# Benefits of Tailoring Hot Isostatic Pressure/Powdered Metal (HIP/PM) and Additive Manufacturing (AM) To Fabricate Advanced Energy System Components

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Presented by:
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*in collaboration with:*

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***NETL Project Manager,***
***Crosscutting Research Division***


*U.S. Department of Energy*

*National Energy Technology Laboratory*

# Statement of Project Objectives

Demonstrate how tailoring HIP/PM, coupled with advances in AM (also known as 3D printing or 3DP) has specific, measurable benefits for fabricating advanced energy (AE) system components.

Goals:

- Validate that AM, in combination with HIP, offers a viable method of producing A-282 components
- Provide key information about cost, manufacturing challenges/opportunities and lead-times when compared to other methods including traditional HIP/PM and casting.

# Relevance to Fossil Energy

For expensive, high nickel alloy components, EIO activities have shown advantages of HIP/PM over other methods such as casting and forging.

- *Savings up to 40% in raw material costs (vs. casting)*
- *Eliminates difficulties resulting from reactivity of these materials in the molten state*
- *Facilitates manufacture of large size requirements associated with FE/AE*
- *Net shape & porosity free parts require less post processing including machining & weld repair*

Work in AM suggests further advantages...

# Potential Significance of the Results of The Work

- Many new advanced alloys for Fossil Energy will require new manufacturing methods
- Supplier Availability will determine the rate for adopting Clean Coal technologies
- Castings, Forgings, and Extrusions are ***THE*** "pinch points"
- Current Supply Base is Mostly Off-Shore
- Saturated with Long Lead Times

Creates opportunity for evolving US industrial base

# Project Approach

- Three new methods of manufacturing advanced alloys are under evaluation:
  1. Directly built AM parts;
  2. AM cans for HIP/PM; and
  3. AM cans produced in the final part material.
- Project is utilizing
  - Binderjet technology (fastest metal 3DP technique, coupled with an alloy specific sintering profile to produce a sufficiently dense part for final HIP
  - Haynes 282, a high nickel material capable of withstanding the severe operating environments required in AE systems

# Project Approach

Project utilizes a Westinghouse gate valve

- Modified to ¼ scale
- 3” x 4” x 2”
- ~ 2.7 lbs -
- wall thickness range ¼” – ¾”

Valve selected for the complexity of its shape & crosscutting applications to other AE systems, including nuclear

# Primary Tasks

1.0 – Project Management & Planning

2.0 – Atomization of A-282

3.0 – Material Characterization & Sintering Methodology (MC/SM) for A-282

4.0 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

5.0 – Produce 1 Valve via AM/3DP and HIP

6.0 – Post Processing Analysis

7.0 – Outreach & Technology Dissemination

# Task 1.0 – Project Mgmt & Planning

Team Leader:

Energy Industries of Ohio

*in collaboration with*

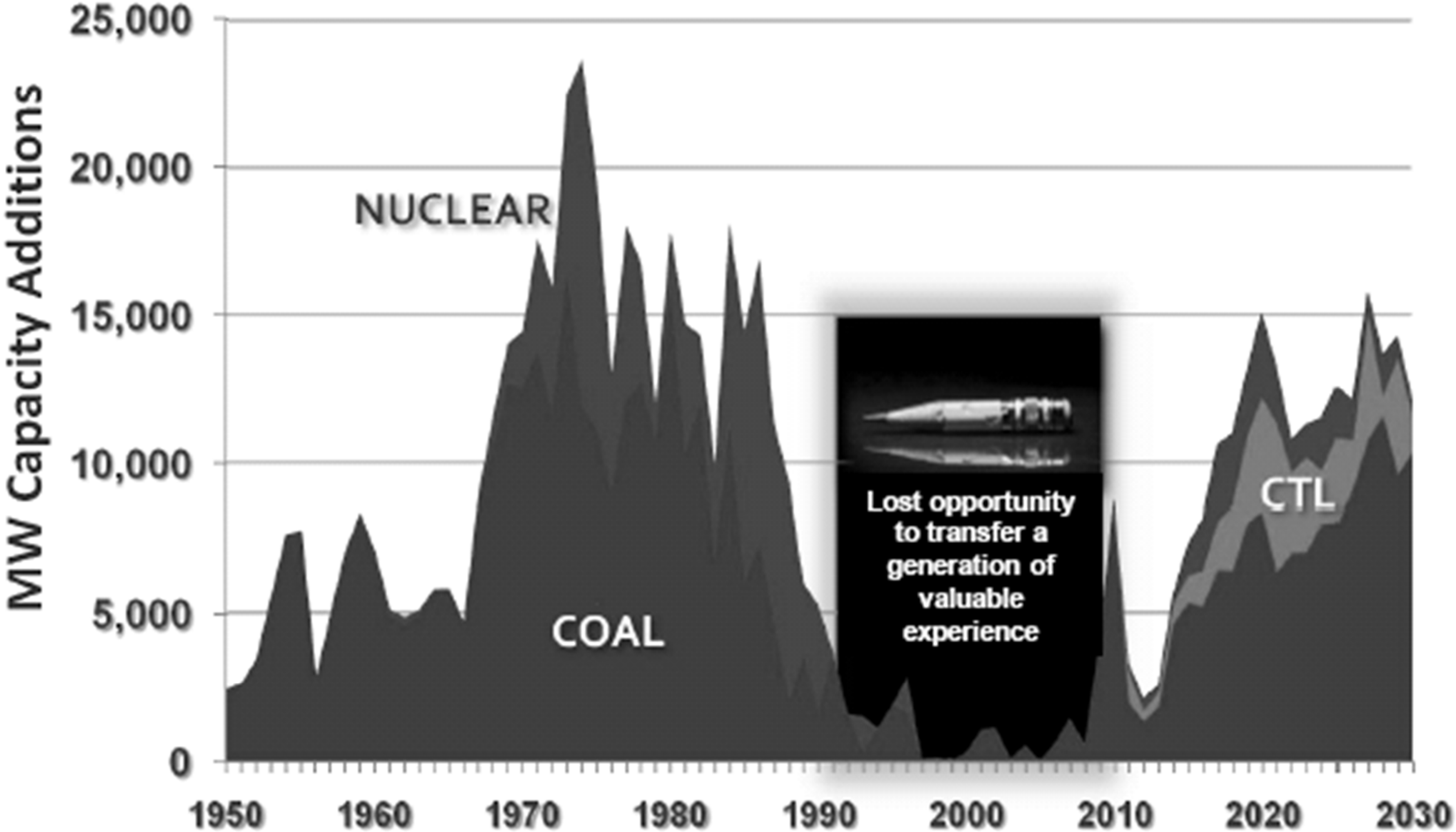
# Project Management & Planning

www.energyinohio.org

## Energy Industries of Ohio

- Non Profit 501(c) 3 Corp
- Facilitate Technology Development for Ohio's Base load Generation
- Implement Efficiency Projects for Energy Intensive User Industries
  - 9 Industries use 30% of all energy
  - Ohio is first for 3 & in the top five for others
- Foster Collaborations & Teams
  - Federal, State, University, National Laboratories & Private Industry
  - Exploit Synergies between supply and demand sectors

# Our Workforce and Skills Challenge




*A Two Decade Gap for Coal; Three Decades for Nuclear*

NETL



Source: EIA AEO'07 reference case and Annual Energy Review 2006

# EIO's Role in US Manufacturing

- Traditional manufacturing +
  - EIO is working with heavy manufacturers (castings, forgings, fabrications etc) to enhance their traditional manufacturing processes
  - Automation, energy efficiency and innovations help to offset higher labor charges domestically.
- Advanced Manufacturing
  - EIO is working on R&D projects involving both new materials and new methods of manufacturing

RESULTS: Not only are we re-shoring for US opportunities, we are also getting foreign companies approaching us with export opportunities

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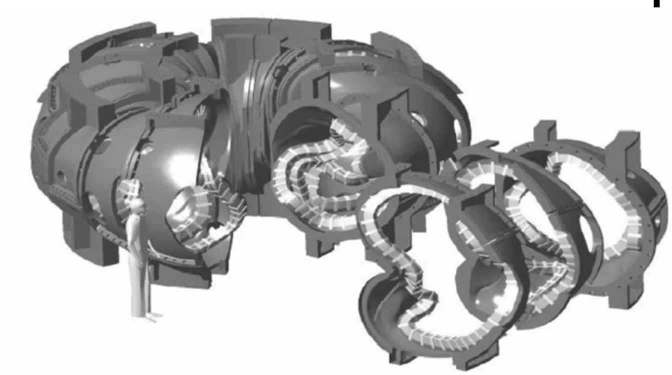
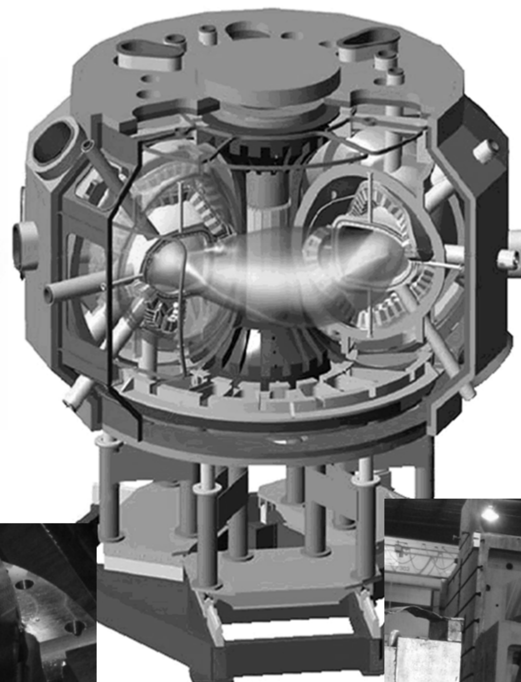
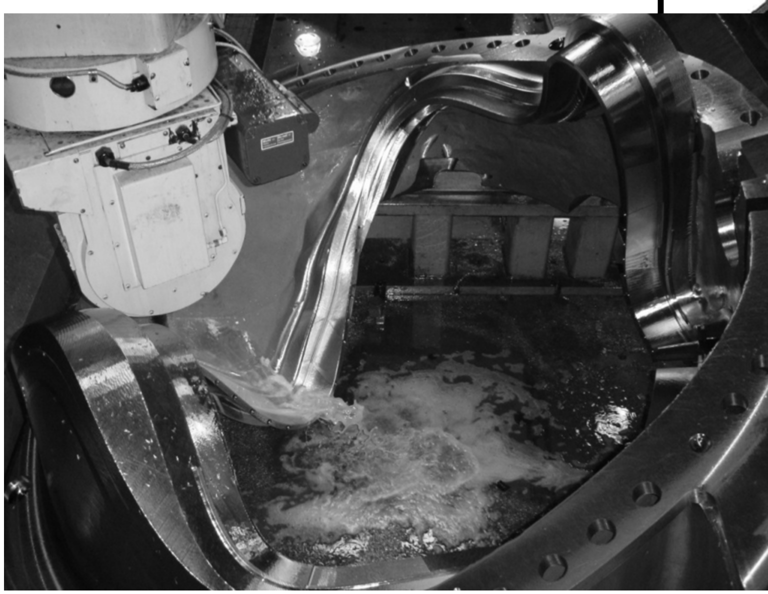
# Technical Background/Project Motivation

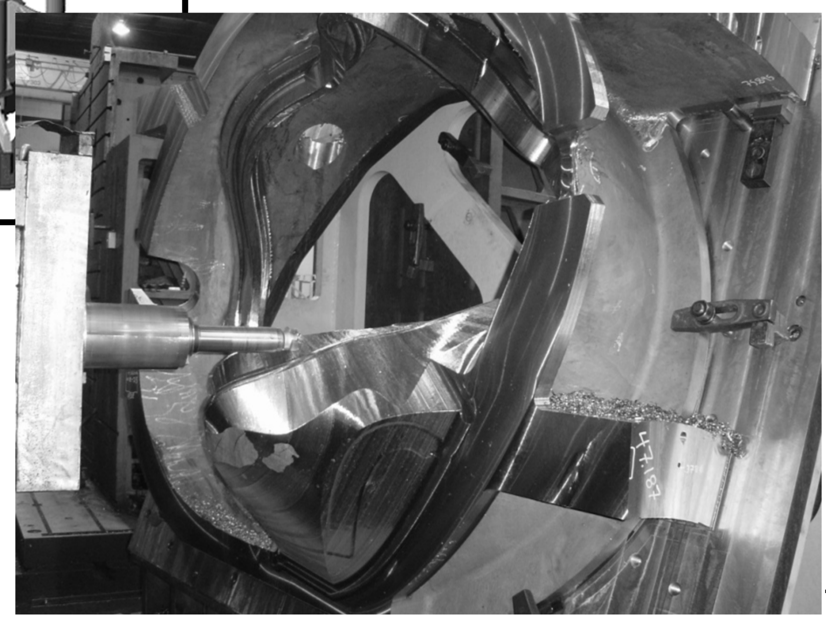
## National Compact Stellarator Program





- EIO charged with prototyping and providing large, high strength Nuclear Castings
- Staff experienced for working with Nuclear supplier industry, Nat'l Labs and Producers





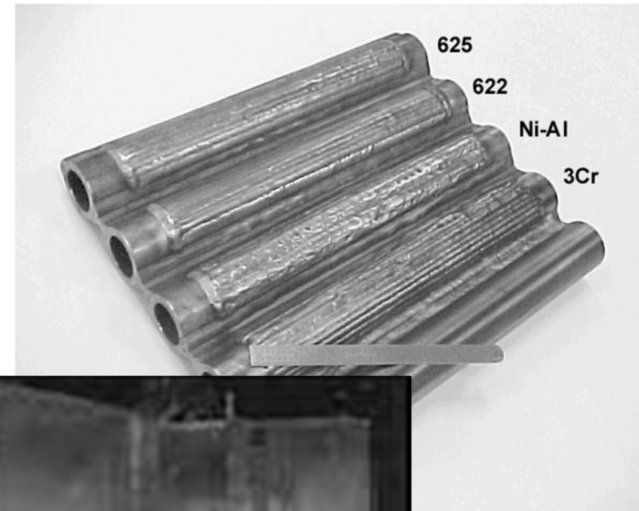
## Slide 12

1 Nancy Horton, 4/26/2015

# Technical Background/Project Motivation

EIO is Prime Contractor for $50M Advanced-UltraSuperCritical Materials Program

- Pulverized Coal CCS technology
- ⇧ Efficiency ⇩Emissions
- Consortium of All U.S. Boiler and Turbine Manufacturers and EPRI
- Goal: 5000psig, 1300ºF main steam and above for net plant efficiency >45%
- New Materials (nickel-based alloys) and designs
- Supply Base is key to commercialization




# A-USC Consortium Members

U.S. DEPARTMENT OF ENERGY

MAKING OHIO COAL THE CLEAN CHOICE

Energy Industries Of Ohio

EPRI ELECTRIC POWER RESEARCH INSTITUTE

OAK RIDGE NATIONAL LABORATORY
MANAGED BY UT-BATTELLE FOR THE DEPARTMENT OF ENERGY

NETL

GE imagination at work

B&W

ALSTOM

RILEYPower
A Babcock Power Inc. Company

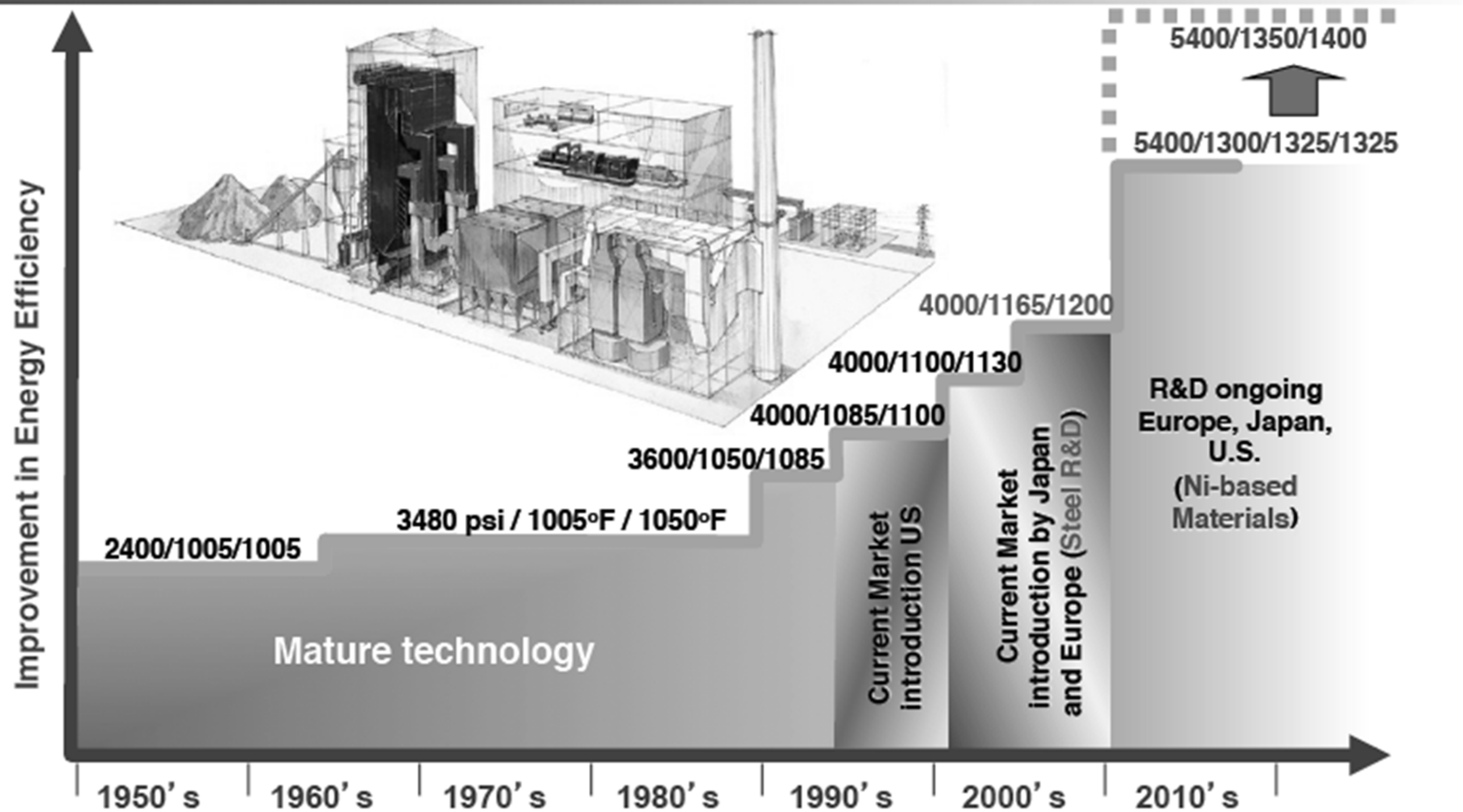
FOSTER WHEELER

SIEMENS*

*Phase 1 only

# A progressive increase in steam conditions has been taking place worldwide

**US A-USC Goal**

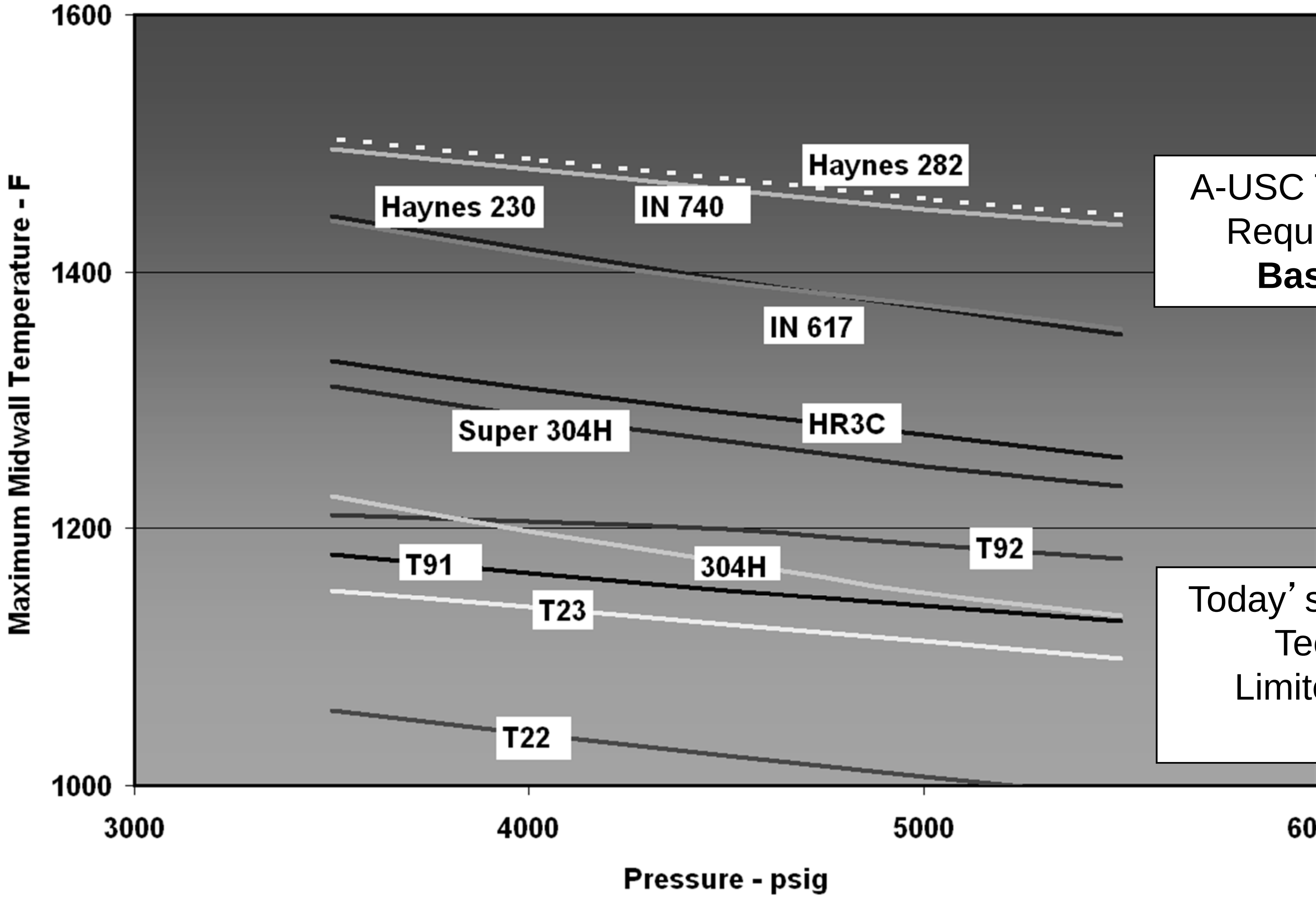



**Cost Effective Materials Have Been Critical to Achieving Increased Efficiency**

*Original Illustration: Courtesy of ALSTOM Power*

ELECTRIC POWER RESEARCH INSTITUTE

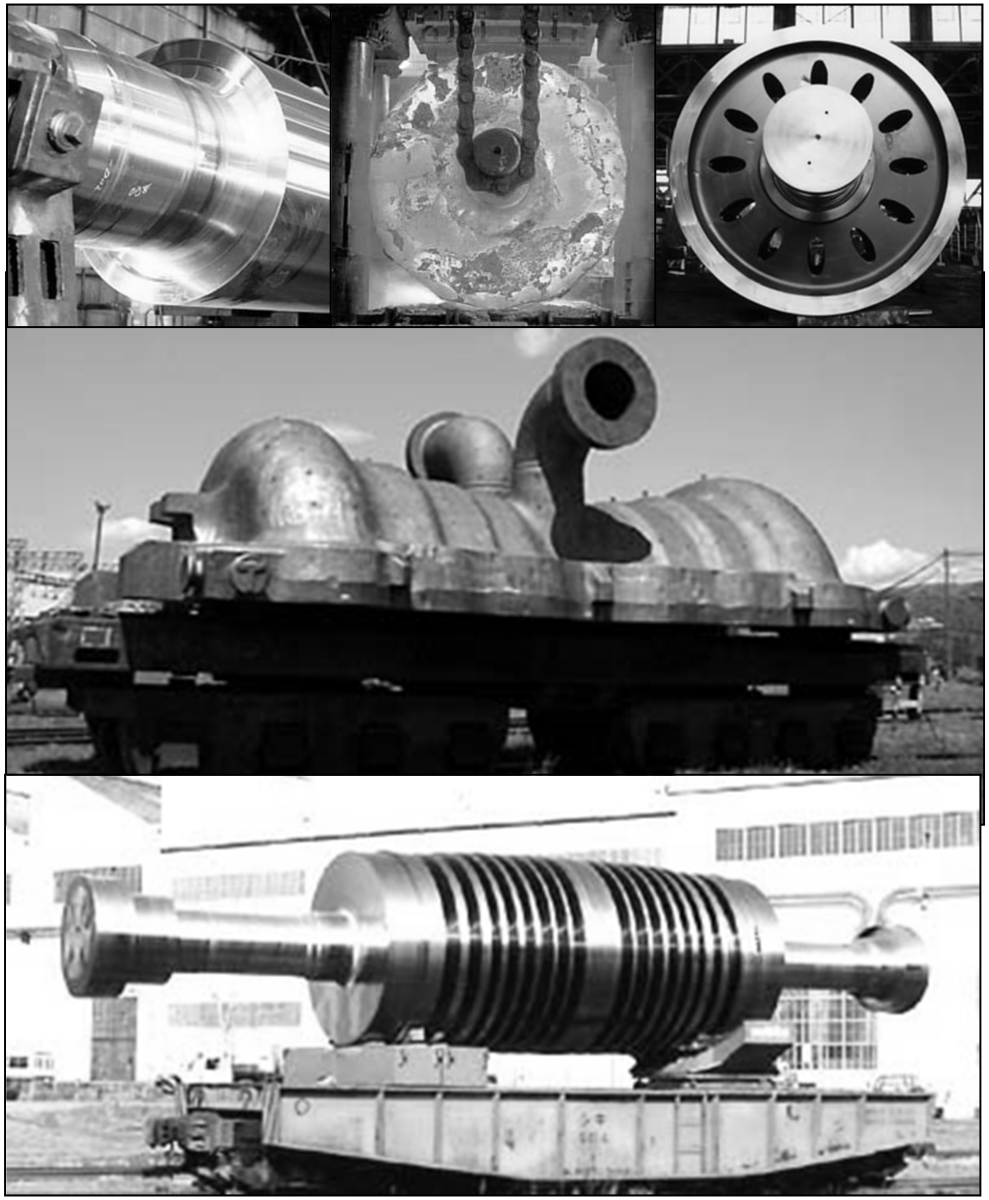
# Materials Selection for A-USC Alloys (Boiler Superheater/Reheater Tubing Strength)




A-USC Technology Requires **Nickel-Based** Alloys

Today's SC & USC Technology Limited by **Steel** Alloys

# UltraSuperCritical (USC) Materials Project – Potential Show-Stoppers



images from Japan Steel Works

**Product Form and Size Limitations**

The U.S. domestic boiler and turbine manufacturers are working to confirm the materials technology and component fabrication feasibility for advanced USC plant components.

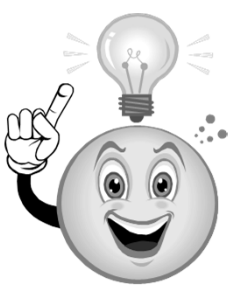
The production capabilities of raw material suppliers and foundries must also be assessed for:

- Large, heavy wall pipe
- Castings
- Forgings

The ultimate plant unit size and other design aspects will be influenced by the size and product form limitations of domestic and worldwide suppliers ( i.e. foundries, forges, etc.) capable of working with these new, high-strength materials.

# Technical Background/Project Motivation (Cont.)

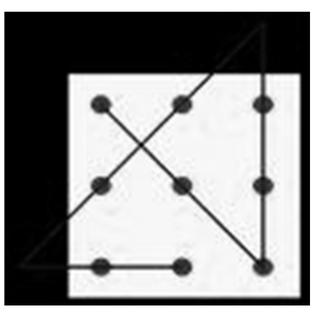
- Both Programs involved locating suppliers
- Found Castings, Forgings, and Extrusions are *THE* "pinch points"
- Found Supplier Base is limited, saturated and foreign
- Found Supplier Base for Coal/Nuclear Overlaps
- Found Supplier Availability will impact the rate for introducing both Clean Coal and Nuclear Systems



Opportunity for Supply Chain Development

# Ohio/TechBelt Opportunity for an Advanced Energy (AE) Supplier Program

- These needs are traditional TechBelt products
- EIO has direct relationships with these industries and their affiliated organizations  FIA, OCMA, OSC, etc.
- Knowledge that their current markets are declining
- Knowledge that they are looking for new markets
- Knowledge that they are capable of transition into AE markets
  - But....They don’t know of Advanced Energy opportunities
  - And....Power Gen potential customers don’t know of them



EIO could connect the dots!

# EIO Approach in Ohio & TechBelt

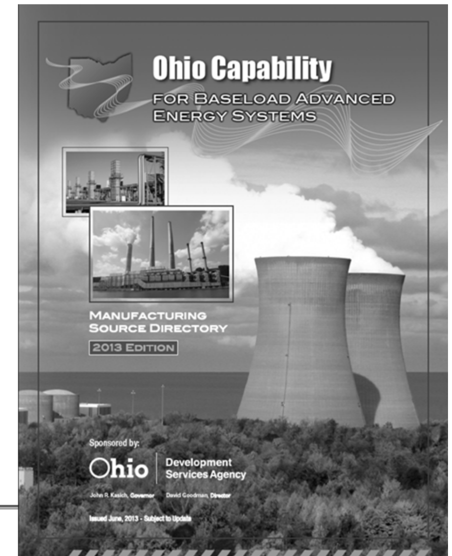
EIO employed a different (bottoms-up) model

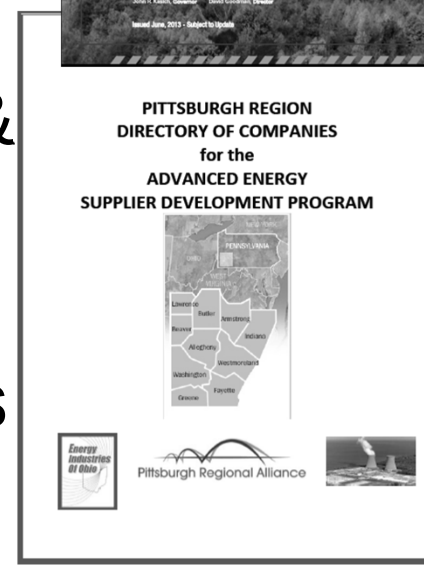
1. Develop the specific "needs envelope" (sizes, alloys, etc.) of target "pinch point" items
   * Worked with key customers from fossil and nuclear
2. Use Industry organizations to ID candidate suppliers
3. Conduct on-site visits to assess interest & ability
4. Facilitate customer interaction and teaming opportunities
5. "Champion" needs for transitional assistance
6. Pursue technology development & demonstration

# EIO Approach in Ohio & TechBelt

## Program Outcomes

- ✓ A Catalogue listing Ohio Suppliers that can meet the AE Power Gen Industry needs – Project was expanded to include Pittsburgh Region
- ✓ Promoting the Catalogue to OEM's & Customers
- ✓ Cultivation of HUBS around pinch points & market/export opportunities
- ✓ Advanced Research, Prototype Development & Industry Expansion



# Technical Background/Project Motivation

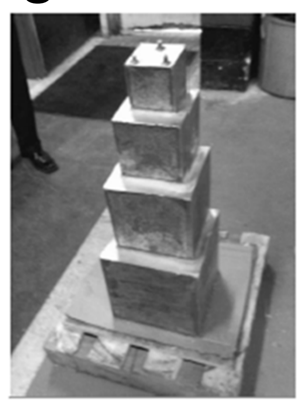
Under the Ohio Program, EIO conducted Research & Technology Development

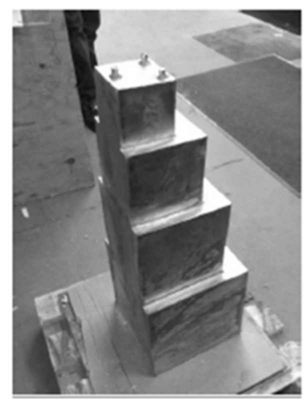
Using A-282

- Produced World's largest Step Casting followed by an AE Valve using A-282



- Working with Carpenter & Bodycote - Duplicated A-282 Step Component using HIP/PM





# Technical Background/Project Motivation

- Additive Manufacturing is a logical progression in seeking new methods for producing FE/AE components
- Dialogue and collaboration with our colleagues at Carpenter, ExOne and Bodycote focused on finding ways to make AM and HIP/PM more competitive
- Potential advantages, including reduced costs and leadtimes, of combining AM with HIP/PM resulted in this project proposal
- Carpenter, ExOne and Bodycote are all highly respected companies in their fields, with facilities in the TechBelt

# Atomization of A-282 PEP – Carpenter Powder Products

Manufactures a broad range of gas atomized loose metal powders and consolidated powder forms

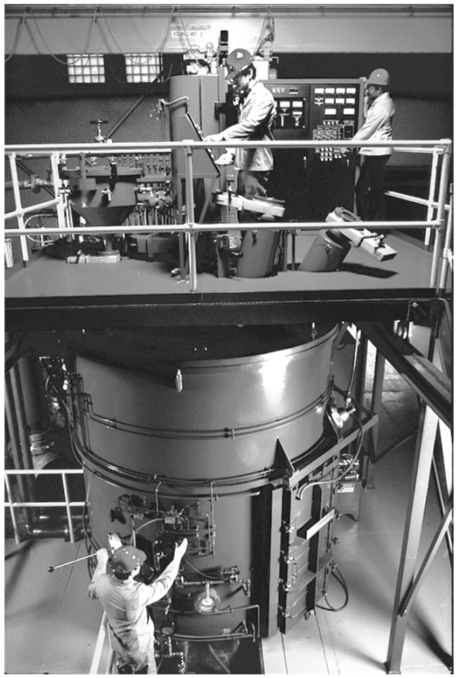
Manufacturing: PA, RI and Sweden

R&D: Reading, PA

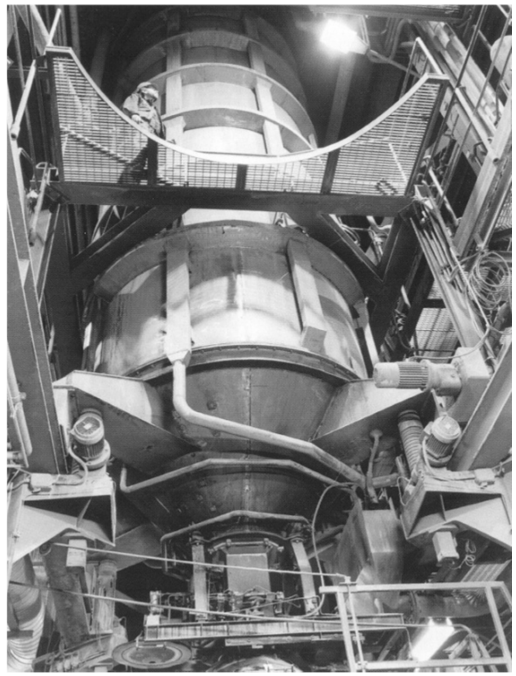
CARPENTER

# PEP – Carpenter Powder Products

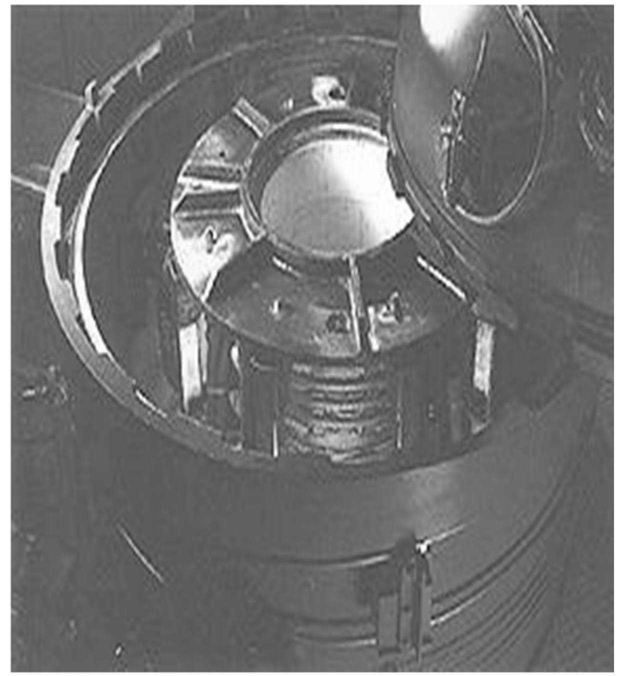
## Leader in Gas Atomization Technology



Bridgeville, PA
- Air Induction
- VIM (2)
- Ar and N



Torshalla, Sweden
- Air Induction (2)
- N



Woonsocket, RI
- Protected atm.
- Ar and N

***Stainless steels, nickel/cobalt base, fine powders, tool steels***
***Capacity – 20,000 Tons***

# PEP – Carpenter Powder Products

## Greenfield Powder Facility – Athens, Alabama

**Features**

•3000 lb. dual VIM furnace **3**

•Two tower design

•Clean rooms

•Argon recycling

•In-line PSD determination

•Satellite control

**Capacity** – 2100 Tons

# PEP – Carpenter Powder Products

## Powder Process Enablers

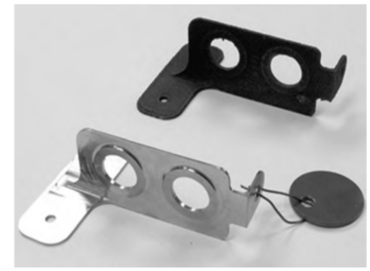
### *Superalloys*

- Gas Turbine Components
- High Temp. Capability

### *HIP Near Net Shapes*

- Isotropic Properties
- Material Utilization
- Fewer Welds
- Less Machining

### *Additive Manufacturing*



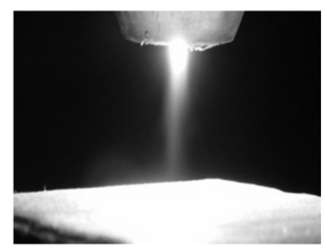
- Complex Shapes
- BTF Ratio
- Imbed inner channels

***Metal Powder Solutions***

### *Metal Injection Molding*

- Complex Shapes
- High Volume Capability

### *Surface enhancement and Joining*



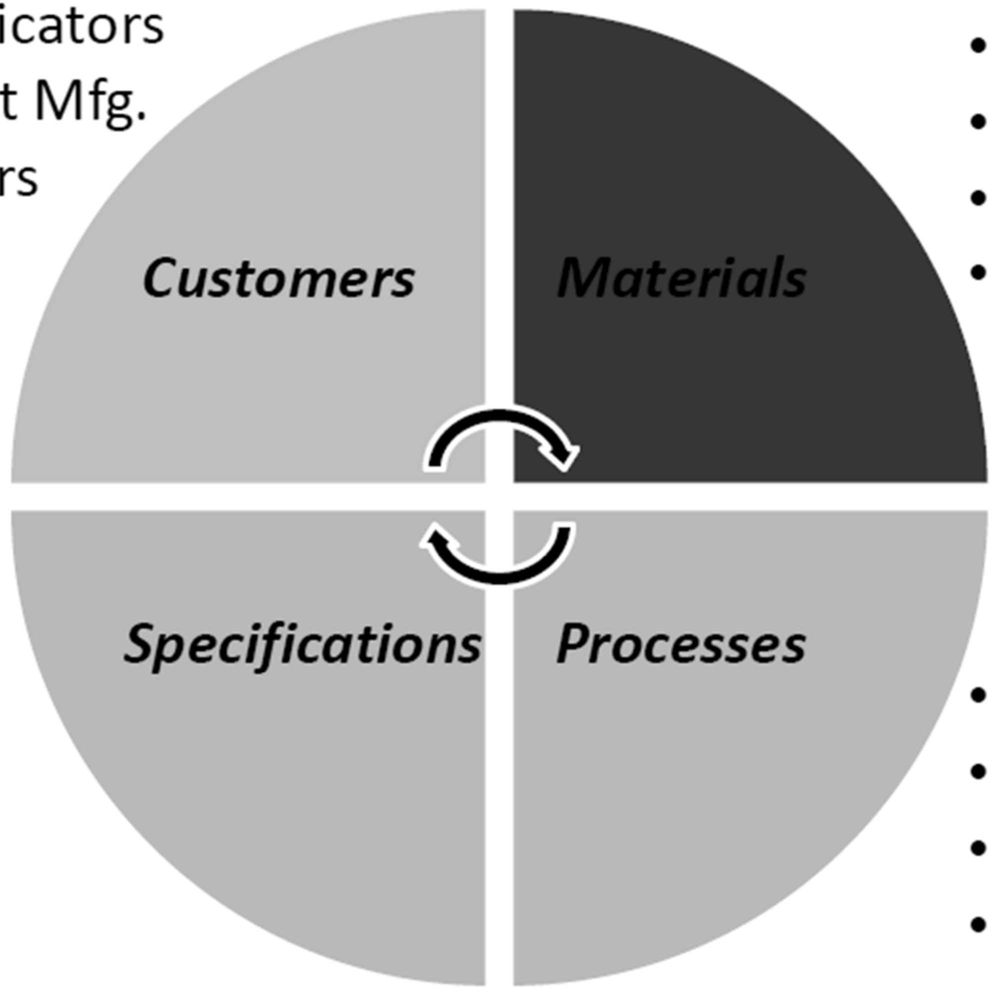
- Corrosion Resistance
- Component Repair

# PEP – Carpenter Powder Products

## Additive Manufacturing Initiative

- Parts Fabricators
- Equipment Mfg.
- Distributors

- Austenitic SS
- Maraging SS
- 718
- 625
- CCM

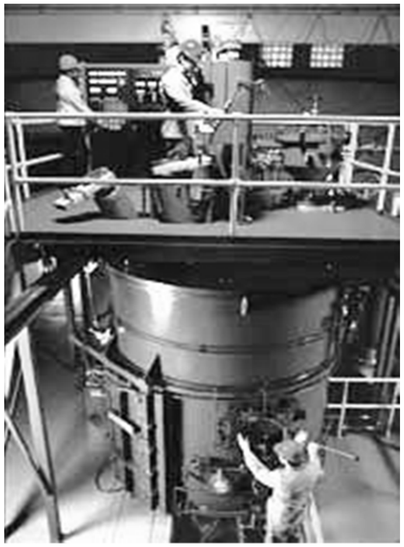



- PSD
- Chemistry
- Flow
- Shape
- Density

- AM process
- Powder re-use
- HIP
- Heat Treatment
- Finishing

# PEP – Carpenter Powder Products

## Program Task 2: Powder Manufacturing


Melting


Chemical Analysis


Screening


Blending


Particle Size Determination

# Project Team Member
# The ExOne Company

## A Global Supplier of Industrial Additive Manufacturing Equipment

- 50-year history of developing and implementing nontraditional manufacturing processes.
- Invested >$80 million in the development and implementation of three-dimensional printing (3DP) since the early 1990s.
- Offers both the services and the equipment for applying 3DP technology for molds / cores used for sand castings and direct metal parts.
- ExOne Production Service Centers are located throughout the United States, Germany and Japan.
- ExOne systems are able to print in a variety of industrial materials with the largest available build sizes.

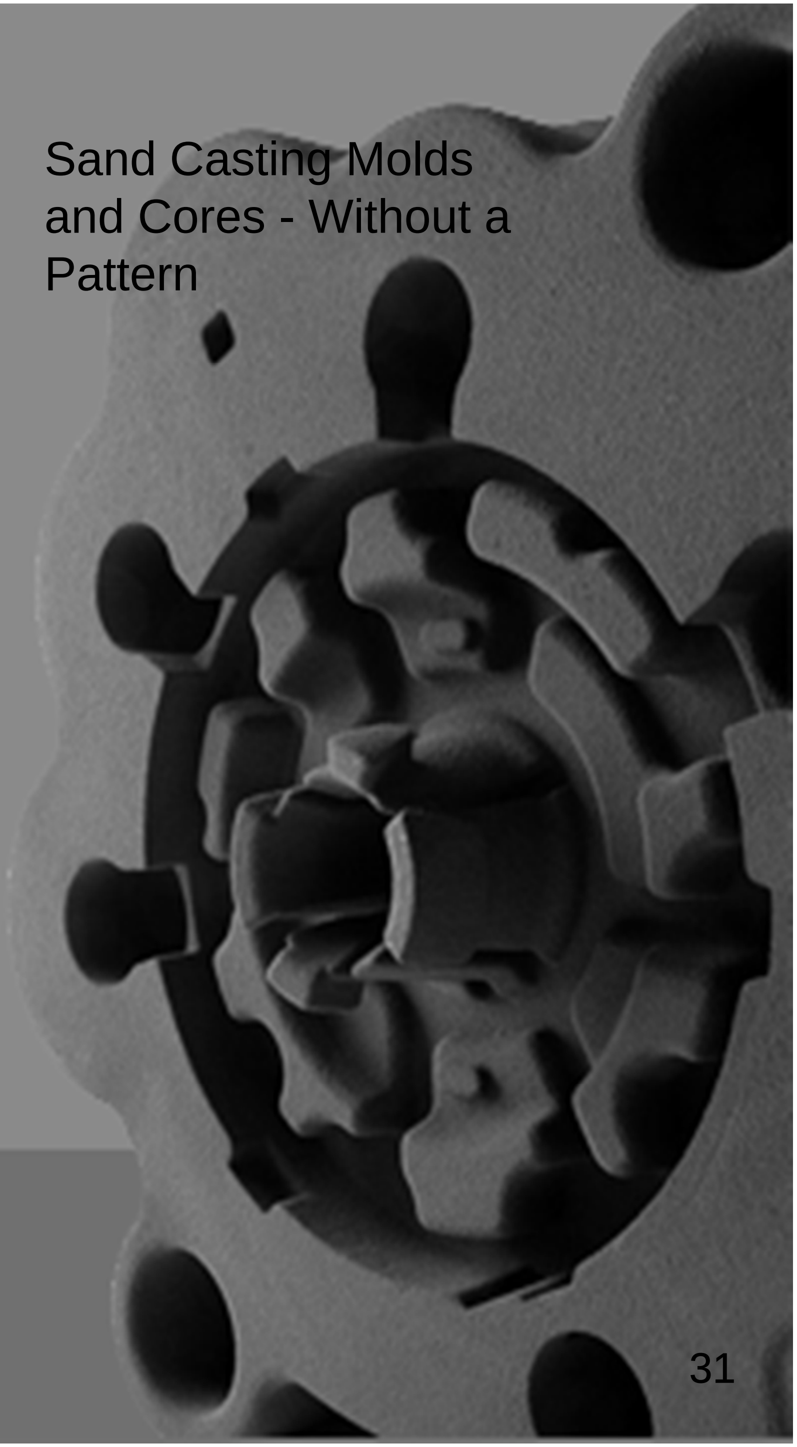

Asia | The Americas | Europe

# ExOne Technologies

Micro Holes and
Features with Advanced
Laser Machining


Industry Class Additive
Manufacturing
Equipment


Functional and
Accurate 3D Printed
Metal Parts

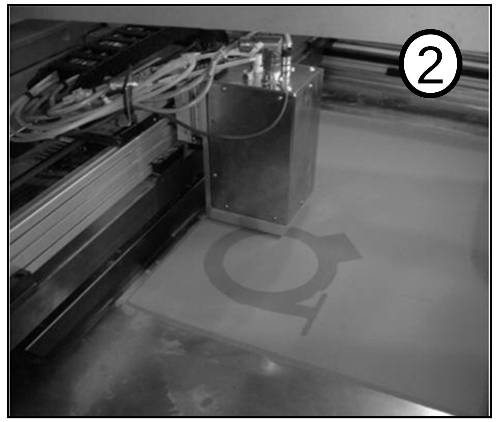


Sand Casting Molds
and Cores - Without a
Pattern

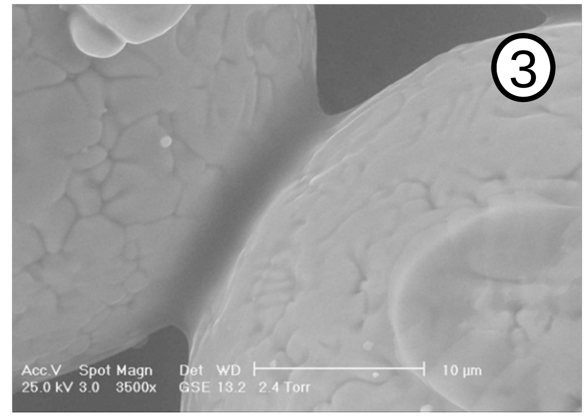
ExOne
DIGITAL PART MATERIALIZATION

# Direct Metal Technology

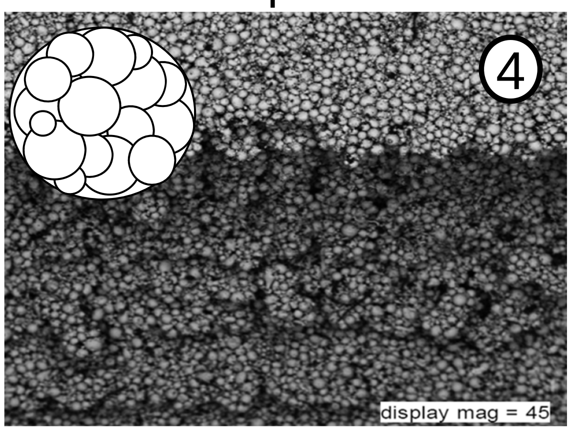

Spreading new layer of metal powder



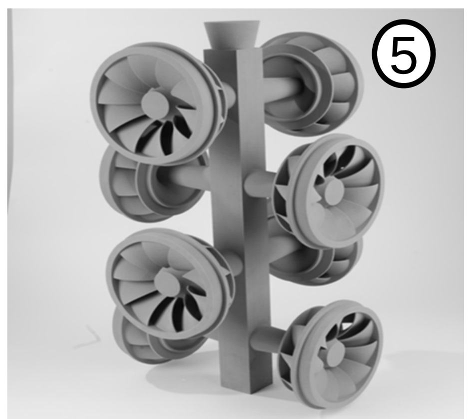

Powder Printing



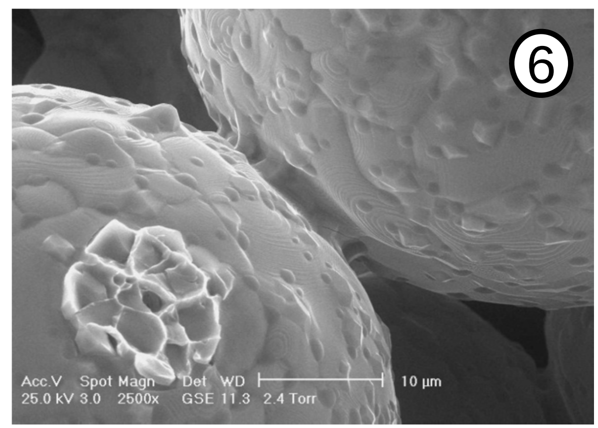

Print-Bonded Particles




Particles agglomerated in one droplet (Voxel)

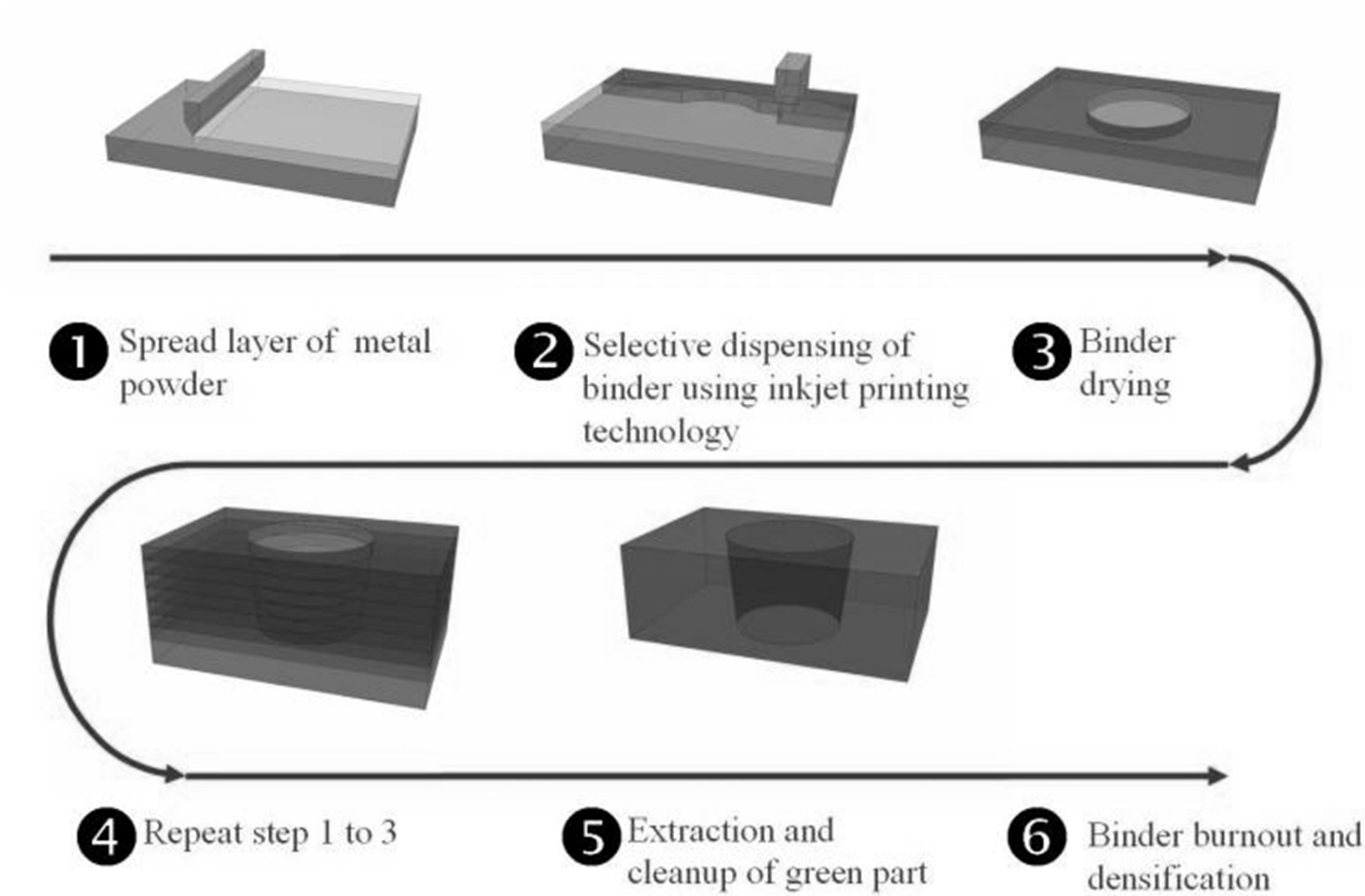



Parts Stilted for Infiltration



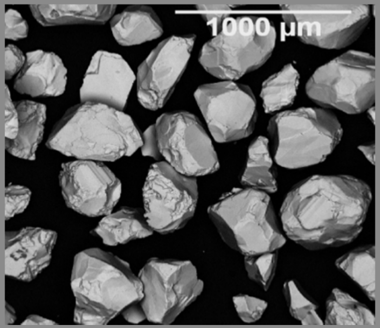

Sintered Particles

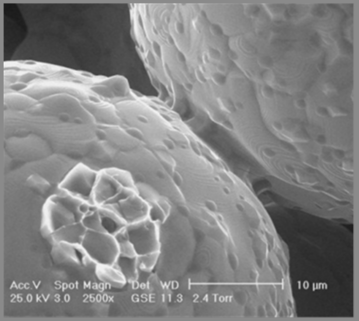
# Direct Metal Technology

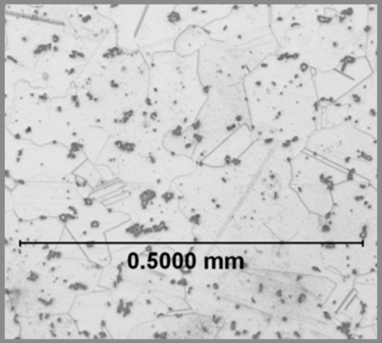


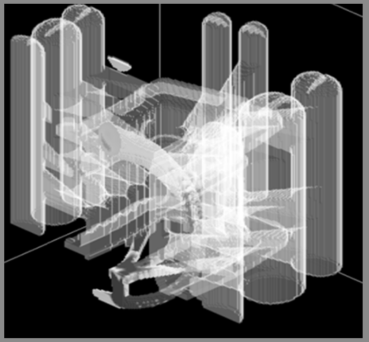
# ExOne Materials Applications Laboratory

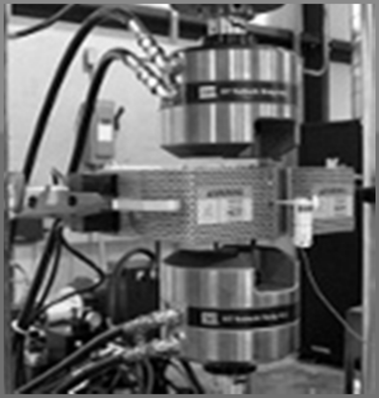
- Materials Analysis
- Mechanical Testing
- Metallography & Microscopy
- Hardness
- …sity
- …of Thermal Expansion

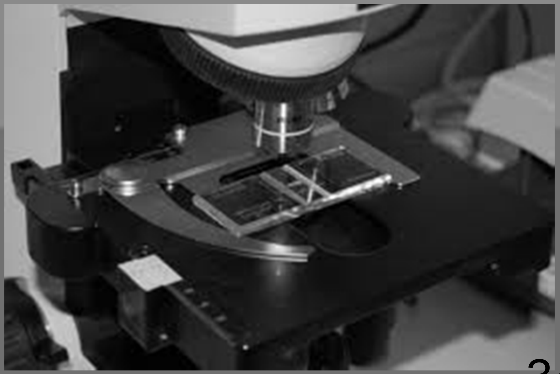


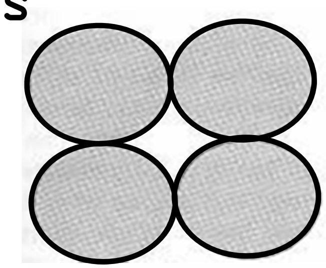





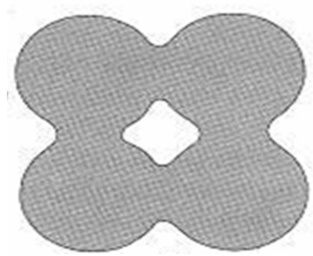
# 3DP is Basic Powder Metallurgy

**Product Forms**

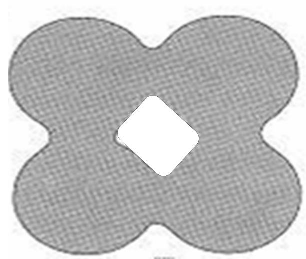
Bonded



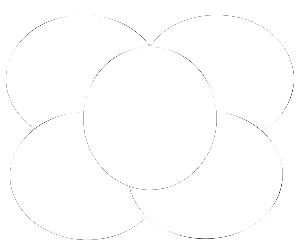
Partially Sintered

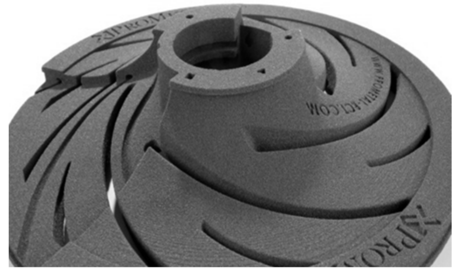


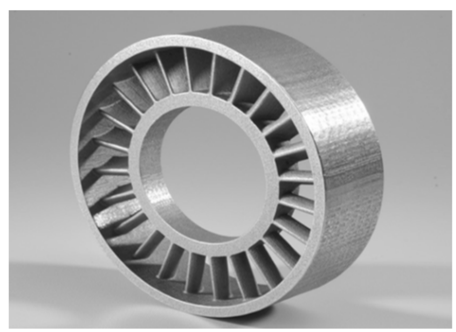
Infiltrated



Highly Sintered

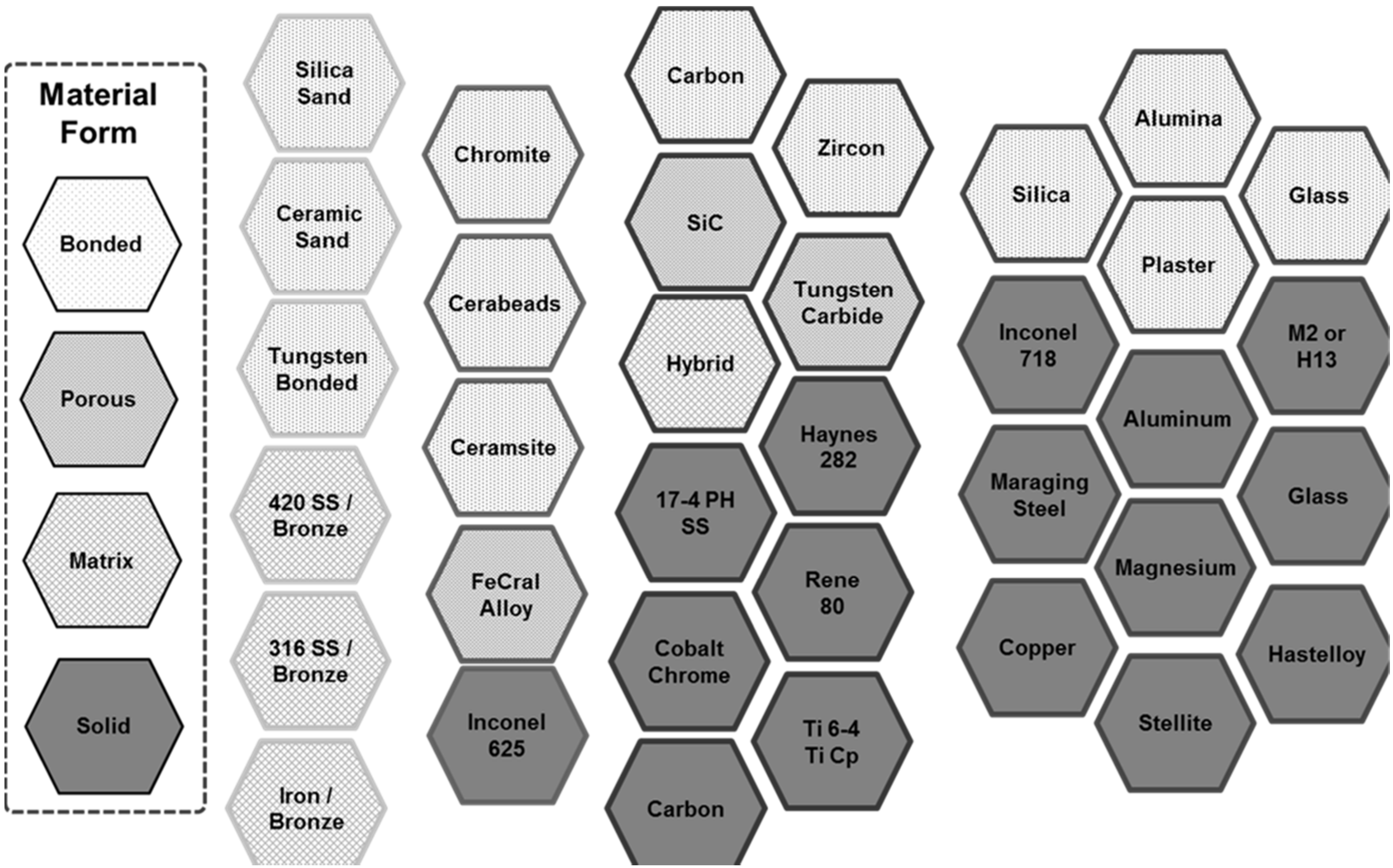






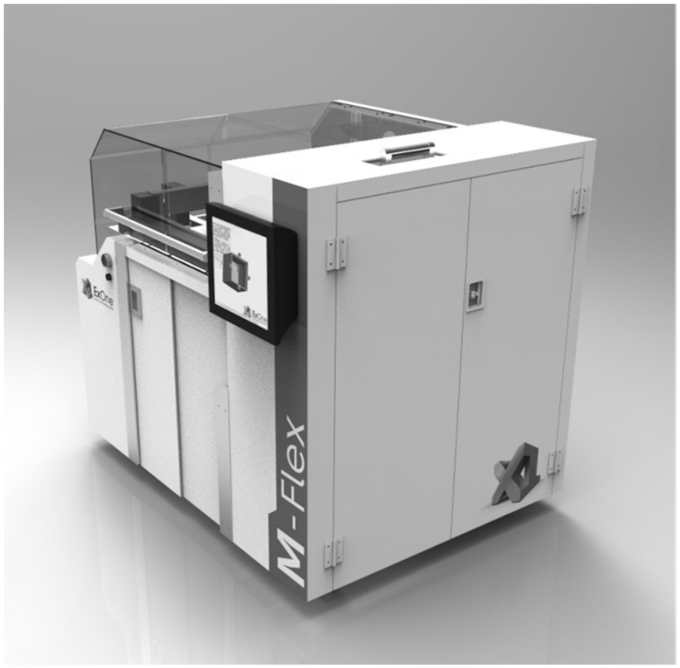
Powder metallurgy is the process of blending fine powdered materials, pressing them into a desired shape or form (compacting {printing}), and then heating the compressed material in a controlled atmosphere to bond the material (sintering). The powder metallurgy process generally consists of four basic steps: powder manufacture, powder blending, compacting

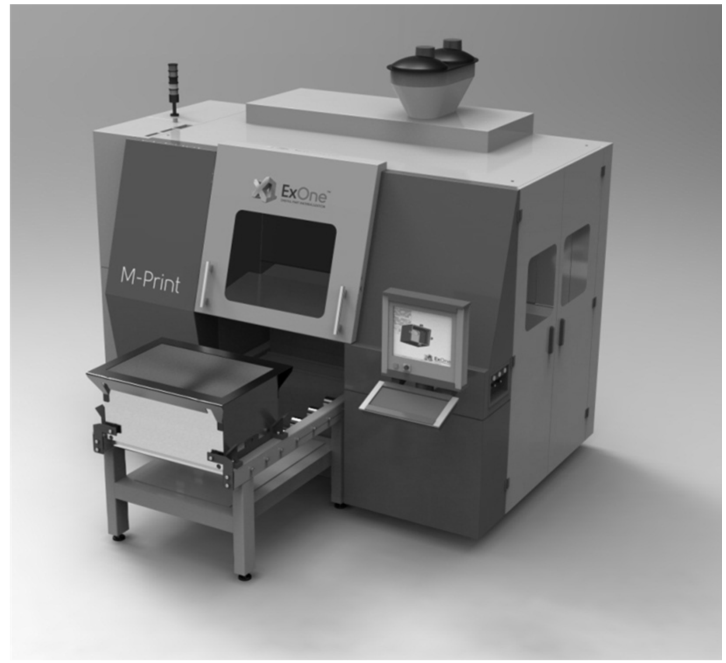
# ExOne – Materials Research



ExOne
DIGITAL PART MATERIALIZATION

# 3DP Binder Jetting Parts – Rapid Production




| System | Speed | Build Rate | Layer Thickness |
|---|---|---|---|
| **M-Print** | 75 seconds per layer | 2052 $cm^3$/hr (125 $in^3$/hr) | Variable with minimum of 0.15 mm (0.006 in) |
| **M-Flex** | 30 seconds per layer | 1200 $cm^3$/hr (73 $in^3$/hr) | Variable with minimum of 0.1 mm (0.004 in) |

# Direct Metal Technology – M-Flex

<u>Build Volume</u>:

15.5 x 9.5 x 9.5 in.

394 x 241 x 241 mm

<u>Layer Thickness</u>:

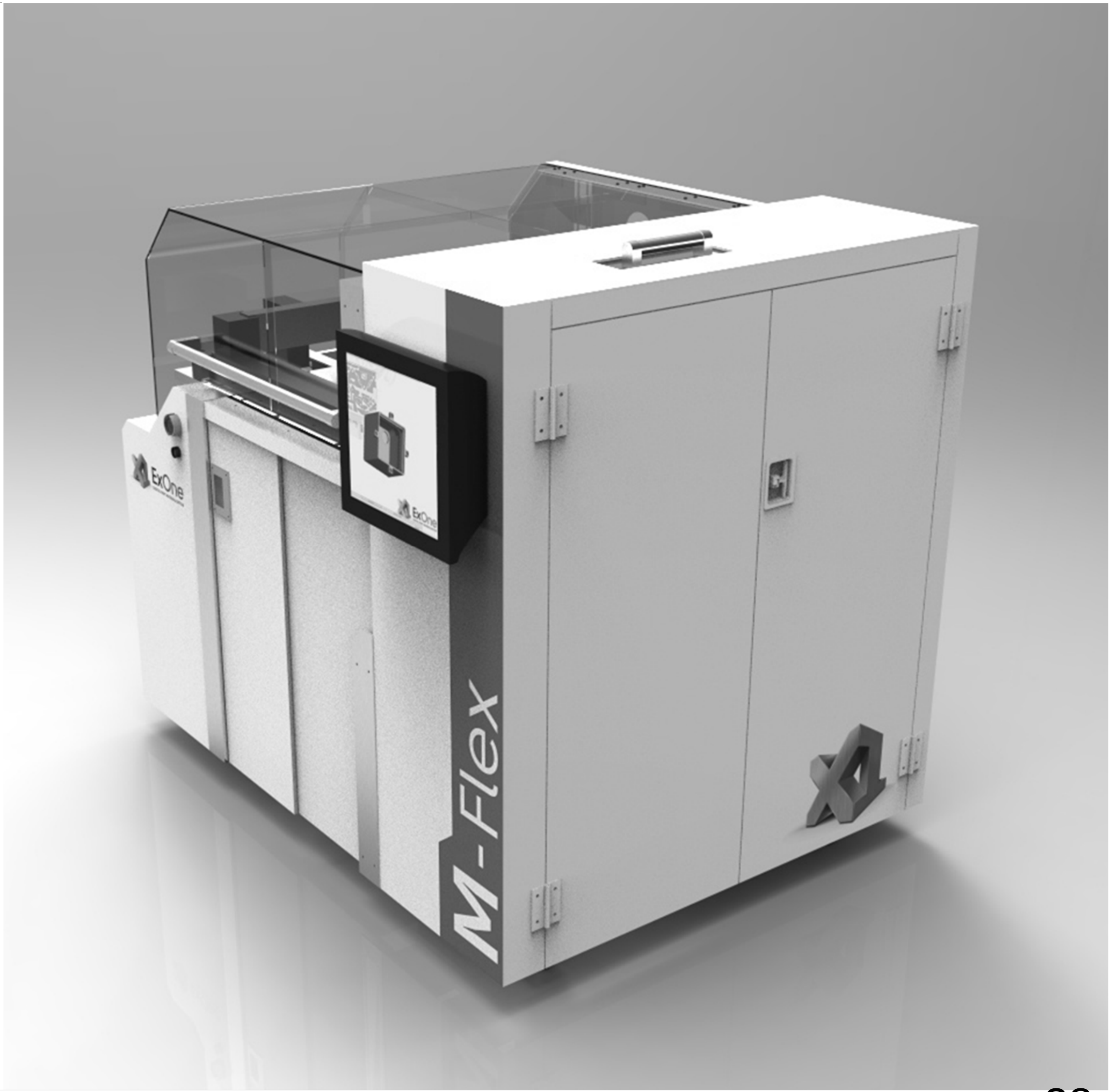
100 or 180 microns

<u>Accuracy</u>:

+/- 0.5%

System includes

de-powdering station
and curing oven



# Direct Metal Technology – M-Print

<u>Build Volume</u>:

29.5 x 15 x 15.75 in.

750 x 380 x 400 mm

<u>Layer Thickness</u>:

100 or 180 microns

<u>Accuracy</u>:

+/- 0.5%

# Team Member Bodycote

- Bodycote operates a global HIP business with the largest equipment network in the world
- Bodycote has over 50 HIP vessels of varying sizes in multiple locations and is able to accommodate large volumes of small products as economically as large individual components.
- Bodycote provides two major HIP routes for customers:
  - HIP Services, providing porosity removal through HIP densification.
  - HIP Product Fabrication, for the manufacture of components through powder metallurgy and diffusion bonding.

Bodycote

# Hot Isostatic Pressure

Hot Isostic Pressure (HIP) combines high temperatures (up to 2,000° C) with isostatically applied gas pressures (up to 45,000 psi) – comparable to the Mariana Trench 11,000m deep in the Pacific Ocean.

# Bodycote HIP Services

- Hot Isostatic Pressing (HIP) combines very high temperature and pressure to eliminate porosity in castings, and consolidate encapsulated powders to give fully dense materials.
- Dissimilar materials can be bonded together to manufacture unique, value-added components.

# Progress on Primary Tasks

1.0 – Project Management & Planning

2.0 – Atomization of A-282

3.0 – Material Characterization & Sintering Methodology (MC/SM) for A-282

4.0 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

5.0 – Produce 1 Valve via AM/3DP and HIP

6.0 – Post Processing Analysis

7.0 – Outreach & Technology Dissemination

# ☑ Task 2 - Atomization of 282

- For the HIP process – powder screened to roughly ~ 250 microns
- For the AM process – powder screened to max size 22 microns

SEM photomicrographs of the AM powder are shown in Figures 1 & 2

Figure 1 - SEM Analysis

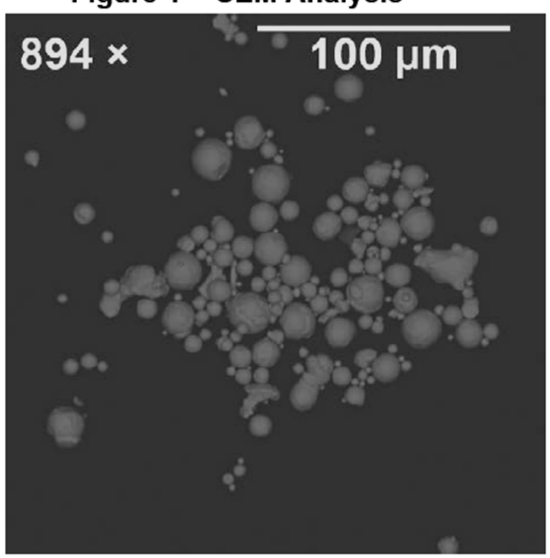
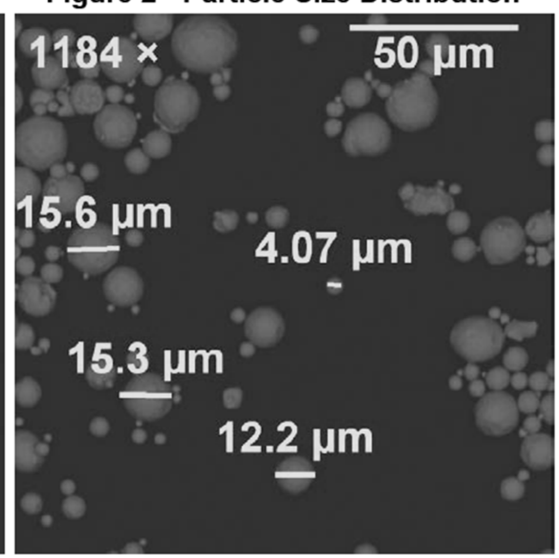



Figure 2 - Particle Size Distribution



# ➔Task 3 – Material Characterization & Sintering Profile

- Binder Saturation Tests were performed to establish the optimal amount of binder to be dispensed on the bed during printing
  - Too little saturation can result in flaking of the sample & poor adhesion from layer to layer
  - Too much saturation can lead to swelled samples

- FINDING:  Determined 80% saturation yielded best results
- Binder is subsequently removed via “burnout” in furnace

# ➔Task 3 – Material Characterization & Sintering Profile

- Testing of the A282 was conducted in a high vacuum furnace producing a vacuum below $3.0\text{x}10^{-5}$
- Three pump downs and backfills with inert gas (96% nitrogen & 4% hydrogen) were done before each run to ensure any moisture was removed from the chamber
- Burnout Temperature 600° C (to remove binder)
- Variables in the test runs included:
  - Furnace Temperature (min 1290° C to max 1325° C)
  - Max Temperature Hold Time (1 hour – 1.5 hour)
  - Ramp-up and Ramp-down Rates (5° C/min to 1° C/min. The ramp rate down from 1315° C to 800° C was also changed from 5° C/min to 1° C/min )
  - Number of samples in a run (ranged from 1 – 3)
  - Size of sample
- FINDING: Achieved 95.35% density before machining, with no distortion or cracks!

# ➔Task 3 – Material Characterization & Sintering Profile

**Furnace Profile: Run 3**

| Furnace Type | Profile Name | File Name | Ramp Type | Units | G-hold Hi | G-Hold Lo | Prog by | Date | Approved by |
|---|---|---|---|---|---|---|---|---|---|
| Centorr C | haynes 282 | sintering 1310c | Rate | Deg C | 10 Deg | 10 Deg | M.O. | 2/13/2015 | |

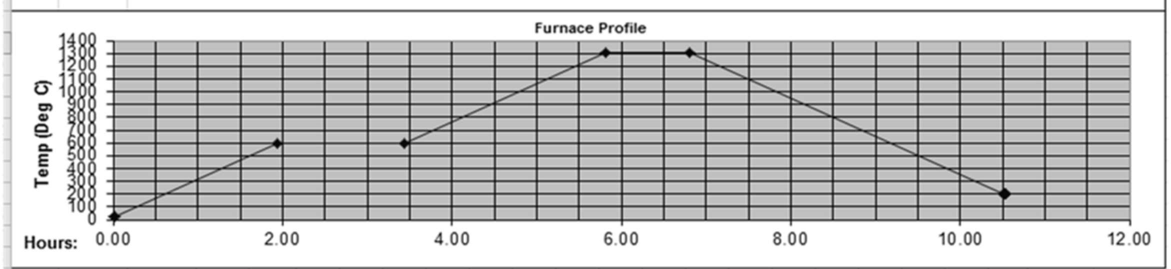
Operation:-> sintering | Powder:-> none | Part Size:-> Small

Remarks:->

| Seg # | Type | Temp Deg C | Time/ Rate | Event: 1 start | 2 spare | 3 spare | 4 cool | 5 fan | 6 hi vac | 7 H2 cyc | 8 PP cyc | 9 N2 gas | 10 H2 gas | 11 Ar gas | 12 Purge | 13 Heat on | 14 Heat Off | 15 spare | 16 Stop | --- G Hold | --- Atm | Calculated Profile Time Hrs | Calculated Profile Temp Deg C |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | | | | | | | | | | | | | 0.00 | 22 |
| 1 | Soak | 22 | 1 | | | | | | | | | | | | | | | | | | | 0.02 | 22 |
| 2 | Ramp | 22 | 5 | | | | | | | | | | | | | | | | | | | 1.94 | 600 |
| 3 | Soak | 600 | 90 | | | | | | | | | | | | | | | | | | | 3.44 | 600 |
| 4 | Ramp | 600 | 5 | | | | | | | | | | | | | | | | | | | 5.81 | 1310 |
| 5 | Soak | 1310 | 60 | | | | | | | | | | | | | | | | | | | 6.81 | 1310 |
| 6 | Ramp | 1310 | 5 | | | | | | | | | | | | | | | | | | | 10.51 | 200 |
| 7 | Soak | 200 | 1 | | | | | | | | | | | | | | | | | | | 10.53 | 200 |
| 8 | Ramp | 200 | 5 | | | | | | | | | | | | | | | | | | | 10.53 | 199 |
| 9 | soak | 199 | 1 | | | | | | | | | | | | | | | | | | | 10.55 | 199 |
| 10 | soak | 199 | 0 | | | | | | | | | | | | | | | | | | | 10.55 | 199 |

**Controller Settings for this Profile:**

| Variable | Setting | Remarks |
|---|---|---|
| Prog# | | this run is under a high vacuum below 3.0 10x-5 three pumpdowns and back fills before going into high Vacuum |
| Purge | | |
| Remarks: | | 95.3% dense no distortion |




For this Run 3 the maximum temperature was increased another 10° C to 1310° C and held for one hour. The details of the profile used for this test are shown in the table at right.

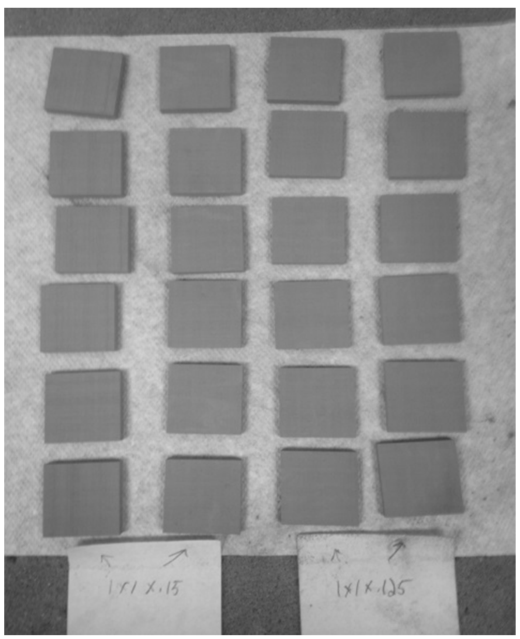

Result: Sample was 95.35% dense with no distortion before machining. The sample is shown at right after machining had been done.

# ➔Task 3 – Material Characterization & Sintering Profile

- Following Successful Test Runs HIP Can Test Samples were printed in "green state" by ExOne in 2 sizes:

  1" x 1" x .125"  and  1" x 1" x .150"
- Crisp edges remained intact during handling

Top View

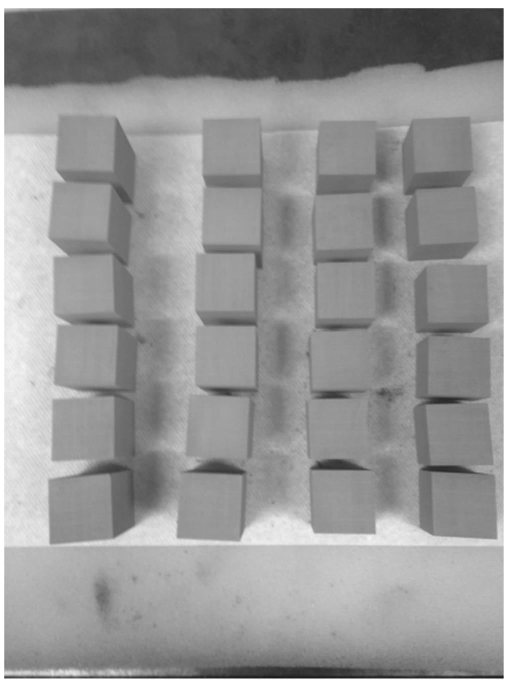



Side View

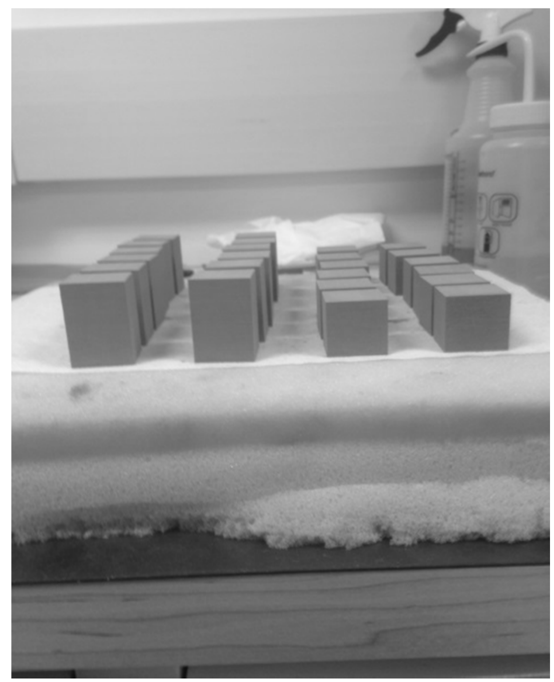
# ➔Task 3 – Material Characterization & Sintering Profile

- AM Valve Test Samples were printed in “green state” by ExOne in 2 sizes:  1” x 1” x 1”  and  1” x 1” x 1.5”
- Crisp edges remained intact during handling

Top View



Side View



# ➔Task 3 – Material Characterization & Sintering Profile

- Test coupons will be used to determine the final furnace profile to achieve the highest density possible.
- Coupons will be used to determine final scaling factor to account for shrinkage
- HIP will be applied to Test Coupons to achieve max density (seeking full density)

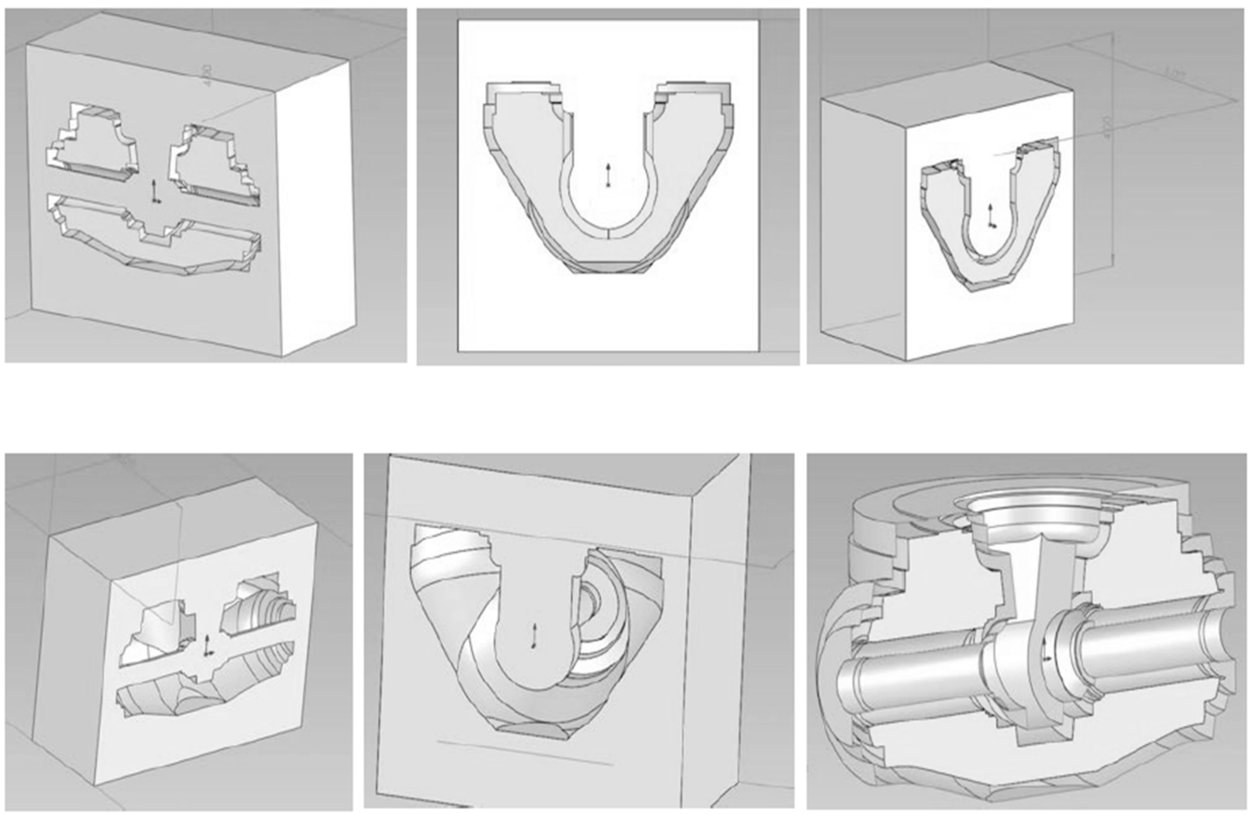
# ➔Task 4 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

Current Progress: Design Cans & Produce CAD Drawings

- Major design challenge: modify the can design to accommodate the fill tube
- ExOne will build a .875” OD X .375” ID X .25” tall socket or collet over the .375” hole in the valve.
- Bodycote will use this feature to socket weld the tube to the valve.
- To test this approach, Bodycote successfully welded a 0.375” OD x 0.083” wall tube to a sample block of Haynes 282 provided by EIO and had zero issues.  Helium leak check was performed and passed.

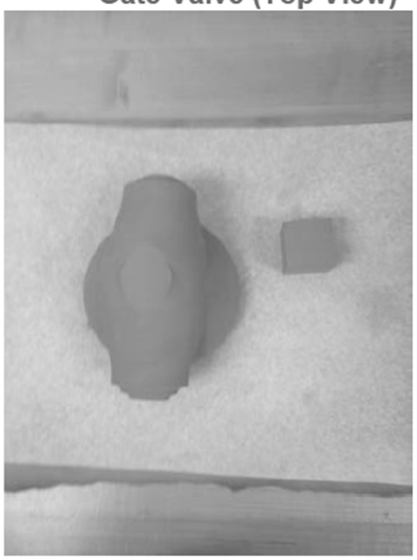
# ➔Task 4 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

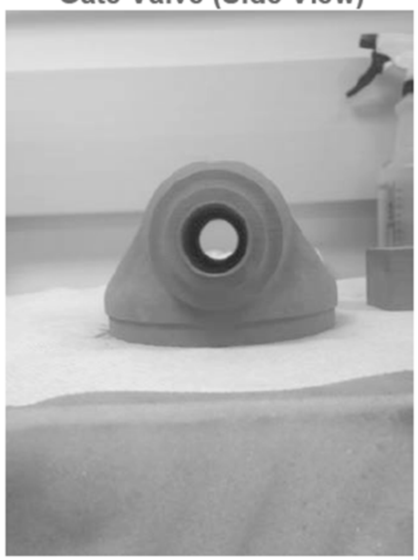
Current Progress: Design Cans & Produce CAD Drawings



# ➔Task 5 – Produce 1 Valve Component via AM/3DP & HIP

## Current Progress: First 3DP Valve Produced


Gate Valve (Top View)


Gate Valve (Side View)


Gate Valve (Bottom View)

The support cylinders on the flange shown in the bottom view image (blue arrows highlight two of them) were added in an attempt to allow the part to shrink uniformly and minimize distortion during sintering

# Summary: Progress To Date (4/27/15)

➔1.0 – Project Management & Planning

☑ 2.0 – Atomization of A-282

➔3.0 – Material Characterization & Sintering Methodology (MC/SM) for A-282

➔4.0 – Produce 2 Valve Components via AM Cans & HIP/PM Manufacturing

➔5.0 – Produce 1 Valve via AM/3DP and HIP

☐ *6.0 – Post Processing Analysis*

➔7.0 – Outreach & Technology Dissemination

# Summary

- Tailoring HIP/PM with advances in AM provides specific, measurable benefits for fabricating advanced energy (AE) system components.
- Three new methods of manufacturing advanced alloys under evaluation include:
  1. Directly built AM parts;
  2. AM cans for HIP/PM; and
  3. AM cans produced in the final part material.
- Potential advantages include lower manufacturing costs, ability to produce more complex designs, improved production efficiency & readily transferrable technology

# Contacts

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