years of volunteer mentorship for FIRST ROBOTICS
- >750 students engaged
- DOE-AMO enabled 400 desktop printers 2014 FIRST Robotics partnering with America Makes.

**Growing Internship Program**
- 114 Students Summer of 2017
- Grown from 50 to over 100 Students in <4 years
- Projects include prosthetics, robotic design, hydraulics, materials characterization, AM simulation, design, etc.

>50 universities have partnered with the MDF
ORNL Manufacturing Capabilities Directly supported development and Scale up of ATF Cladding

ATF FeCrAl insertion in Hatch-1
Courtesy of John Williams
## Working with Oak Ridge National Laboratory

**Mechanisms for enhancing, developing & improving your idea/technology**

<table>
<thead>
<tr>
<th><strong>User Agreement</strong> (non proprietary)</th>
<th><strong>Strategic Partnership Project</strong> (Proprietary)</th>
<th><strong>Cooperative Research &amp; Development Agreement</strong></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Length of engagement</strong></td>
<td>As defined by agreement.</td>
<td>Longer-term basis of a year or more.</td>
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<tr>
<td>Up to 12 months.</td>
<td></td>
<td></td>
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<tr>
<td><strong>Cost to Company</strong></td>
<td>Full cost recovery.</td>
<td>Cost-share required.</td>
</tr>
<tr>
<td>No cost.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Intellectual Property Rights</strong></td>
<td>Companies own intellectual property</td>
<td>Companies own inventions they make during the collaboration and have an option to negotiate an exclusive license in a specific field of use to inventions made by ORNL.</td>
</tr>
<tr>
<td>Each party owns its own inventions.</td>
<td>made or created using corporate funds as a result of these engagements.</td>
<td></td>
</tr>
<tr>
<td>Jointly developed inventions will be</td>
<td></td>
<td></td>
</tr>
<tr>
<td>jointly owned.</td>
<td></td>
<td></td>
</tr>
<tr>
<td><strong>Protection of Generated Information</strong></td>
<td>Companies paying for services with corporate funds can treat all generated data as their proprietary information.</td>
<td>Commercially valuable information generated under a CRADA may be protected for up to 5 years, depending on funding source.</td>
</tr>
<tr>
<td>Information generated is publicly</td>
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<td></td>
</tr>
<tr>
<td>available.</td>
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**ORNL Partnerships.**
Technical Approach: Industry Collaborations

Explore
• Opportunity for industry to discover and apply new manufacturing technologies

Engage
• Work with MDF staff to develop scope of work

Execute
• Phase 1 $40K, Phase 2 $200K
• 1:1 Cost Match
• Non-Negotiable CRADA
• ~90-day cycle time from review to a signed agreement

Currently 37 active Collaborative Research and Development Agreement partners, and 140 total

<table>
<thead>
<tr>
<th>Status</th>
<th>Phase 1</th>
<th>Phase 2</th>
<th>TOTAL</th>
</tr>
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<tbody>
<tr>
<td>Pending Agreement</td>
<td>13</td>
<td>1</td>
<td>14</td>
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<tr>
<td>Active</td>
<td>31</td>
<td>6</td>
<td>37</td>
</tr>
<tr>
<td>Complete</td>
<td>79</td>
<td>10</td>
<td>89</td>
</tr>
<tr>
<td><strong>Total</strong></td>
<td>123</td>
<td>16</td>
<td>140</td>
</tr>
</tbody>
</table>

In addition, the state of TN Funds Research to Provide Innovation in Manufacturing

Evaluation of advanced polymers with tunable reaction kinetics for AM

Medium Area Additive Manufacturing (MAAM) for composite AM

Using AM to fabricate small modular hydropower devices
40 Systems and >$12M of Industry Provided Equipment

**Electron Beam Melting**
- Developing in-situ characterization, feedback, and control
- Heated powder bed
- Expanding range of materials (Ti64, CoCr, 625, 718)
- Precision melting of powder materials

**Metal Wire & Powder Feedstock**
- Metal wire and powder feedstock allows for improved mechanical properties and surface finishes
- Will work with advanced materials for large-scale welding such as 410ss

**Laser Metal Deposition**
- Site-specific material addition
- Application of advanced coating materials for corrosion and wear-resistance
- Repair of dies, turbines, etc.

**Selective Laser Melting**
- Unheated powder bed
- Wide range of material choices (316L, 17-4 PH, H13, Al, Ti, 718, 625)
- Precision melting of metal powders
- Up to 630 x 400 x 500mm build volume

**Metal Binder Jetting**
- Metal matrix composites and sintered materials including:
  - Stainless steel + bronze
  - Tungsten + titanium
  - Ceramics + sand
- Large build volumes (10 x 10 x 16in)
- Fast build times (30 sec/layer)

**Large-Scale Welding**
- Open-air environment
- MIG welding arm with 6 DOF and 2 rotational degrees
- Print size not restricted
- Uses low-cost welding torches and wire
- CAD-to-path functionality

**Large-Scale Laser Metal**
- Reducing buy-to-fly ratio of aerospace components
- Using 4kW laser and two 10kW lasers to melt Ti64 wire
- Inert system with argon-filled tent
- Prints ~10cubic inches/hr.

**Hot Isostatic Press**
- First rapid-quench HIP in America
- 180mm diameter
- Can reach pressures of 30000psi when cooled from 3000C
- Can HIP and heat treatment in same cycle

**Large-Scale Polymer Deposition**
- Deposits up to 1000lbs. of pellet feedstock material per hour
- Build volume up to 20’ long x 6’ wide x 8’ tall
- Printed >37 different polymers and composites
- Dual material capabilities

**Ingersoll Large-Scale Polymer Deposition**
- Under development
- Will have 48’ x 23’ x 10’ build volume
- Target deposition rate of 1000 lbs./hr.
- Will be 10x larger and faster than previous commercial systems
- Cross-linking between layers
- 2-part resin

**Thermoset Dual Material Extrusion**
- Capable of depositing 300mL/minute
- Can control material properties and speed on the fly
- Cross-linking between layers
- 2-part resin

**Large-Scale Thermoset Deposition**
- 16’ x 8’ x 3.5’ build volume
- 4 axes + coordination with pumping system
- Can print up to 50”/second depending on material
- 2-part resin

New facility 110,000 sq. feet total with 40,000 sq. feet of high bay
Partnering with Industry

Over 180 industry partners

Material Suppliers

Equipment Suppliers

End Users

>21,300 visitors total

>3,200 companies

Dozens of workshops and public outreach events

56 industry fellows
Innovation Crossroads Program
Yellowstone Energy Company Overview

Key Differentiators

• Only advanced reactor to use commercially available nuclear fuel
• Molten nitrate salt coolant used extensively in concentrated solar power and chemical industries
• Seamlessly integrates thermal energy storage into plant design

Innovation Crossroads Program

• Lab embedded entrepreneurship program supported by AMO
• 2 year fellowships and $200-350k to work with ORNL
• Yellowstone is member of 1st cohort

Yellowstone Energy is designing a modular molten nitrate salt cooled reactor with integrated thermal energy storage to meet future market demands
Office of Nuclear Energy under the GAIN initiative provides an excellent pathway to collaborate with MDF on nuclear energy related projects.

Two mechanisms are available to industrial partners:
- NE Vouchers
- Industry FOA

FOA Awarded in FY-18: Establishment of an integrated advanced manufacturing and data science driven paradigm for advanced reactor systems.
Questions?