
# Advanced and Additive Manufacturing Technologies for Liquid Rocket Engine Components

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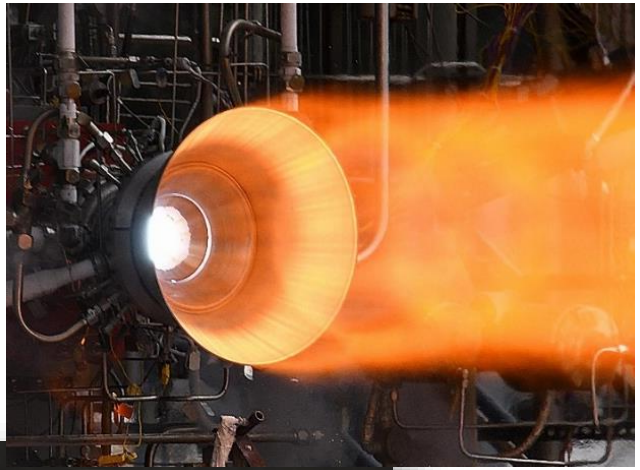
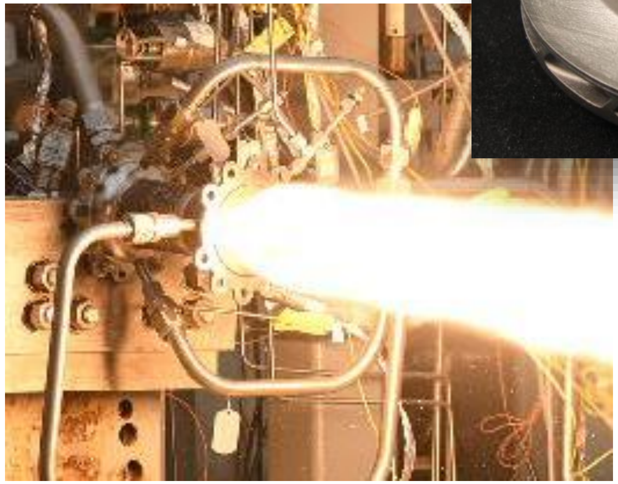
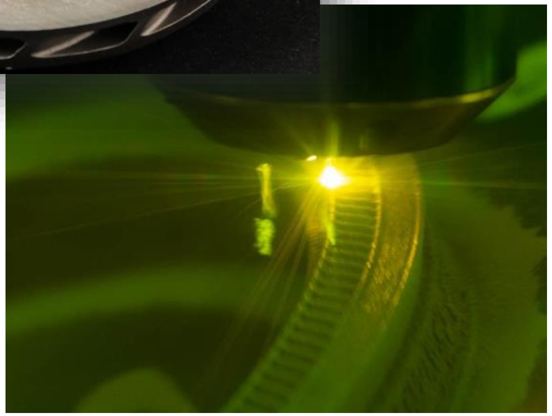
AIAA Liquid Rocket Engine Overview Training

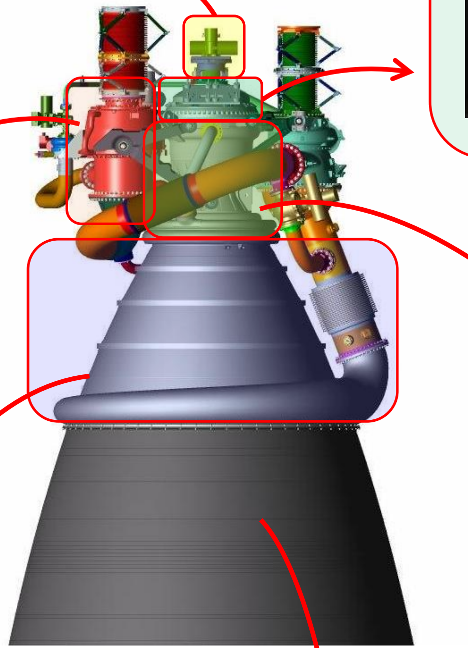
# Overview of Advanced Manufacturing

- Introduction
  - Overview of Liquid Rocket Engine Components
  - Background and goals at NASA
- Materials for Liquid Rocket Engine Applications
  - Requirements for Materials
  - Environments – operation and manufacturing
- Overview of Additive Manufacturing (AM) Technologies
  - Chambers
  - Nozzles
  - Injectors
  - Turbomachinery
- Focus of Techniques for Additive Manufacturing
  - Laser Powder Bed Fusion (L-PBF)
  - Blown Powder Directed Energy Deposition
  - Laser Wire DED
  - Wire Arc Additive Manufacturing
  - Comparison
- Design Applications in AM
  - Why select one process over another?
  - Limitations
- AM Component Applications in liquid rocket engines
- Development and Testing
- New Developments
  - Multi-metallic
  - Performance Improvements
- Summary

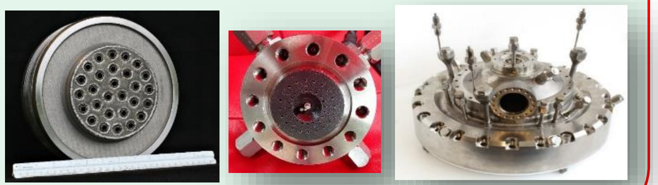



# Advanced and Additive Manufacturing being used across all components on liquid rocket engines

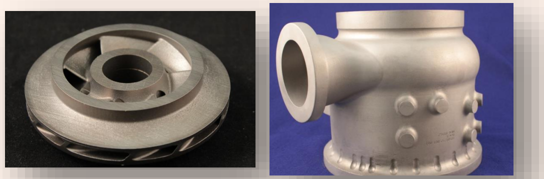


## Augmented Spark Igniters

## Injectors



## Turbomachinery



## Combustion Chambers

## Channel-cooled Nozzles

## Uncooled Nozzle Extensions

## Valves, Lines Ducts

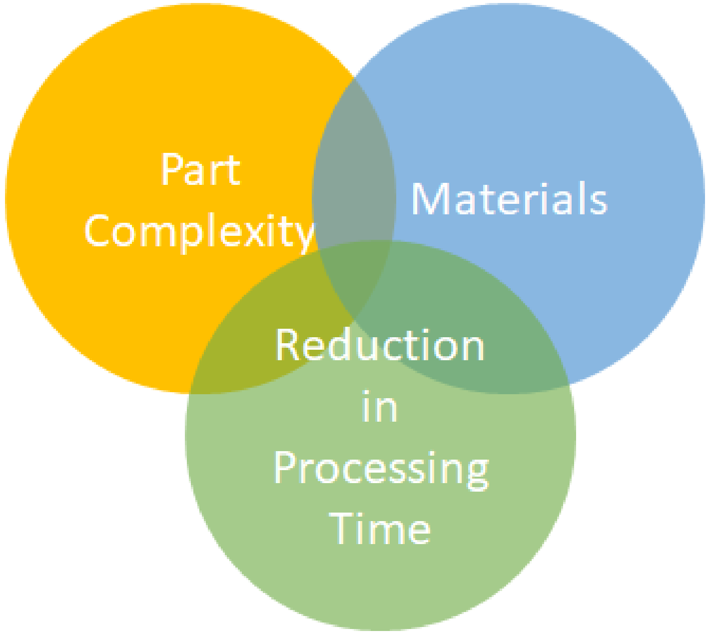
# Objectives of Advanced Manufacturing for Rocket Engines

## Develop. Explore. Inspire.

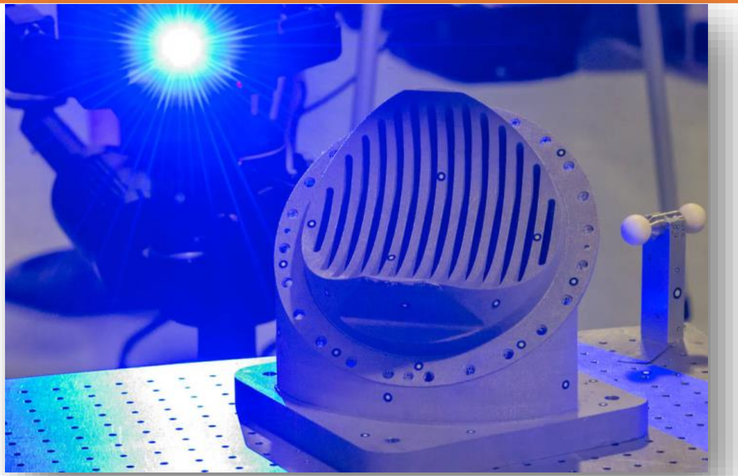
- Direct alignment with program and mission goals for exploration through high performance and cost reduction
  - **Establish and evolve advanced manufacturing and additive supply chain for NASA projects**
- Enable other NASA projects, government, commercial space, and industry partners
- Develop advanced applications and low technology readiness level (TRL) processes and materials for liquid rocket engines
- Complete material testing and characterization, application development, relevant testing in liquid rocket engine hot-fire environments
- Provide rigor and methodology for certification of additive processes
- Disseminate data through technical reports, conferences, and other publications to allow industry to further evolve and improve

# Why Metal Additive Manufacturing (AM) for rocket engines?

- Metal Additive Manufacturing (AM) provides significant advantages for lead time and cost over traditional manufacturing
  - Lead times reduced by 2-10x and cost reduced by more than 50% depending on the part
- Complexity is inherent in liquid rocket engines and AM provides new design and performance opportunities
- Materials that are difficult to process using traditional techniques, long-lead, or not previously possible are now accessible using metal additive manufacturing



# Additive Manufacturing for flight applications



**Successful hot-fire testing of full-scale Additive Manufacturing Part to be flown on NASA's Space Launch System (SLS) RS-25 Pogo Z-Baffle –** Used existing design with additive manufacturing to reduce complexity from <u>127 welds to 4 welds</u>

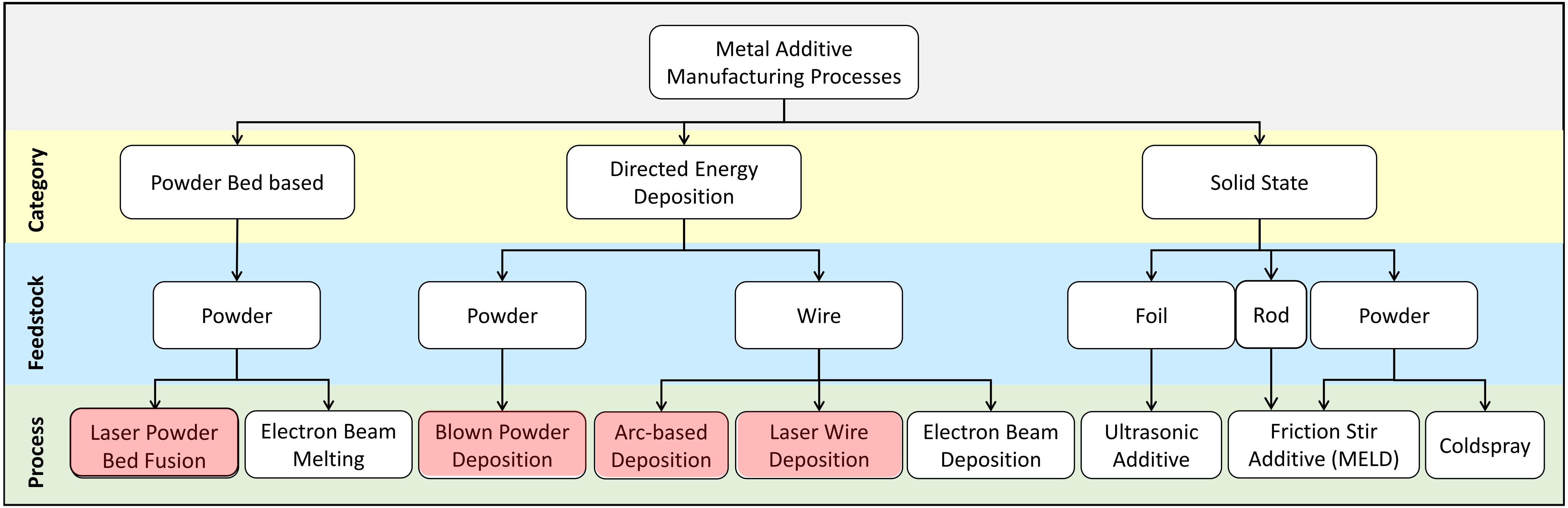
Ref: Andy Hardin, Steve Wofford/ NASA MSFC

# Introduction to Additive Manufacturing Terminology

- **Additive Manufacturing** – process of joining materials to create objects from 3D model data
- This presentation will focus exclusively on metals
- Additive manufacturing is not a solve-all; consider trading with other manufacturing technologies and use only when it makes sense
- Complete understanding of design process, build-process, and post-processing critical to take full advantage of AM
- Additive manufacturing takes practice!

- AM = Additive Manufacturing
- L-PBF = Laser Powder Bed Fusion
- DED = Directed Energy Deposition

# Focus of Metal AM Technologies

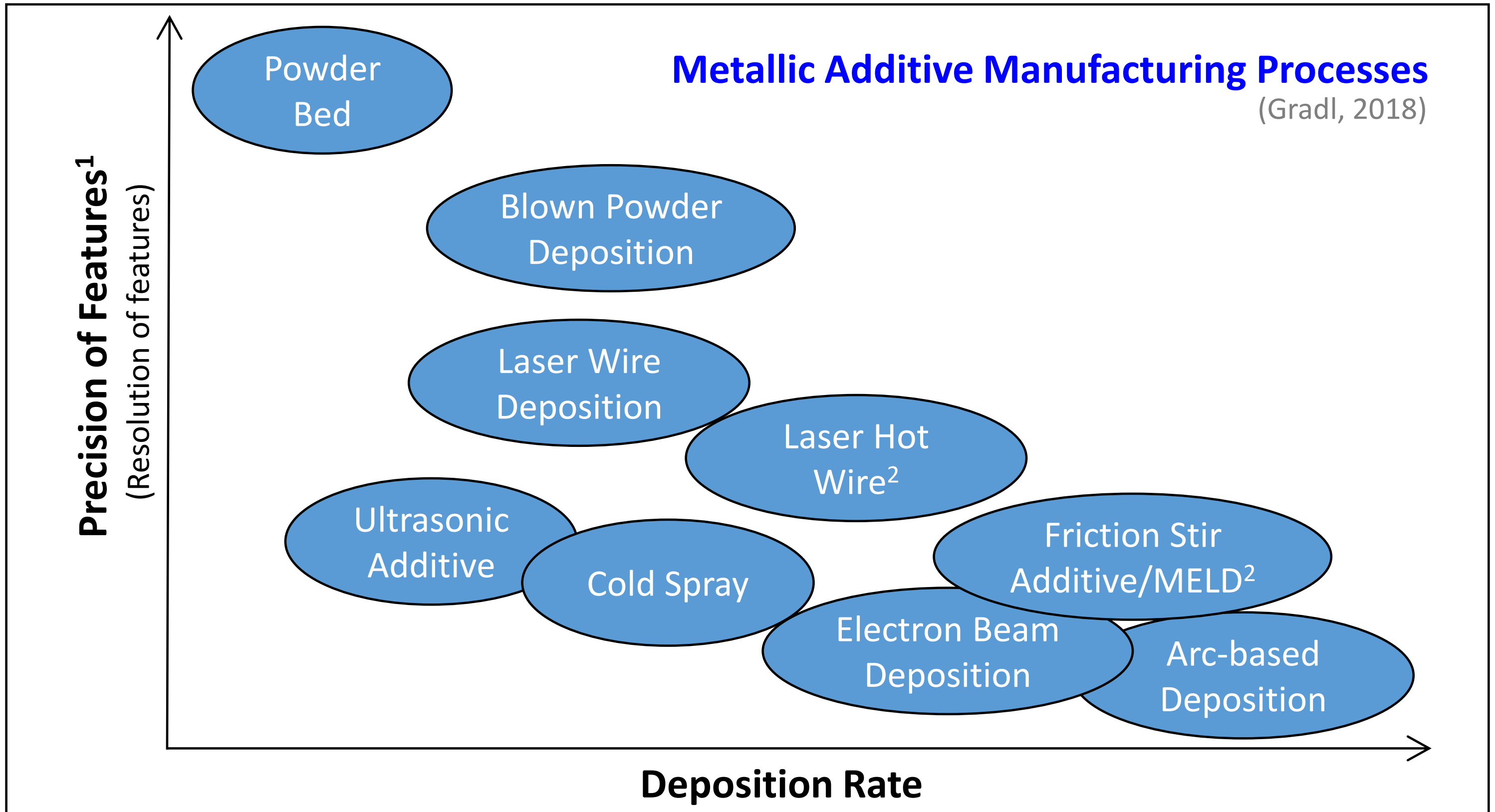



*Does not include all metal AM processes

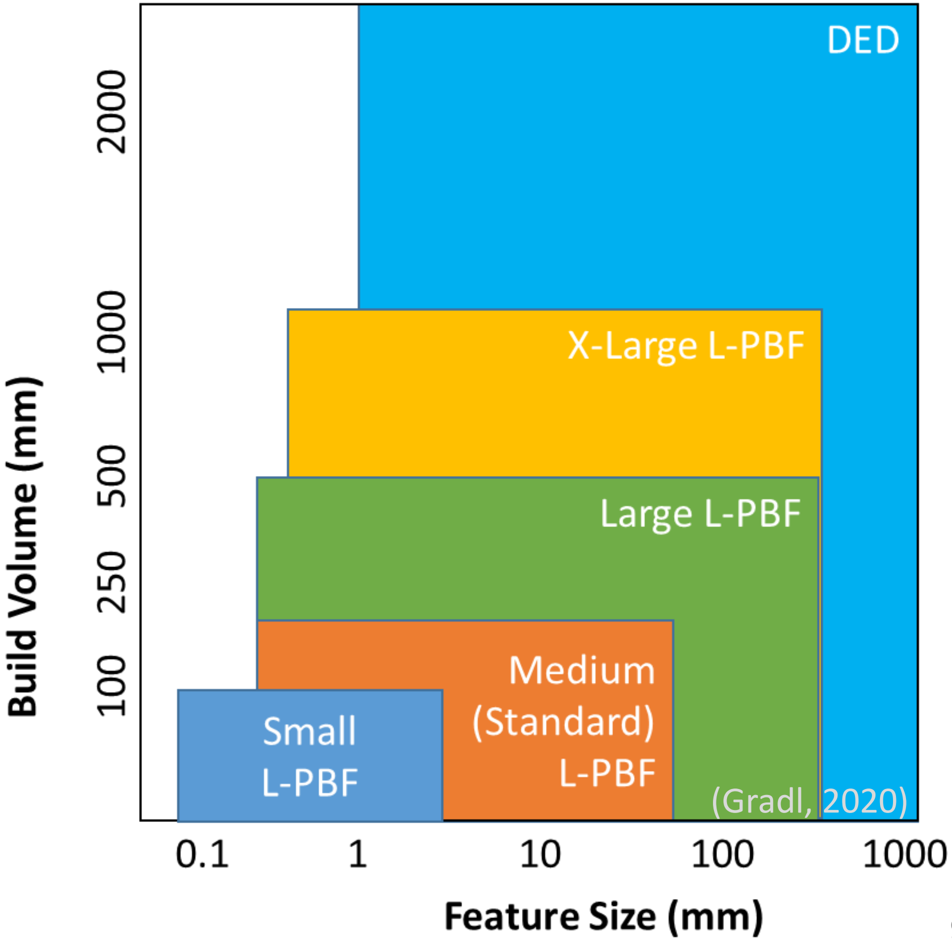
# Trades and Selection of Metal AM Technologies

Complexity of Features | Scale of Hardware | Material Physics | Speed of Process

Cost | Material Properties | Internal Geometry | Availability




[1] Precision refers to the as-built state and does not encompass hybrid techniques and/or interim machining operations that would increase resolution. There are a lot of other factors not considered in this chart, including heat inputs to limit overall distortion.
[2] Technology still under development



# Materials for Liquid Rocket Engines

Industry Materials developed for L-PBF, E-PBF, and DED processes *(not fully inclusive)*

## Ni-Base
**Inconel 625**
**Inconel 718**
Hastelloy-X
Haynes 230
Haynes 282
Haynes 188
Monel K-500
C276
Rene 80
Waspalloy

## Cu-Base
**GRCop-84**
**GRCop-42**
C-18150
C-18200
Glidcop
CU110

## Al-Base
AlSi10mg
A205
F357
6061 / 4047

## Fe-Base
SS 17-4PH
SS 15-5 GP1
SS 304
SS 316L
SS 420
Tool Steel (4140/4340)
Invar 36
SS347
**JBK-75**
**NASA HR-1**

## Ti-Base
Ti6Al4V
γ-TiAl
Ti-6-2-4-2

## Co-Base
CoCr
Stellite 6, 21, 31

## Refractory
W
W-25Re
Mo
Mo-41Re
Mo-47.5Re
**C-103**
Ta

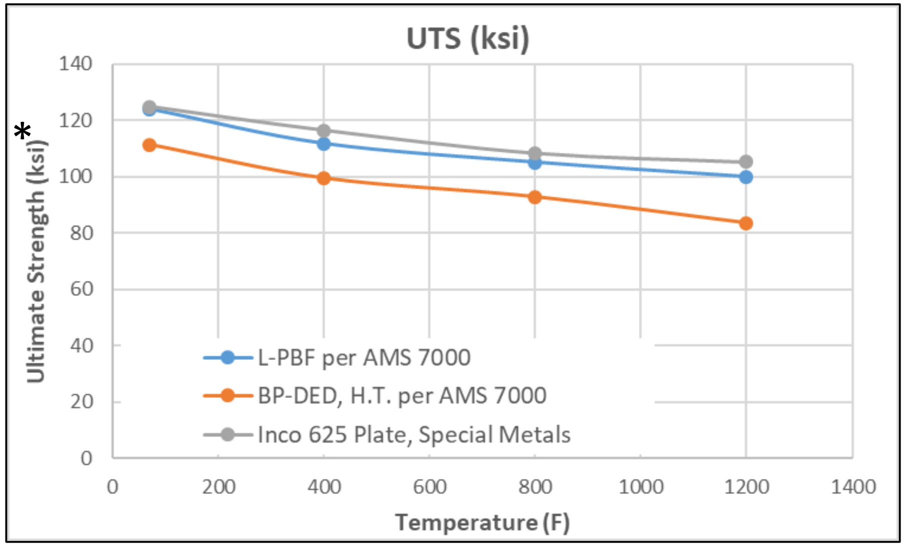
## Bimetallic
**GRCop-84/IN625**
**C-18150/IN625**

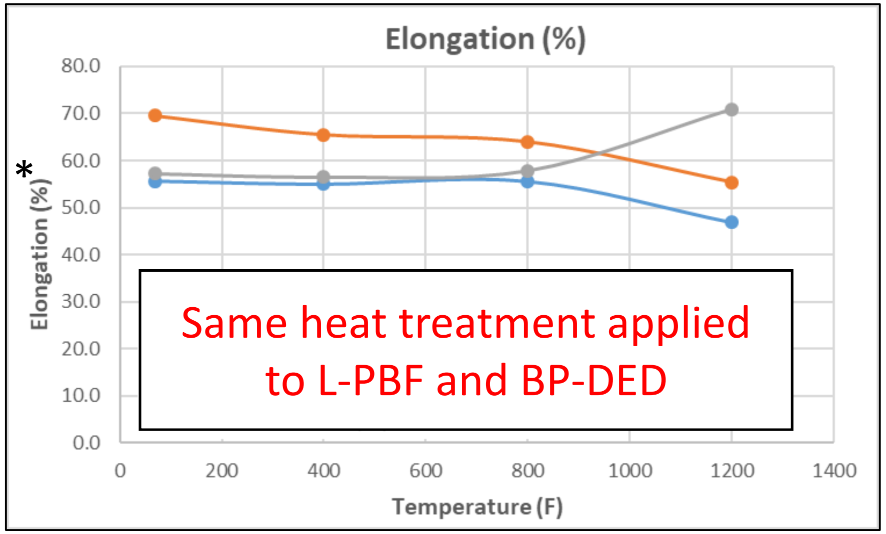
## MMC
Al-base
Fe-base
Ni-base

# AM Material Property Overview

- In general, once AM processes are refined they can yield near wrought properties
- Material properties are highly dependent on the type of process (L-PBF, DED, UAM, Coldspray,….), the starting feedstock chemistry, the parameters used in the process, and the heat treatment processes used post-build
- Each AM process results in different grain structures, which ultimately have an effect on properties
- Heat treatments should be developed based on the requirements and environment of the end component use
- Properties should be developed after AM process is stable and parameters confirmed

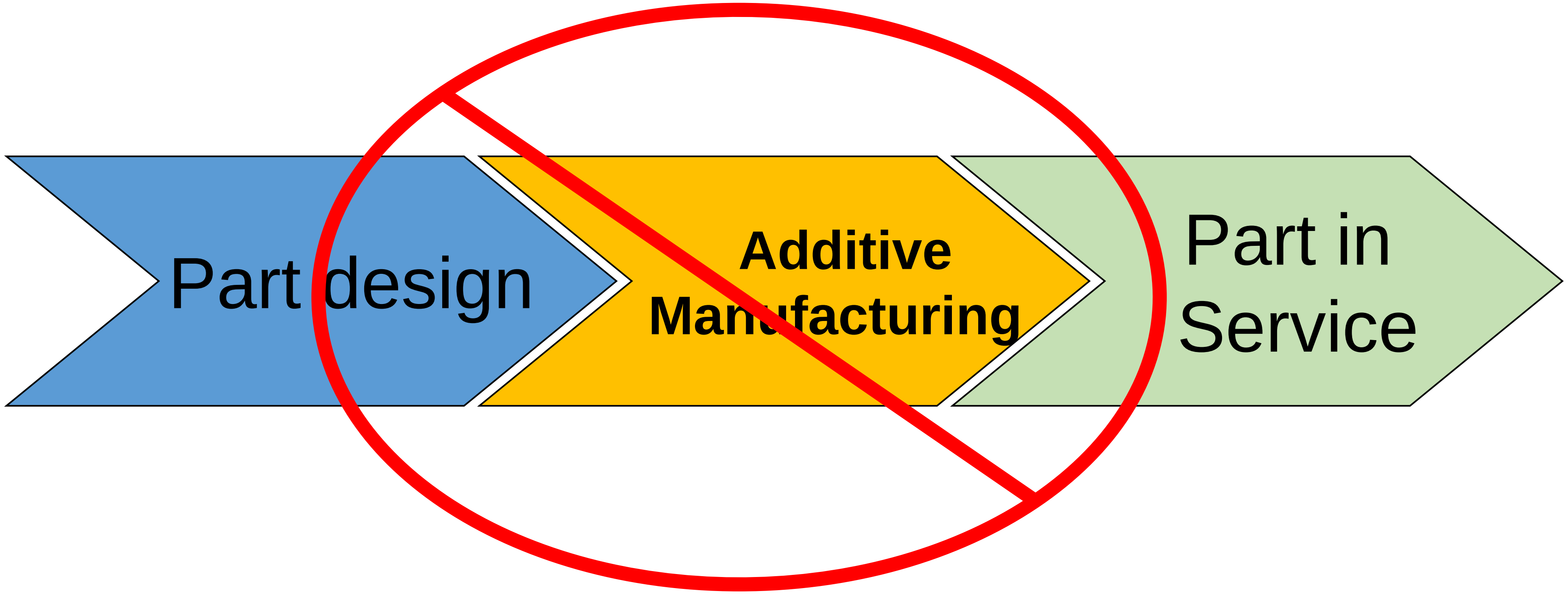
**Example of Inconel 625, L-PBF and BP-DED (Typical)**



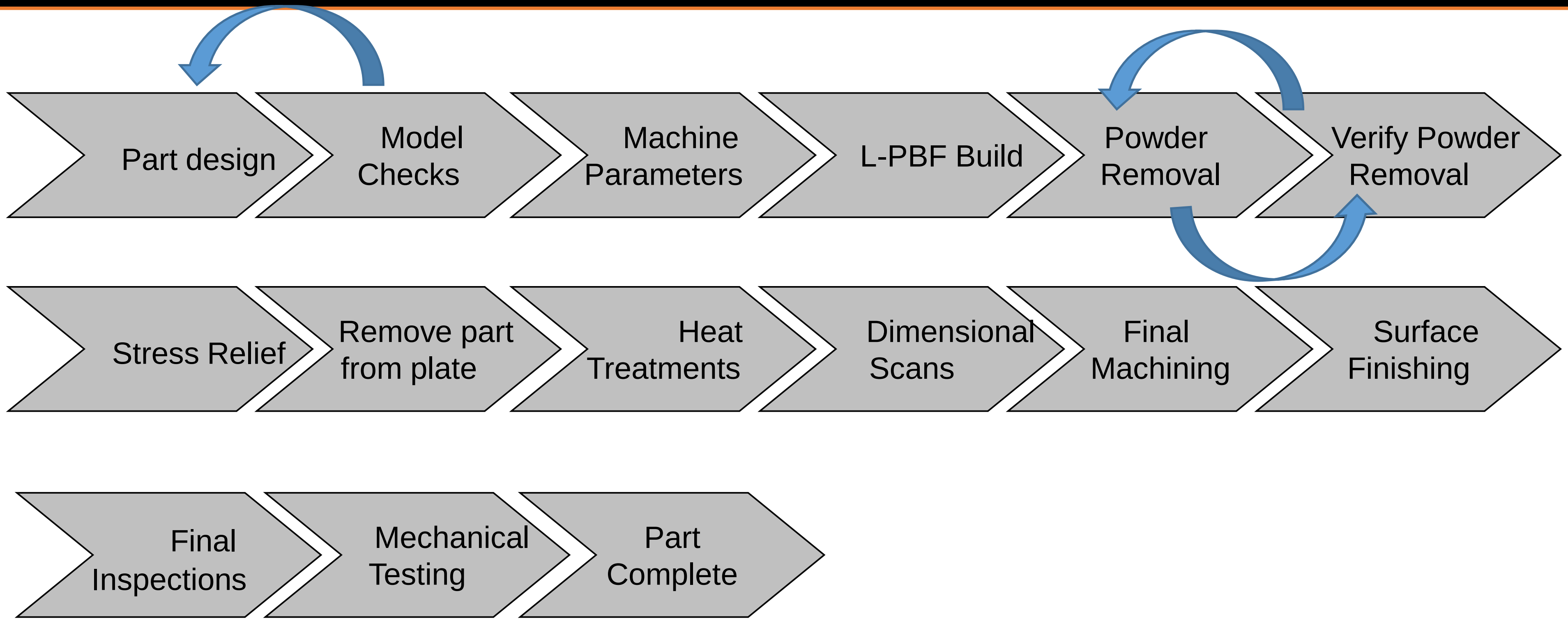




*Not design data and provided as an example only

# Perceived Process Flow for AM



# Actual Process Flow

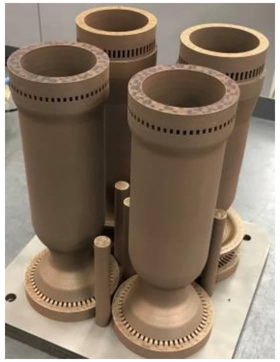



Each process step also includes a series of additional tasks in order to properly design, build, or complete post-processing

# Advantages and Disadvantages of AM

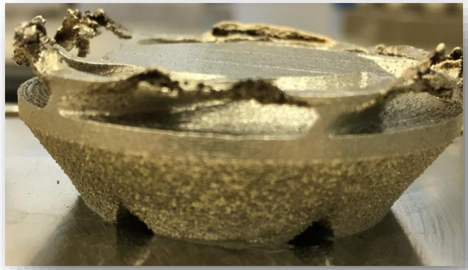
## Advantages:

- Components that are highly complex and low production rate.
- Features that could not be fabricated by other methods.
- Increased design freedom and customization.
- High feature resolution.
- Near net-shape complex geometry.
- Part count reduction.
- Performance improvement (i.e. weight reduction).
- One-off and discontinued parts.
- Shorter lead times.
- Properties are better than cast (but not wrought).

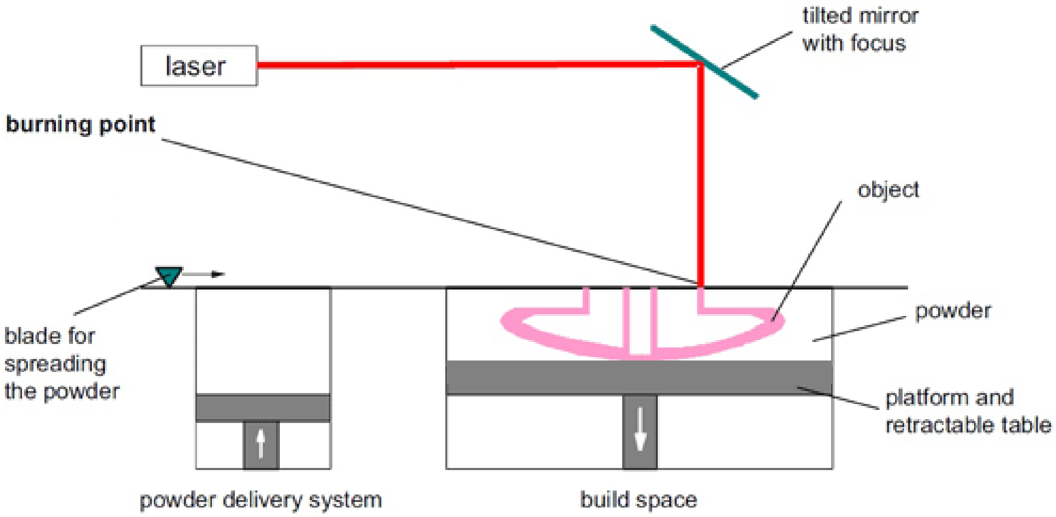
## Disadvantages:

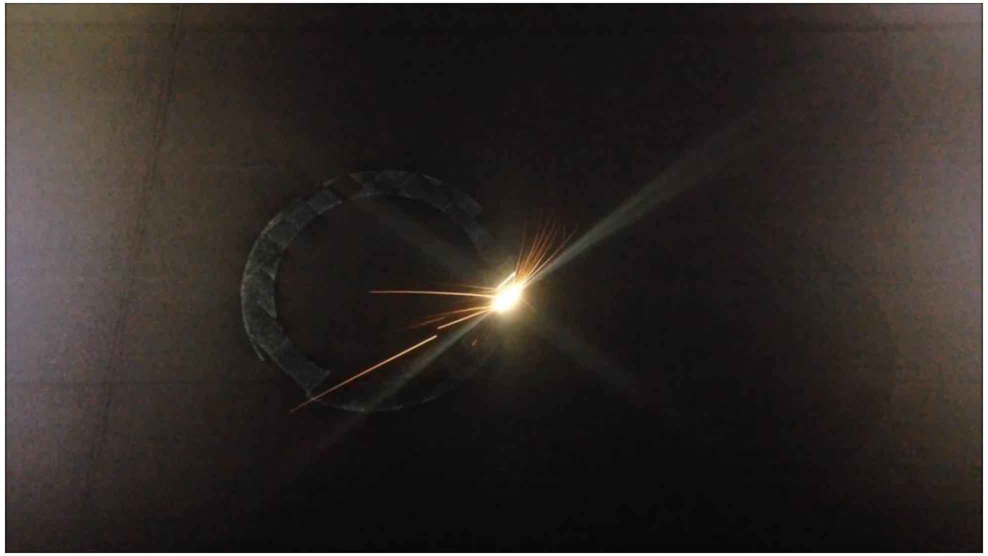
- Limited to weldable alloys
- Design constraints: overhang surfaces, minimum hole size.
- Surface roughness.
- As built microstructure will require post processing.
- Substantial touch labor.
- Waste generation: spent powder, build plates, failed builds.
- *MORE* expensive than traditional manufacturing (high hourly rates offset by reducing labor costs)

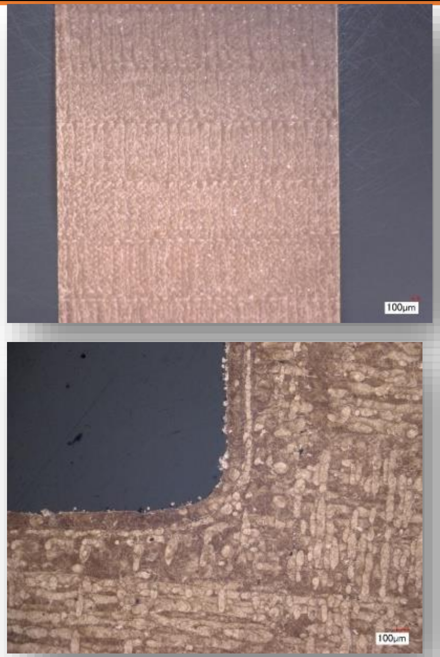


# Powder-bed based Processes

VDI-Guideline 3404 (2009) Additive Fabrication-Rapid Technologies (Rapid Prototyping) – Fundamentals, Terms and Definitions, Quality Parameter, Supply Agreements. (2014).

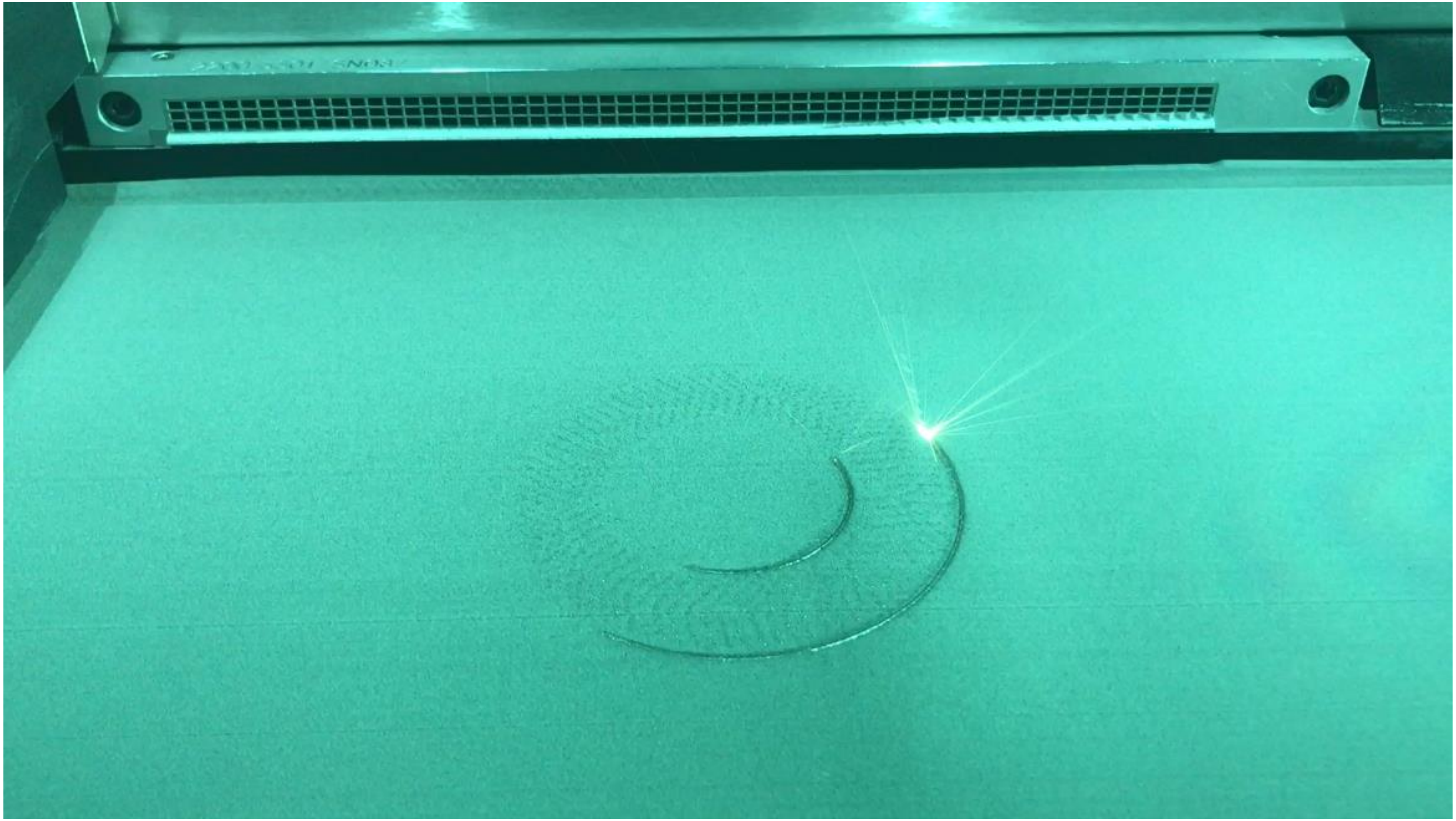




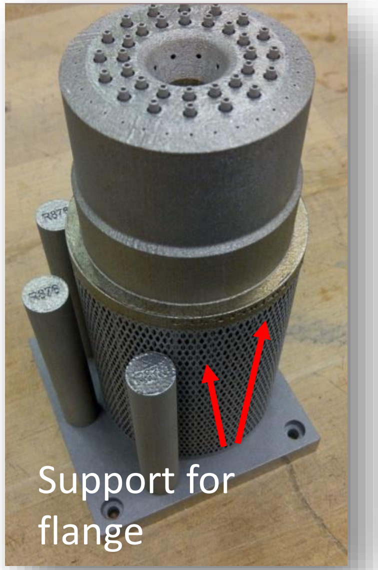
- **Selective Laser Melting (SLM)**
  - Basic Process: Uses a layer-by-layer powder-bed approach in which the desired component features are sintered and subsequently solidified using a laser. Used widely in combustion devices applications.
  - Advantages: Allows for high resolution, fine features, including complex internal designs to be fabricated, such as cooling channels
  - Disadvantages: The scale for SLM is limited and does not provide a solution for all components
- **Electron Beam Melting**
  - Basic Process: Similar to SLM, but uses an electron beam instead of a laser. Not frequently used in combustion devices applications.
  - Advantages: Build is performed under vacuum, which can be useful for reactive materials such as titanium

# L-PBF Operations

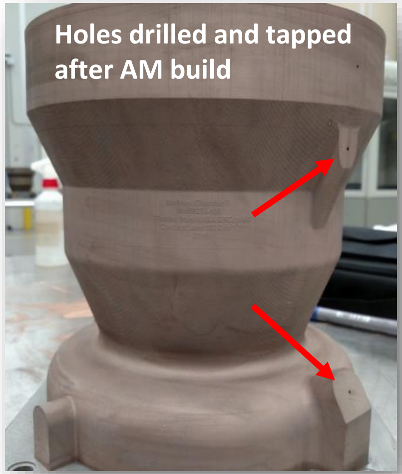


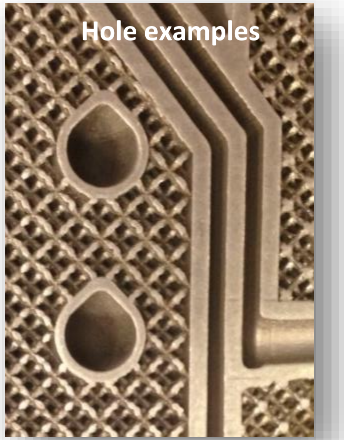
# Basic Design Rules for L-PBF

- The machine will print (or attempt to) what is in the model
- Angled feature designs are limited (measured from horizontal)
  - Features <45º with respect to the built plate normally require support
  - Features >45º with respect to the built plate normally do not require support
  - Consider features in all dimensions
- Horizontal holes cannot be printed as true holes if larger diameter
  - Largest unsupported hole ~ .250”
  - Smallest hole/feature ~.030”
- Overhangs can be created, but require supports (and subsequent removal)
- New machine and software developments are evolving and opening the design space even further
- Design and analysis needs to consider surface finishes for internal and external features
- Internal passages may need to be oversized to account for burn-thru or undersized hole
- Support material should be understood in design phase
- Print orientation is critical – evolve the CAD design with AM machine operator or vendor
- Post-processing steps must be considered in design phase







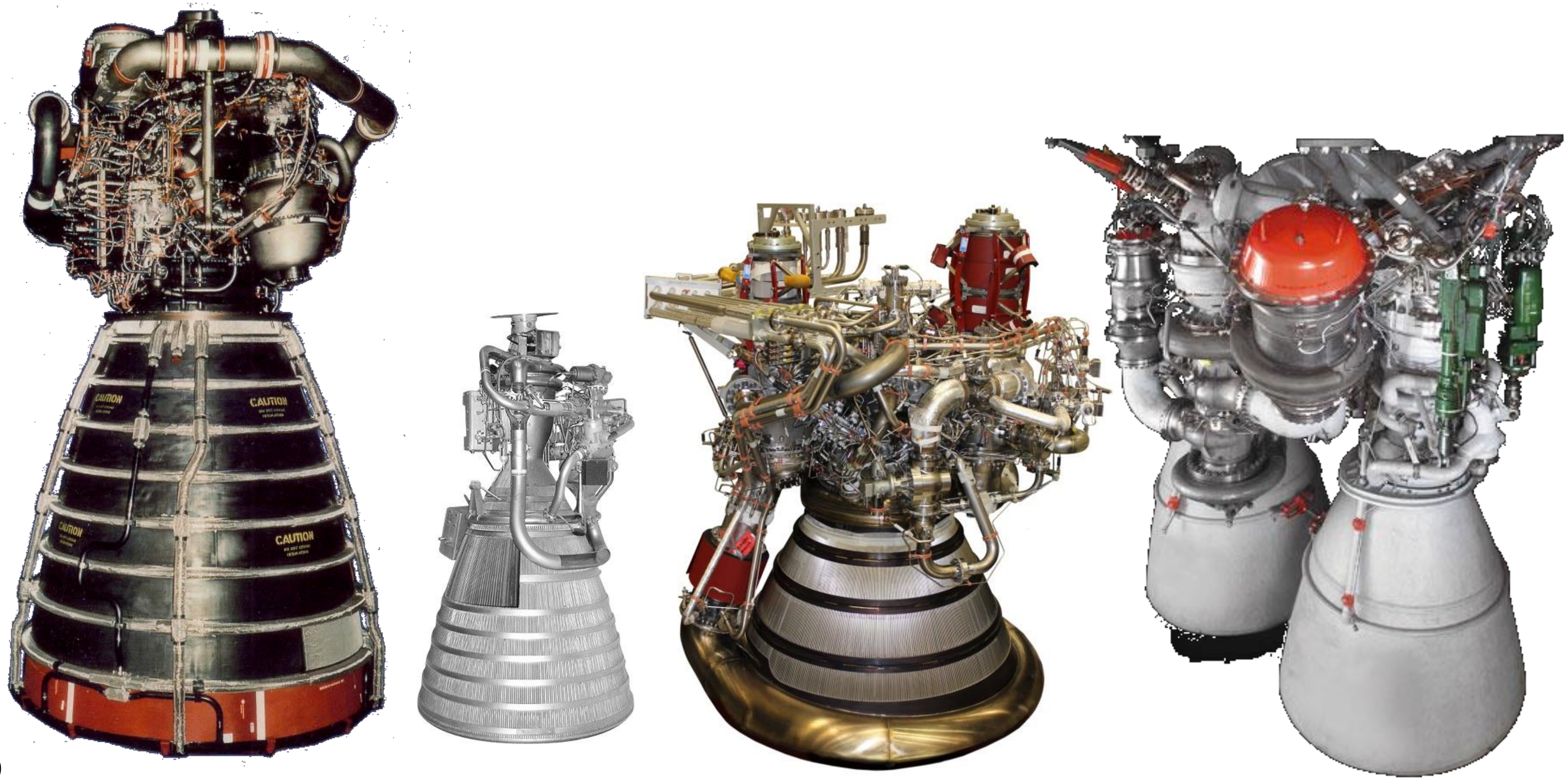



# Focus of L-PBF and Examples

- Extreme environments, complex shapes, and new materials
  - Combustion Chambers (regen-cooled)
  - Injector
  - Cryogenic Fluid Management
  - In-space thrusters
  - Turbomachinery (Fuel and LOX)
    - Pump and turbine ends of rotating
  - Nozzles
  - Ignition systems
  - Valves
  - Lines, ducts

# Need for Large Scale AM Technologies

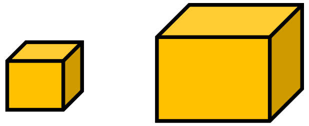
**SSME/RS-25** | **RL-10A-4** | **J-2X, Regen Only** | **RD-180**




90″ | 46″ | 70″ | 56″

**Nozzle Exit Dia.**

L-PBF Build Boxes



10x10x10 15.5x24x19
(inches)

Gradl, P., Greene, S., Protz, C., Bullard, B., Buzzell, J., Garcia, C., Wood, J., Osborne, R., Hulka, J. Cooper, K. Additive Manufacturing of Liquid Rocket Engine Combustion Devices: A Summary of Process Developments and Hot-Fire Testing Results. 54th AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum, (AIAA 2018-4625). July 9-12, 2018. Cincinnati, OH.

# Various Directed Energy Deposition (DED) Technologies

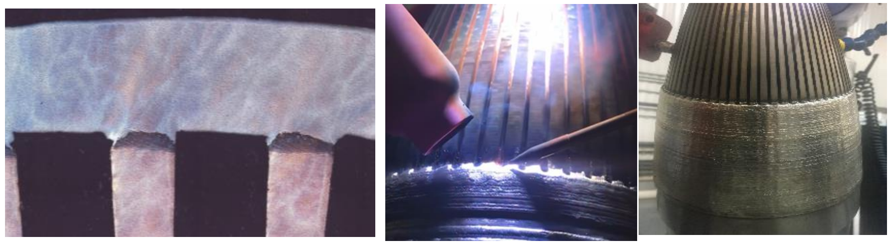
Freeform fabrication technique focused on near net shapes as a forging or casting replacement and also near-final geometry fabrication. Can be implemented using powder or wire as additive medium.

**Blown Powder Deposition**

Melt pool created by laser and off-axis nozzles inject powder into melt pool; installed on gantry or robotic system

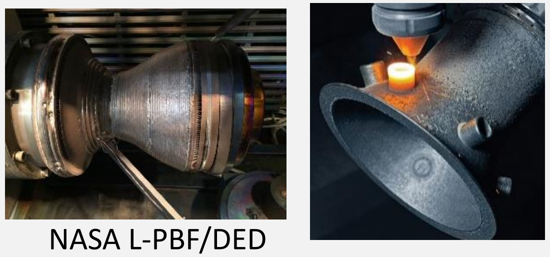
**Laser Wire Deposition**

A melt pool is created by a laser and uses an off-axis wire-fed deposition to create freeform shapes, attached to robot system



**Integrated and Hybrid AM**

- Combine L-PBF/DED
- Combine AM with subtractive
- Wrought and DED

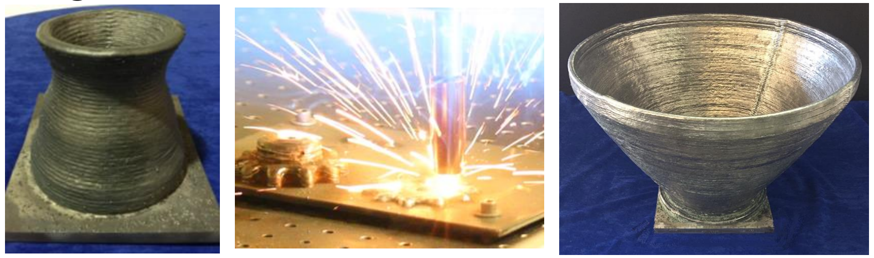


NASA L-PBF/DED

*Photos courtesy DMG Mori Seiki and DM3D

**Arc-Based Deposition (wire)**

Pulsed-wire metal inert gas (MIG) welding process creates near net shapes with the deposition heat integral to a robot



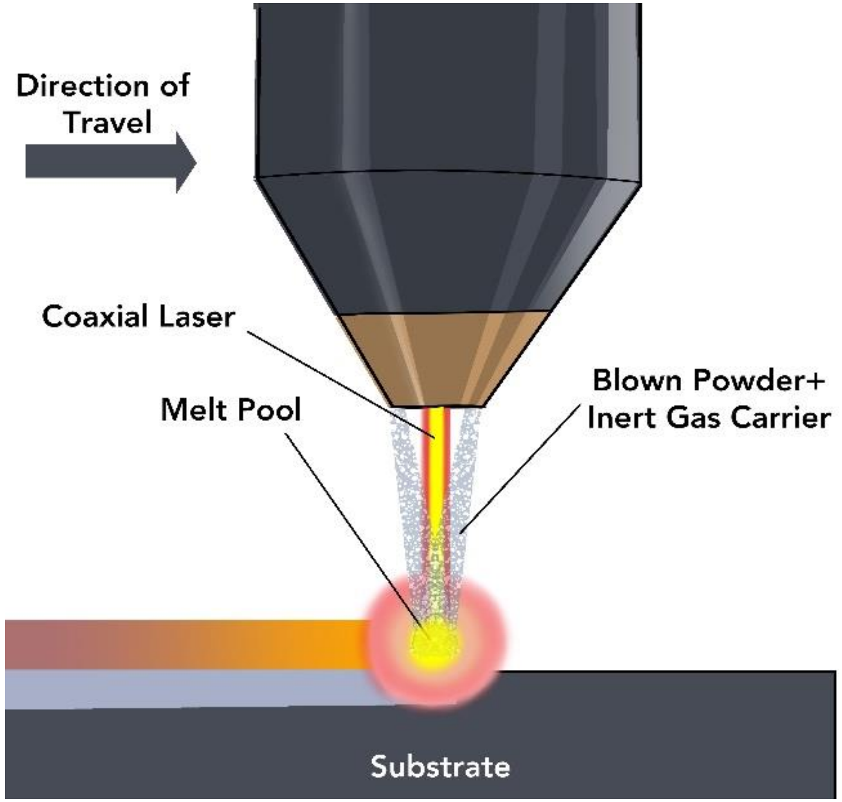
**Electron Beam Deposition (wire)**

An off-axis wire-fed deposition technique using electron beam as energy source; completed in a vacuum.

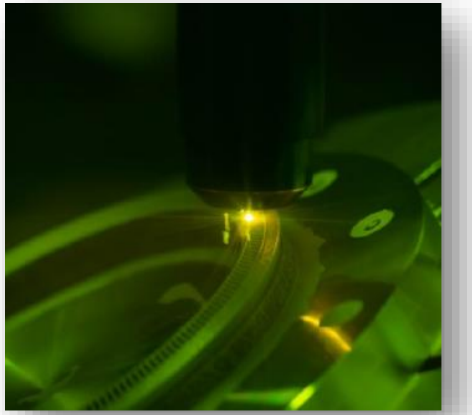
# Overview of Blown Powder DED for Nozzles

## Blown Powder Directed Energy Deposition (DED)

- Basic Process: Coaxial laser energy source with surrounding nozzles that inject powder (within inert gas) fabricating freeform shapes or cladding
- Advantages: Large scale (only limited by gantry or robotic system), multi-alloys in same build, high deposition rate
- Disadvantages: Resolution of features, rougher surface than L-PBF, higher heat input




DED NASA HR-1 Liner



Integrated Channel DED Nozzle

718, 1:4 Scale

JBK-75, IN625, NASA HR-1 Manifolds

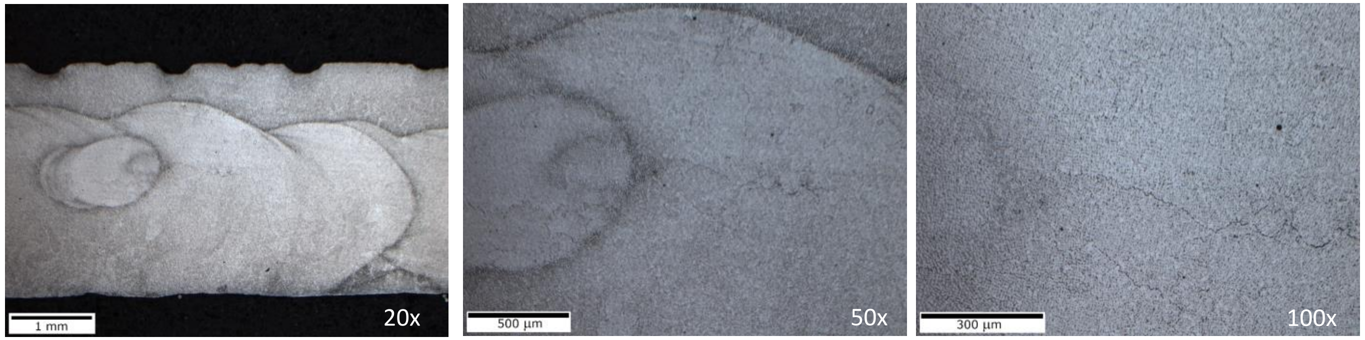
JBK-75 Integrated Channel

# Blown Powder DED

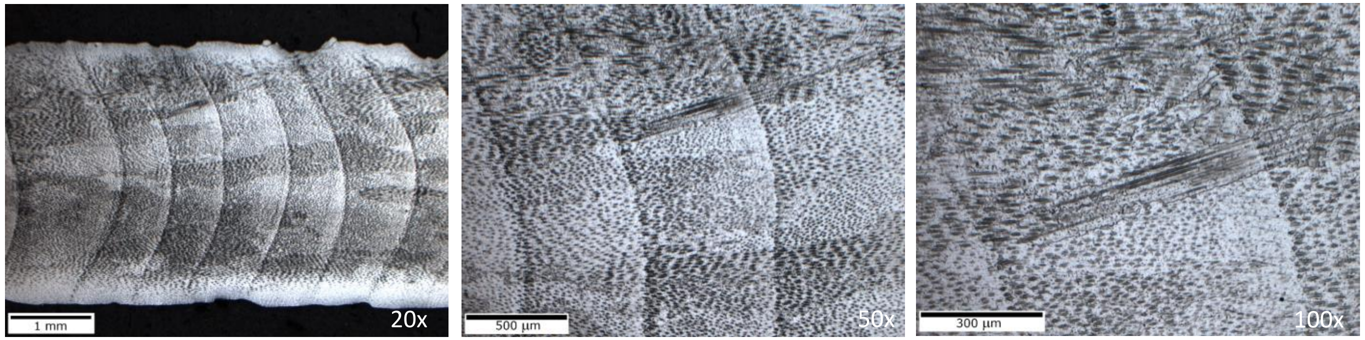
# Directed Energy Deposition

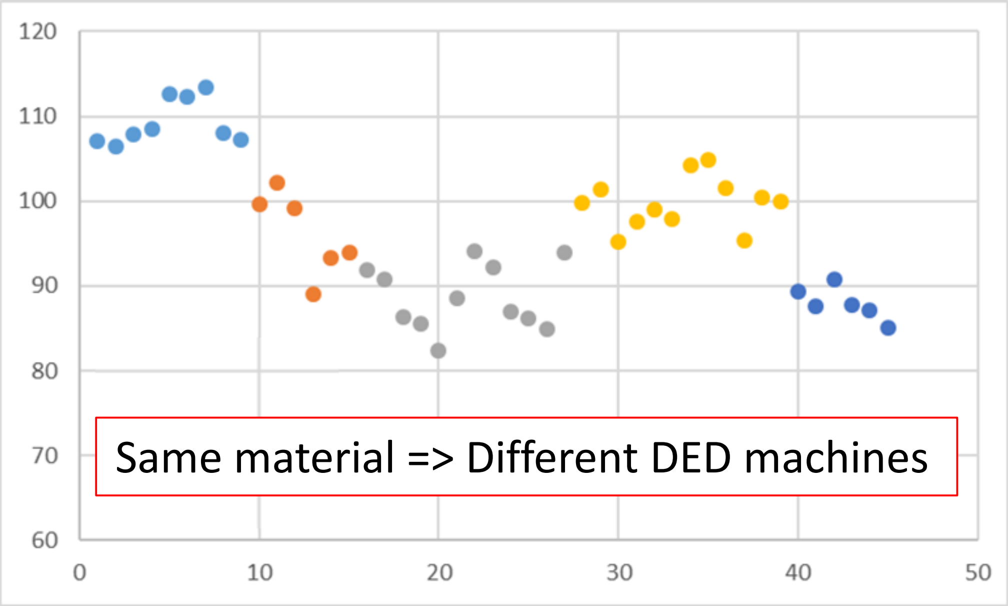
Material properties are dependent on a number of processing parameters (material, build rates, environment, orientation… ) => highly variable

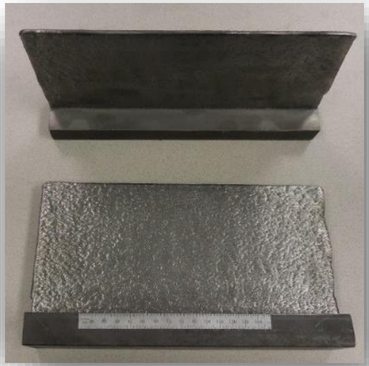
Inco 625 As-Built - Hoop

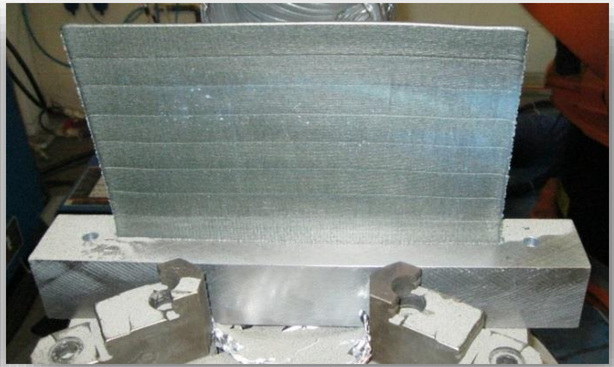



Inco 625 As-Built - Axial





# Example of Large Scale DED Nozzle Components

## DED provides the ability to fabricate components much larger than powder-bed based technologies

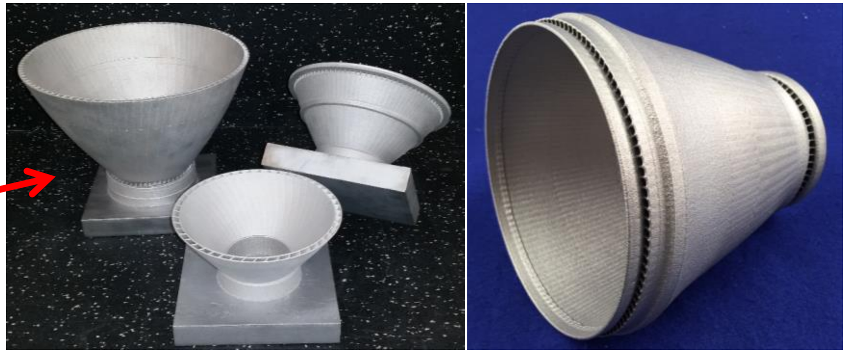
- Scale is limited by gantry or robotic control systems
  DED offers a complementary solution to L-PBF (SLM)

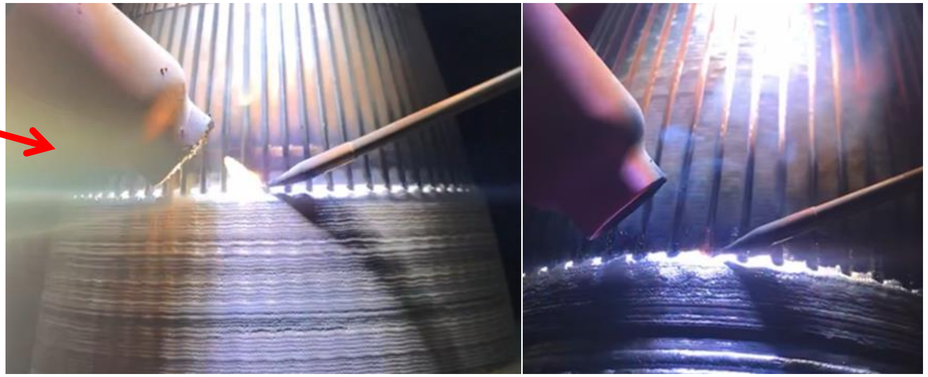
Example of ½ Scale RS25
Nozzle Liner in JBK-75
**(no integral channels)**



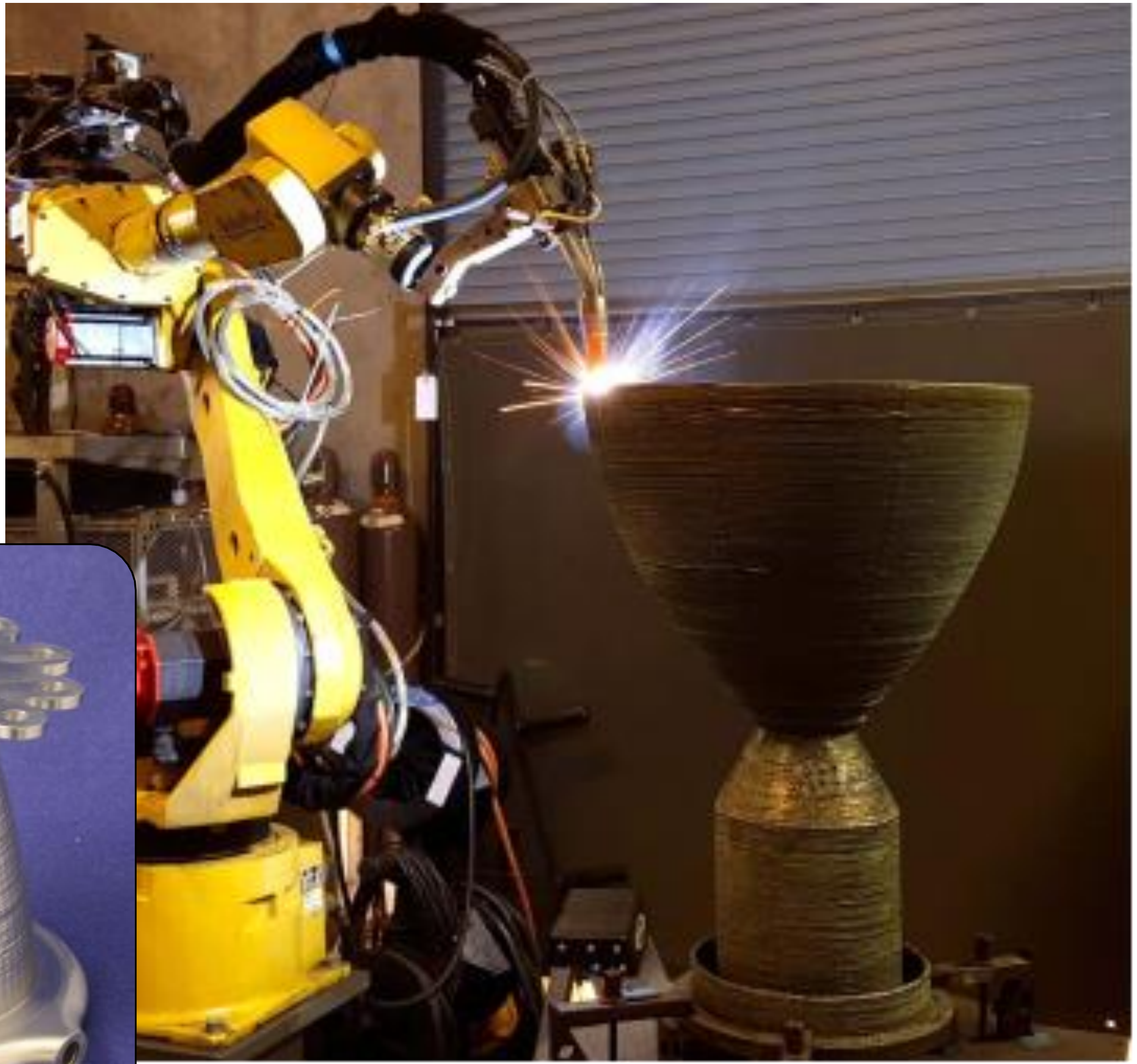
# NASA Advancement of Nozzle Manufacturing Techniques and Materials

| Process | Nozzle Application | Materials |
|---|---|---|
| **Blown Powder DED** | • Integrated Channel Wall Nozzle (single Piece)<br>• Nozzle Liners<br>• Nozzle Manifolds | • Inconel 625<br>• Inconel 718<br>• Haynes 230<br>• JBK-75<br>• NASA HR-1<br>• GRCop-84/42 |
| **Arc-based DED or WAAM** | • Nozzle Liners<br>• Nozzle Manifolds | • Inconel 625<br>• Haynes 230<br>• JBK-75<br>• NASA HR-1 |
| **Laser Wire Direct Closeout (LWDC)** | Closeout of nozzle/chamber liners with milled channels and cladding of structural jacket | • Inconel 625<br>• Haynes 230<br>• JBK-75<br>• NASA HR-1<br>• SS347<br>• C-18150-Monel<br>• C-18150-Inconel 625 |





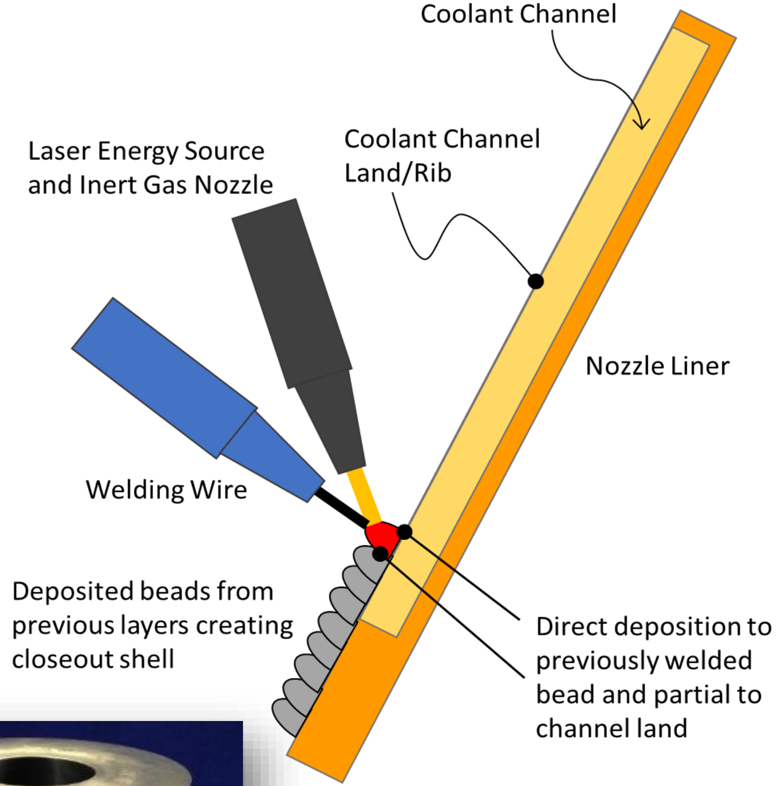
# Wire Arc-Based Deposition
## Wire Arc Additive Manufacturing (WAAM)

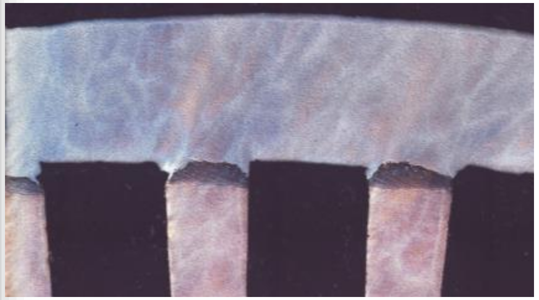



Keystone Synergistic under NASA SBIR and IRAD

# Laser-wire Deposition
## Laser Wire Direct Closeout (LWDC) Technology

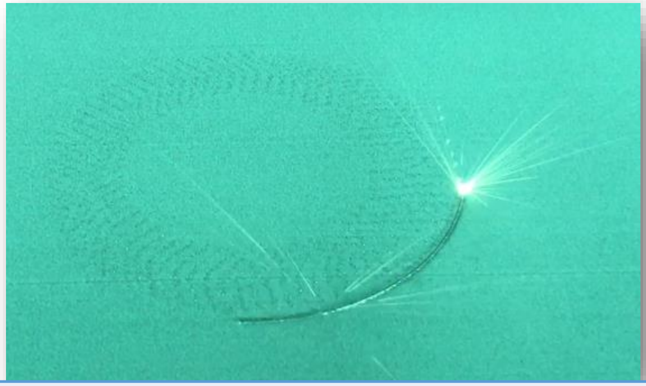
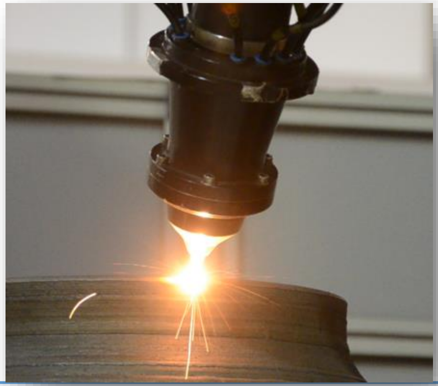
- Laser Wire Direct Closeout (LWDC) is an additive manufacturing technique that locally bonds filler wire to the channel ribs and provides a structural jacket fabricated "in place"
  - Freeform welding process without need for filler within the channels
- No material "drop-thru" into channels



# Comparison of L-PBF with DED

**Different methods for different components!**

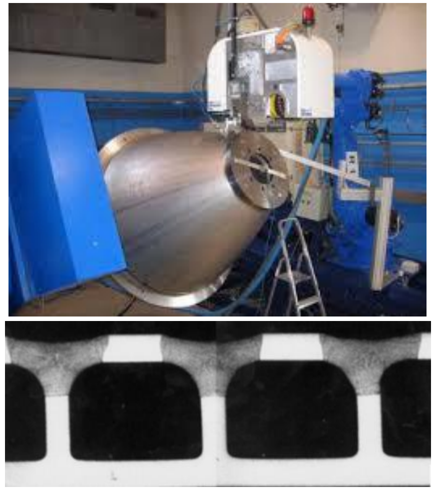
| | **Laser Powder Bed Fusion (L-PBF)** | **Directed Energy Deposition (DED)** |
|---|---|---|
| |  |  |
| **Feature Resolution / Complexity** | High resolution of features<br>Wall thicknesses and holes <0.010” | Medium resolution of features<br>Walls >0.040” and limited holes |
| **Deposition Rate** | Low build rates<br><0.3 lb/hr | High Build rates<br>lbs per hour (some systems >20lb/hr) |
| **Multi-alloys / Gradient Materials** | Monolithic materials in single build | Option for multi-alloys or gradients within single build |
| **Materials Available** | High number of materials available and being developed | High number of materials available and being developed |
| **Production Rates** | Higher volume with several parts in a single build | Generally limited to single builds; longer programming/setup time |
| **Scale / Size of components** | Limited to existing build volumes<br><15.6” dia or 16”x24”x19” | Scale is limited to gantry or robot size |
| **Added Features / Repair** | No (limited) ability to add material to existing part | Can add material or features to an existing part |

# Actively-cooled Nozzle Manufacturing Overview

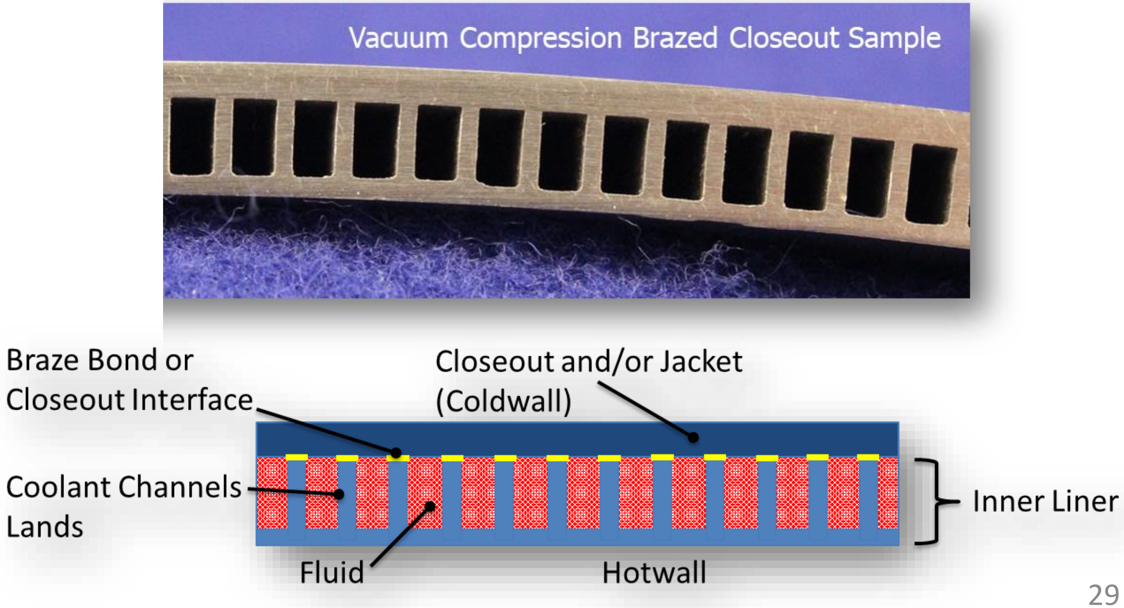
- Various technologies exist for fabrication of actively-cooled nozzle structures to contain high pressure coolant and expansion of hot-gases in the core flow
- The most challenging process is the closeout process
  - Traditional manufacturing used brazed tube-wall nozzle construction, brazed channel wall nozzle fabrication techniques
  - New manufacturing technologies, such as laser welded sandwich wall, vacuum compression brazing and pressure assisted HIP braze, and additive manufacturing offer new design and fabrication advantages for nozzles

**RS-25/SSME Brazed Nozzle**

**RL-10 Brazed Chamber/Nozzle**



**Laser Welded Sandwich Wall**
Courtesy: GKN Aerospace



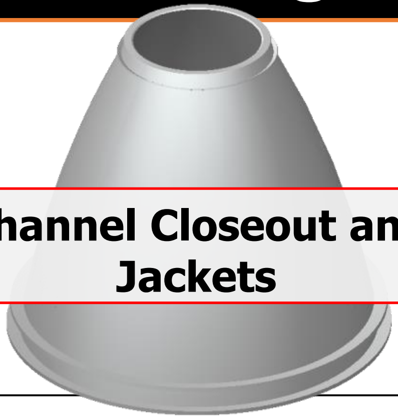
# Overview of Channel Wall Nozzle (CWN) Fabrication Technologies

### Liner Fabrication

- Forging
- Spin Forming
- Shear Forming
- Powder Metallurgy
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Multi-Piece L-PBF
- Platelets
- Explosive Forming
- Coldspray
- Casting
- Hydroforming
- Vacuum Plasma Spray

### Channel Forming/Slotting

- Slitting Saw
- End Milling
- Water Jet Milling
- Electrochemical
- Plunge EDM
- Pulsed ECM
- Multi-Piece L-PBF
- Platelets
- Freeform DED Cladding



### Channel Closeout and Jackets

- Pressure Assisted Braze
- Standard Atmosphere Braze
- Multi-Piece L-PBF
- Vacuum Plasma Spray
- Electroplating
- Coldspray
- Directed Energy Deposition
  - Blown Powder Laser
  - Laser Wire Direct Closeout
  - Arc-based Wire
- Explosive Bonding
- Ultrasonic
- Laser Welding
- Diffusion Bonding
- Platelets
- Casting
- Composite Overwrap

### Manifold Application

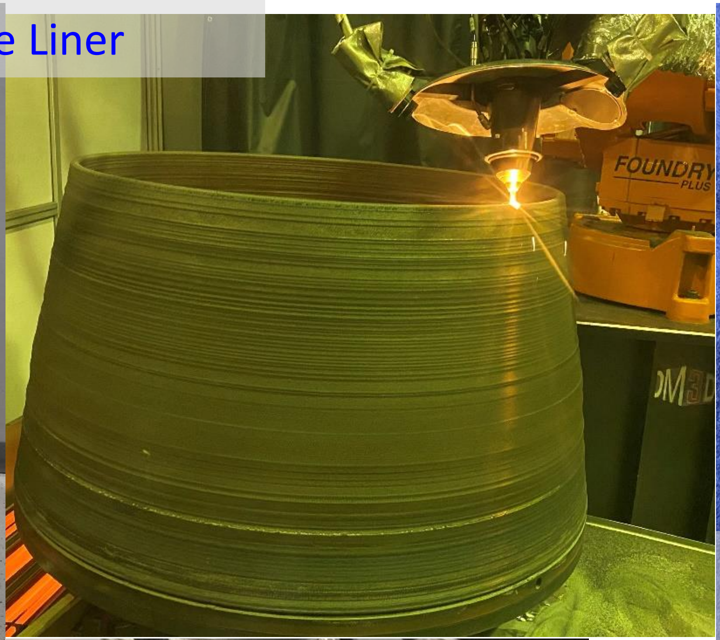
- Wrought and Machined
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Multi-Piece L-PBF
- Platelets
- Casting
- Molded Composites

***Ref:*** Gradl, P. "Rapid Fabrication Techniques for Liquid Rocket Channel Wall Nozzles". AIAA-2016-4771, Paper presented at 52nd AIAA/SAE/ASEE Joint Propulsion Conference, July 27, 2016. Salt Lake City, UT.

# Examples of Blown Powder DED for Large Structures

30k-lbf Class DED Liner, NASA HR-1

½ Scale RS25 Nozzle Liner

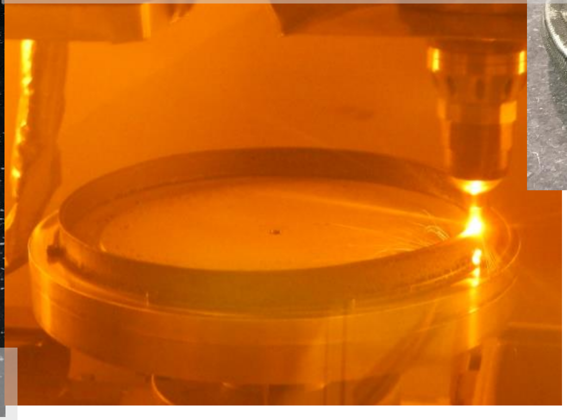



Rem Surface Engineering under SBIR

Exploratory Polishing Techniques for DED Processes

Integral Channel DED Nozzles

Blown Powder DED Manifolds



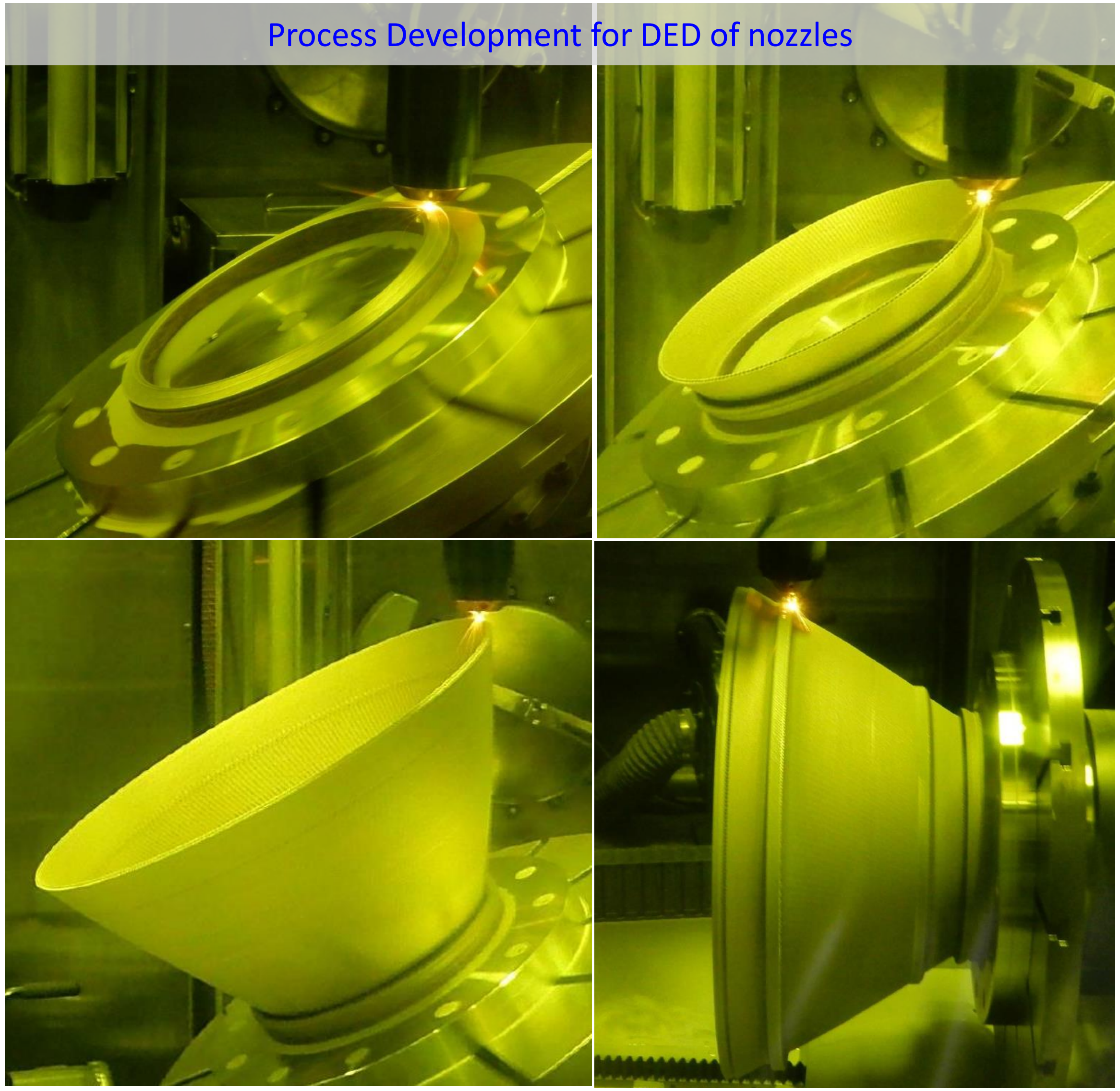
Bimetallic Nozzle with L-PBF and DED (RAMPT Project)

# Small Feature Blown Powder DED Nozzle Fabrication

Integral Channel DED Nozzles 30-40” Diameter

Hot-fire Testing of Integral-channel DED Nozzles

Process Development for DED of nozzles

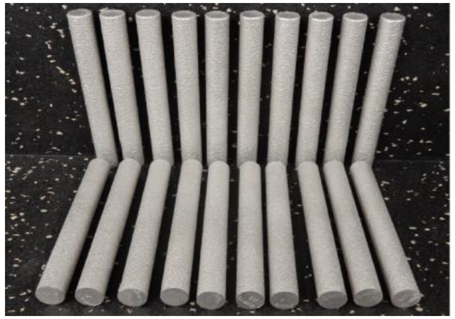


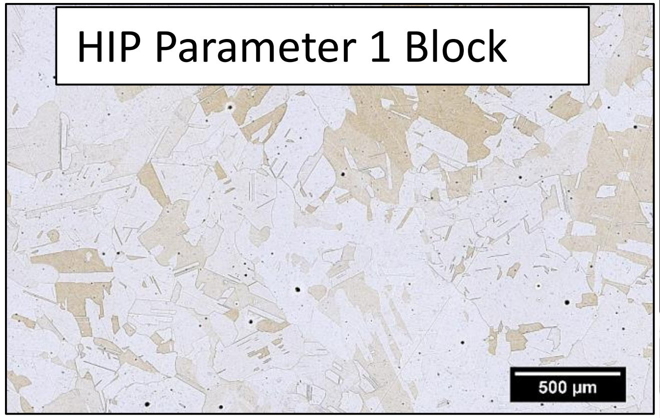
RPM Innovations (RPMI) under NASA-RAMPT Project

# New Materials using Additive Manufacturing NASA HR-1 and JBK-75

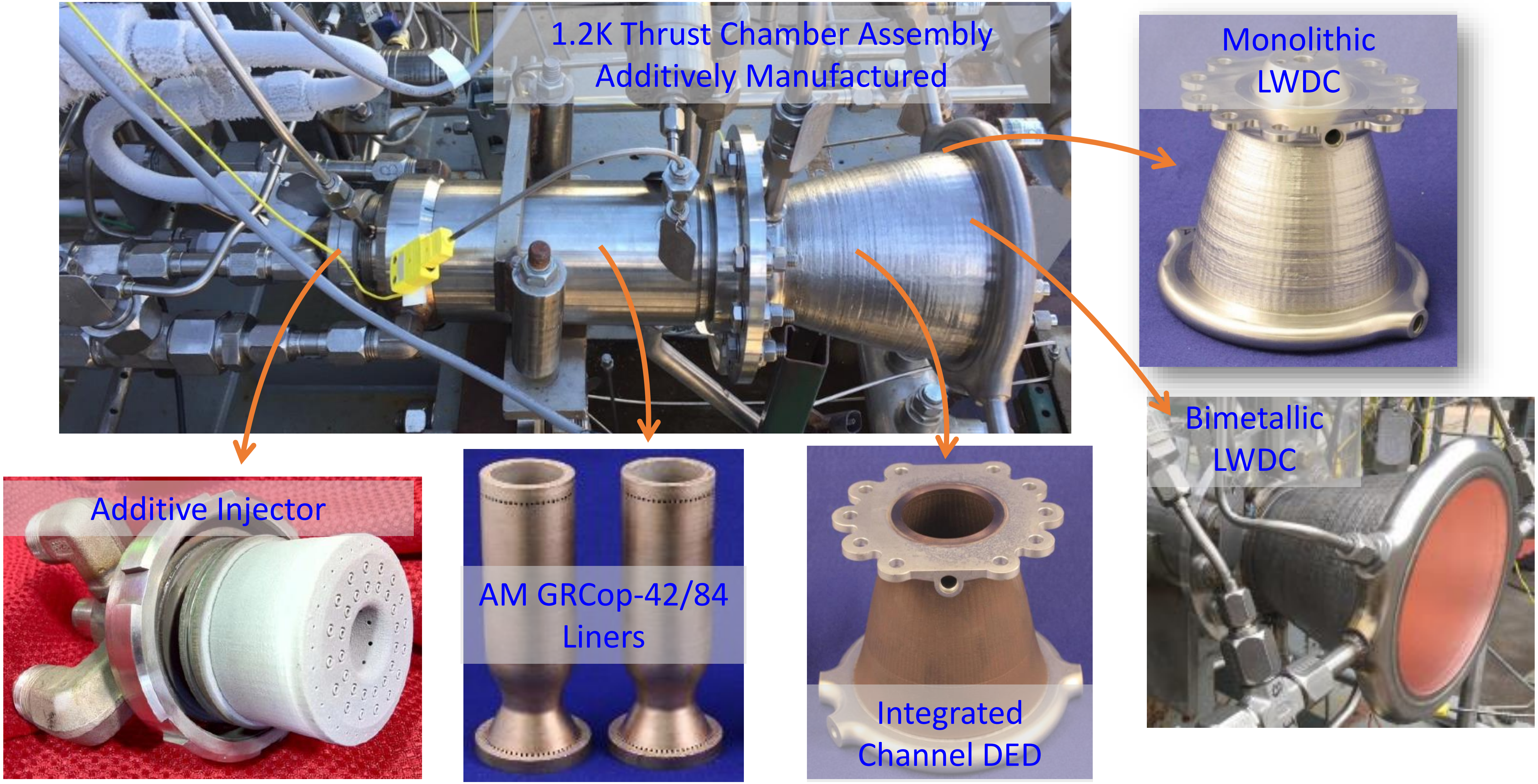
- NASA HR-1 is a high-strength Fe-Ni-base superalloy that resists high-pressure hydrogen environment embrittlement (HEE), oxidation, and corrosion.
- “HR” stands for **H**ydrogen-**R**esistant (HEE resistant)
- Originally derived from JBK-75, the development for NASA HR-1 started in late 1990 at the M&P lab and HEE resistant composition was identified in 1992.
- In addition to its HEE resistance, NASA-HR-1 has approximately 25% higher yield strength than JBK-75 and exhibits no ductility loss in a 5 ksi high pressure hydrogen environment
- NASA-HR-1 is a unique alloy that extends the compositional range of existing HEE-resistant Fe-Ni-base superalloys.

| | A-286 | JBK-75 | NASA HR-1 |
|---|---|---|---|
| Fe | 56.1 | 51.5 | 41.2 |
| Ni | 25.5 | 30.0 | 34.0 |
| Co | - | - | 3.3 |
| Cr | 14.8 | 14.8 | 15.0 |
| Mo | 1.3 | 1.3 | 2.0 |
| W | - | - | 1.8 |
| Ti | 2.1 | 2.2 | 2.5 |
| Al | 0.2 | 0.3 | 0.3 |





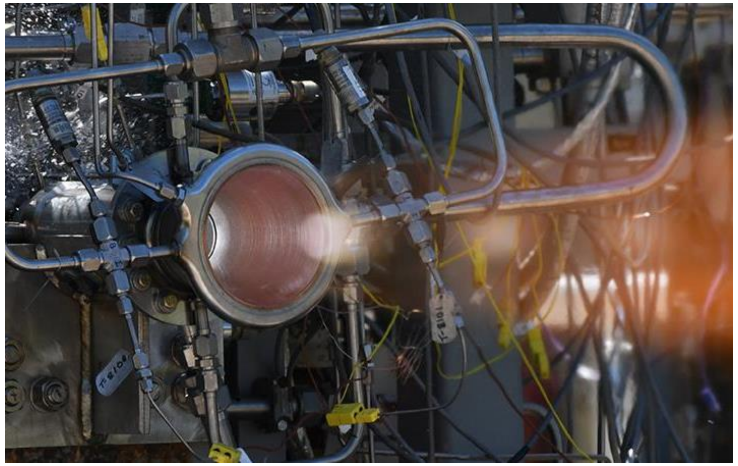

# Configuration for Nozzle Hot-fire Testing

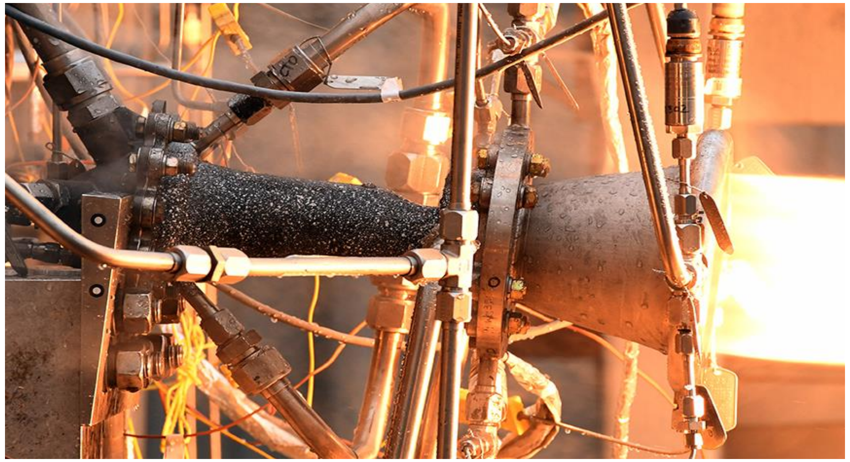


# Hot-fire Testing Summary
# Nozzle Materials and Configurations

- Several techniques – LWDC, Integrated-channel DED, WAAM, WJM
- Various materials have been evaluated and demonstrated for monolithic and bimetallic channel wall nozzle applications
- Development and hot-fire testing completed in a variety of potential liquid engine applications
- >10,000 sec of hot-fire time and 229 starts

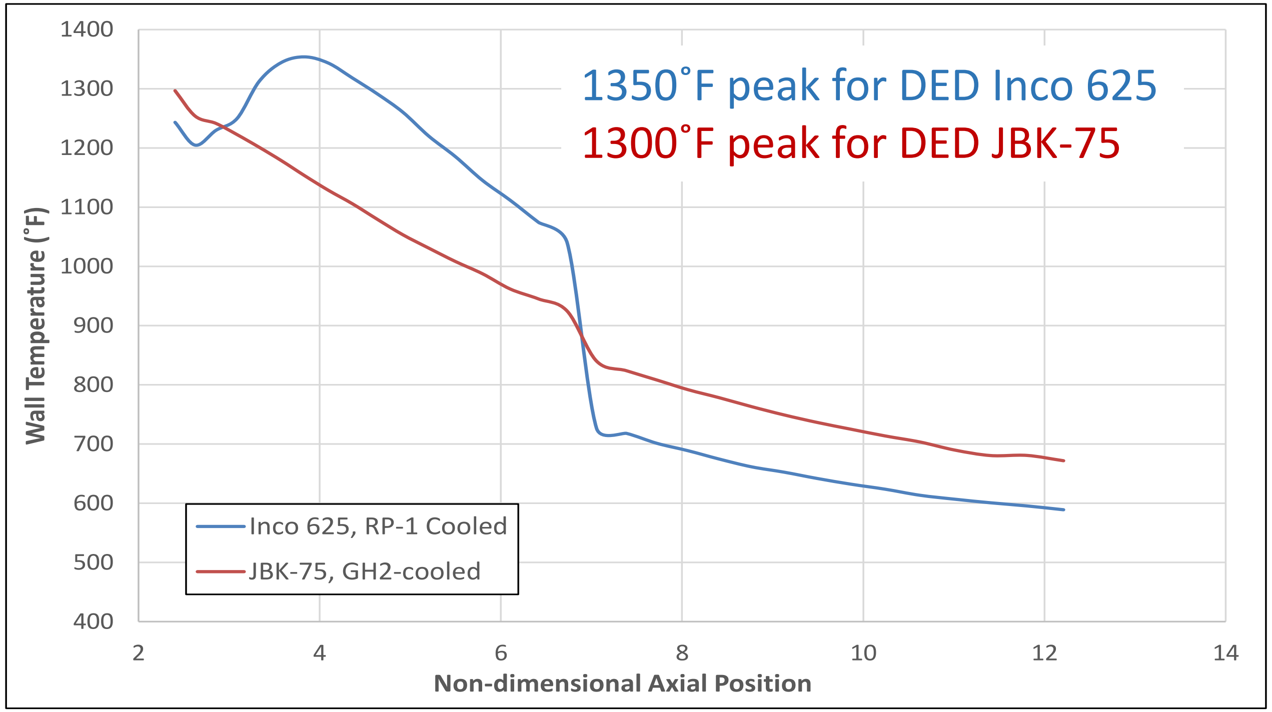
| Program | Propellant | Process | Material | Starts | Time (sec) |
|---|---|---|---|---|---|
| PH034 | LOX/GH2 | LWDC | **SS347** | 4 | 160 |
| PH034 | LOX/GH2 | LWDC | **Inco 625** | 10 | 1060 |
| PI100 | LOX/GH2 | LWDC | **Haynes 230** | 1 | 180 |
| PI100 | LOX/GH2 | LWDC | **C-18150-Inco/Monel** | 3 | 540 |
| PJ038 | LOX/GH2 | LWDC | **C-18150-Monel 400** | 60 | 1830 |
| PI100 | LOX/GH2 | LWDC | **C-18150-Monel 400** | 9 | 1130 |
| PJ038 | LOX/GH2 | DED | **JBK-75** | 114 | 4170 |
| PH034 | LOX/GH2 | DED | **Inco 625** | 1 | 15 |
| PI084 | LOX/RP-1 | DED | **Inco 625** | 27 | 1057 |

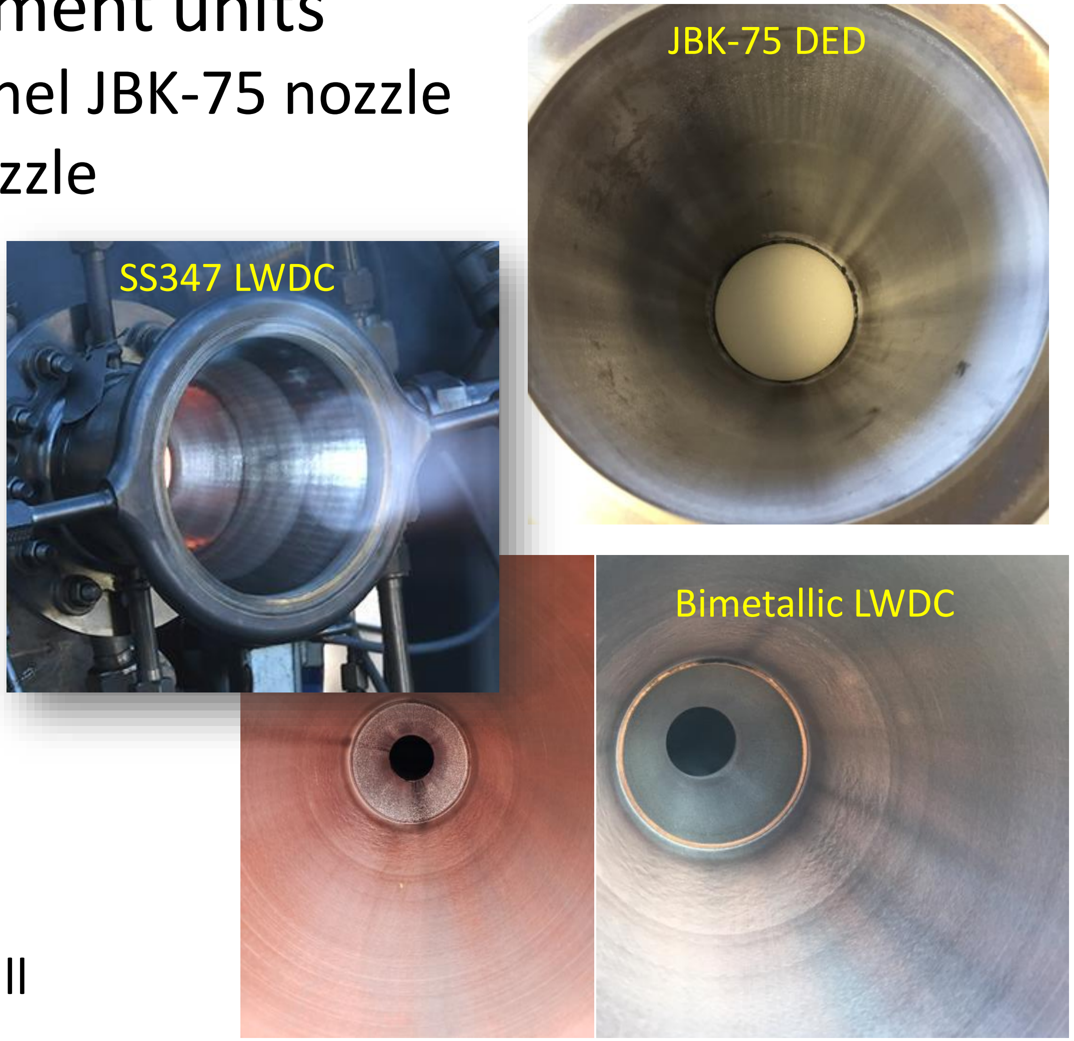




# Nozzle Hot-fire Testing Results

- Completed hot-fire testing on (9) development units
- 229 tests and >10,142 seconds on development units
  - 114 starts and 4,170 sec on DED Integral channel JBK-75 nozzle
  - 60 starts and 1,830 sec on bimetallic LWDC nozzle

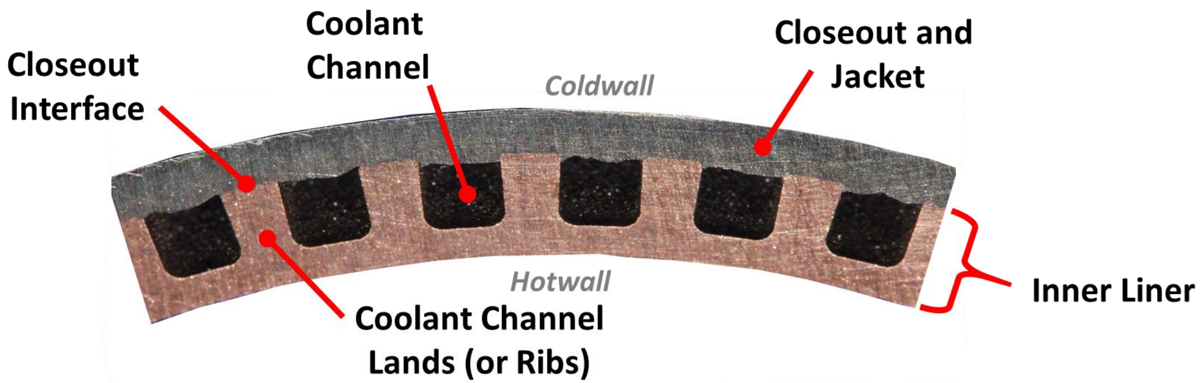



- Test conditions chosen intentionally to provide aggressive wall temperatures with high cyclic reversal loads

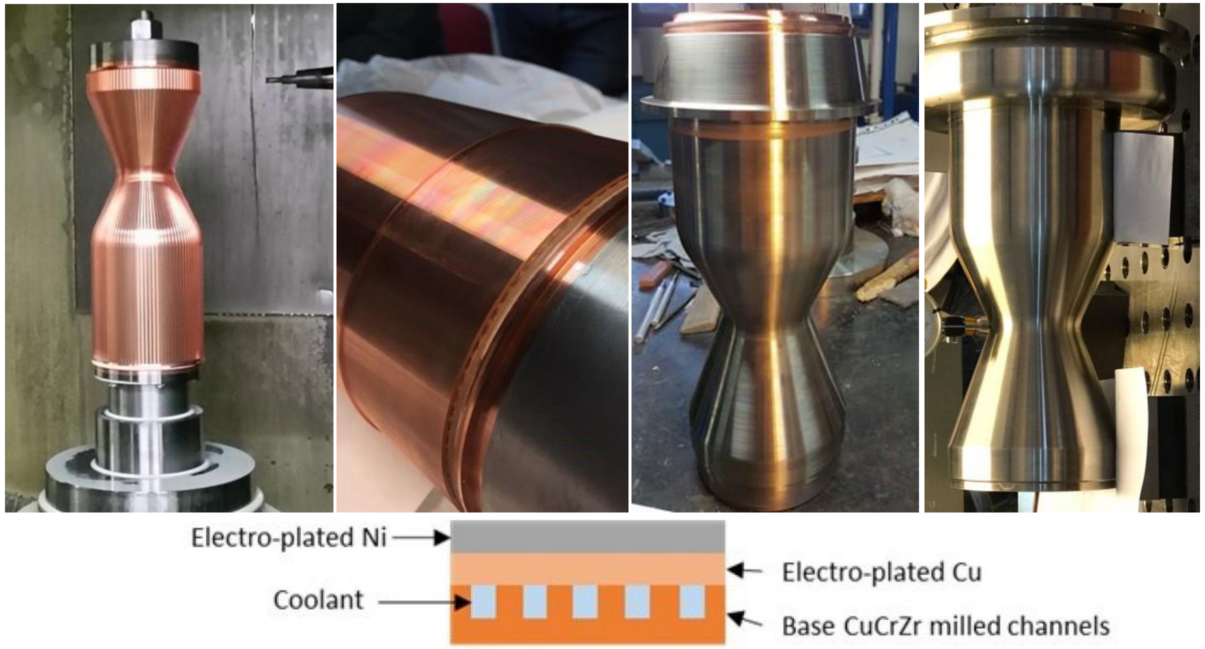
# Traditional Manufacturing of Chambers

- The most common techniques for channel-wall chamber fabrication includes electroplating closeout and brazed closeout
- Tube-wall structures have also been used on various engines, such as F-1, RS-27 and RL10




RL-10 Brazed Chamber/Nozzle

RS-25 HIP-bonded Chamber




**Electroplated Chamber Closeout**

Photos Courtesy: Avio

# Overview of Combustion Chamber Fabrication Technologies

**Liner Fabrication**

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- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
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- Casting
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- End Milling
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**Manifold Application**

- Wrought and Machined
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Platelets
- Casting
- Molded Composites

# Additive Manufacturing of GRCop-alloys

High performance combustion chambers for liquid rocket engines require a high conductivity and high strength copper-alloy for the channel-cooled liner

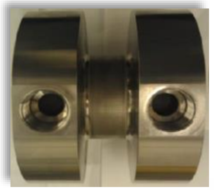
- <u>Objective:</u> Demonstrate copper-alloy additive manufacturing (AM) technology to significantly reduce the lead-time and costs for combustion chamber fabrication
- Since 2014 NASA has been developing and maturing AM for GRCop-alloys
  - Specifically Selective Laser Melting (SLM) or Laser-Powder Bed Fusion (L-PBF)
  - Focused on GRCop-84 (Cu-8%Cr-4%Nb) and GRCop-42 (Cu-4%Cr-2%Nb)
  - Integral channels using L-PBF significantly reduces operations
  - Demonstrated secondary AM processes for bimetallic jackets
- Several NASA programs have and are making use of additively manufactured SLM chambers and NASA has accumulated significant development time

# Additive Manufactured Combustion Chambers using Laser Powder Bed Fusion (L-PBF)

- MSFC has developed over 25+ unique AM chambers between 2013-2020
  - Materials: GRCop-84, GRCop-42, C-18150, Monel K-500, Inco 625, Inco 718
  - Propellants: LOX/GH2, LOX/LCH4, LOX/RP-1
  - Additive Process: L-PBF and L-PBF/DED
- Over 300+ starts and 20,000+ seconds of hot fire test at NASA on GRCop-alloys
  - Industry has also completed significant development of AM chambers in various materials
  - Completed cycle testing on GRCop-42 >168 starts and 7,400 seconds
- Chambers have been fabricated using L-PBF powder bed AM technique, with a few test articles incorporating DED techniques for a bimetallic end product.

2013 – 2015 | 2016 | 2017 | 2018 | 2019 / 2020

Feasibility Hardware



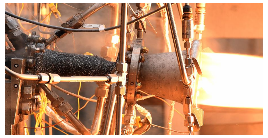
**1.2K Workhorse**
GRCop-84

**MET1**
GRCop-84

**LOX/RP1 Faceplate**
GRCop-84

**LCUSP 3.0**
GRCop-84

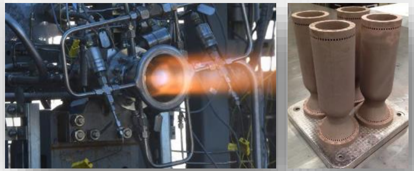
**2.4K LOX/RP-1**
GRCop-84



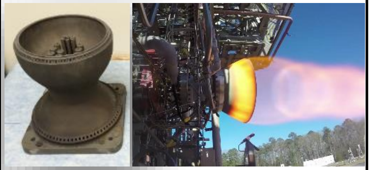
**Cycle Testing**
GRCop-42

**META4**
GRCop-84

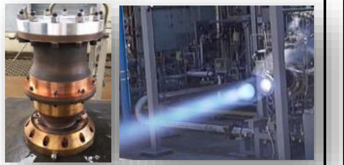
**1.2K Commercial-produced Liners**
GRCop-84 and C-18150



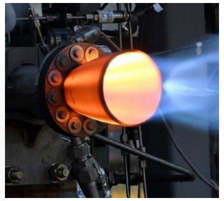
**LCUSP 2.2**
GRCop-84



**META4 #2**
GRCop-84



**2K Methane**
GRCop-84

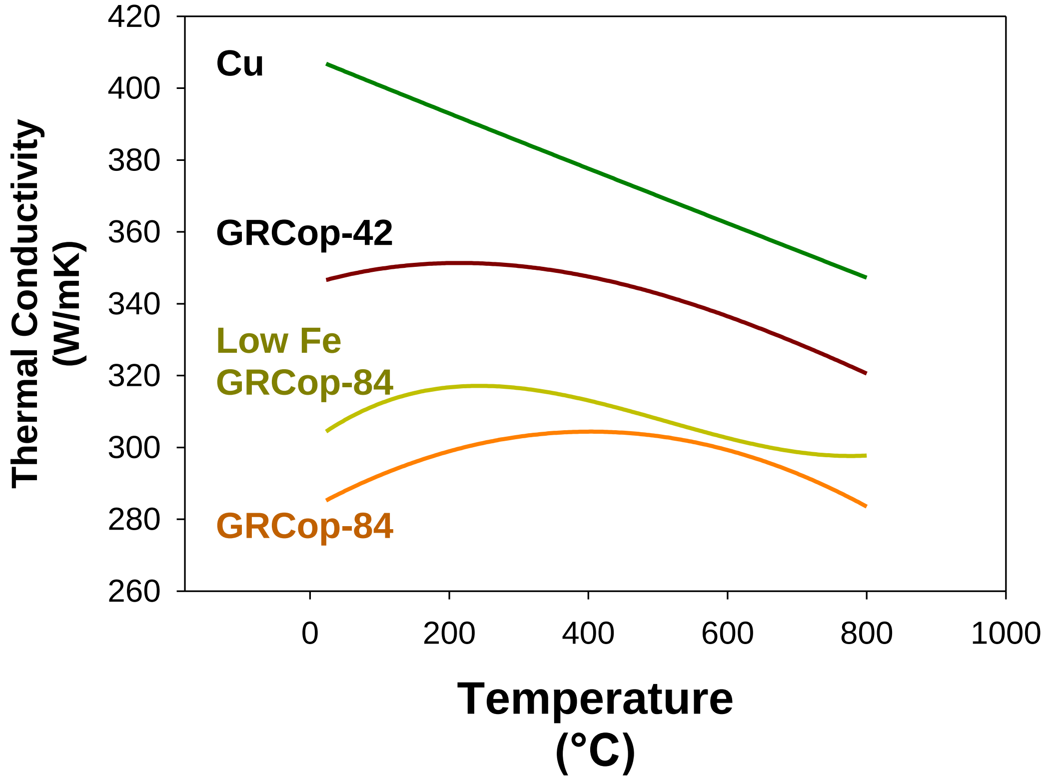


**MET1.2**
GRCop-84

**LOX/H2**
GRCop-42

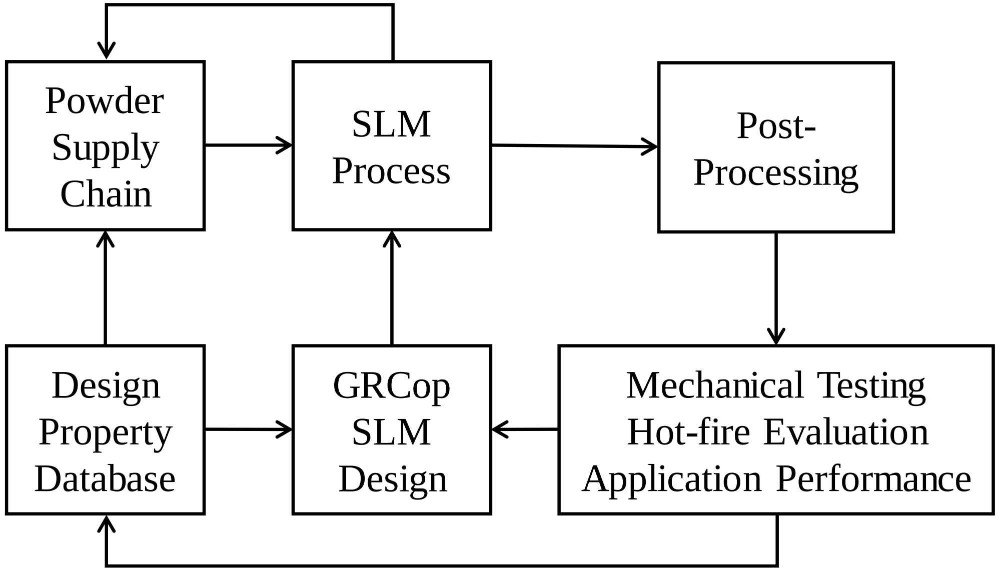
# New Materials using Additive Manufacturing
## GRCop Copper-alloys for High Heat Flux

- GRCop-alloys resist oxidation and blanching during thermal and oxidation-reduction cycling
- A maximum use temperature around 800°C, depending upon strength and creep requirements
- Good mechanical properties at high use temperatures (2x of typical copper)
- Lower thermal expansion to reduce thermally induced stresses and low cycle fatigue (LCF)
- Established powder supply chain
- Mature AM process that meets wrought properties and repeatability



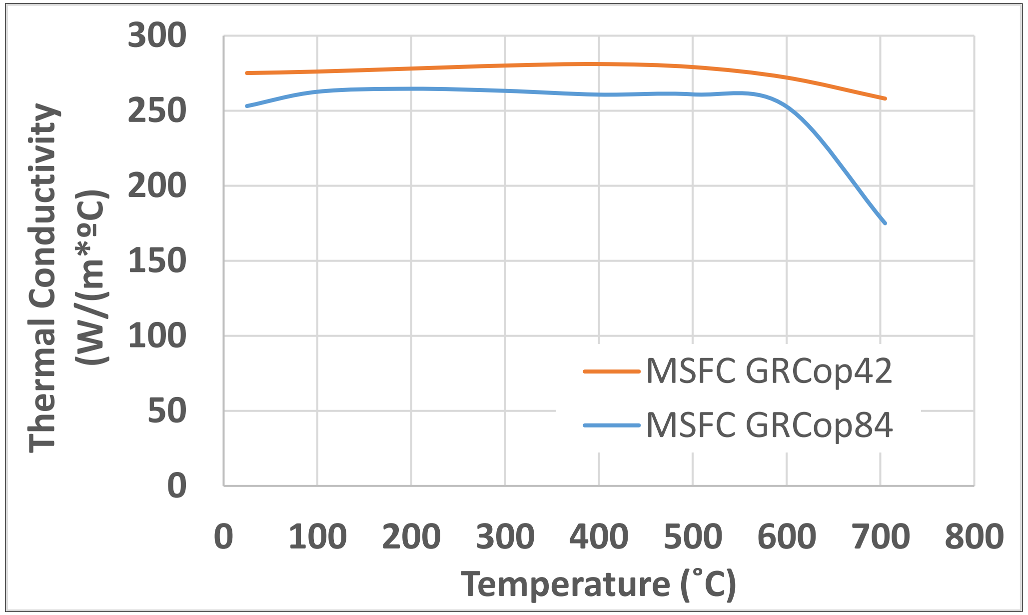
# Objectives During AM GRCop-alloy Development

1. Establishing, maturing, and controlling the powder supply chain
2. Scalability and transfer of the SLM process to various machines and size scales
3. Optimal work flow and processing time of GRCop-42 and GRCop-84
4. Characterizing the material and establishing a database of AM properties for design engineers
5. Understanding property and microstructural sensitivities to powder supply, print parameters, and design features
6. Developing best design practices for the SLM GRCop alloy use in combustion chambers
7. Demonstrating component hardware in a relevant environment and testing at aggressive conditions to validate designs and property databases
8. Dissemination of data to US industry partners and US commercial print service vendors.



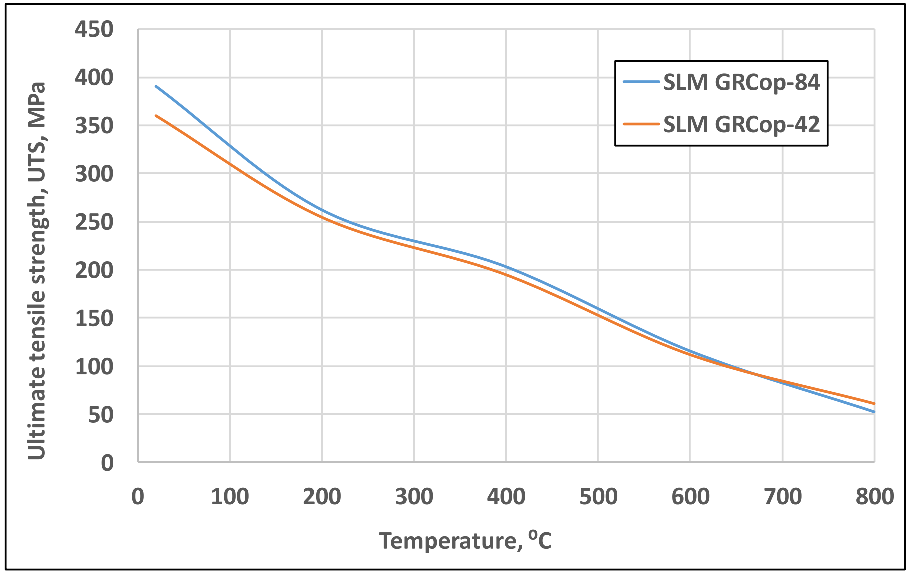
# Comparison GRCop-84 and GRCop-42

| Element | GRCop-42 Wt % | GRCop-84 Wt % |
|---|---|---|
| Cr | 3.1 – 3.4 | 6.2 – 6.8 |
| Nb | 2.7 – 3.0 | 5.4 – 6.0 |
| Fe | Target <50 ppm | Target <50 ppm |
| O | Target <400 ppm | Target <400 ppm |
| Al | <50 ppm | <50 ppm |
| Si | <50 ppm | <50 ppm |
| Cu | Balance | Balance |
| Cr:Nb Ratio | 1.12 – 1.15 | 1.12 – 1.15 |



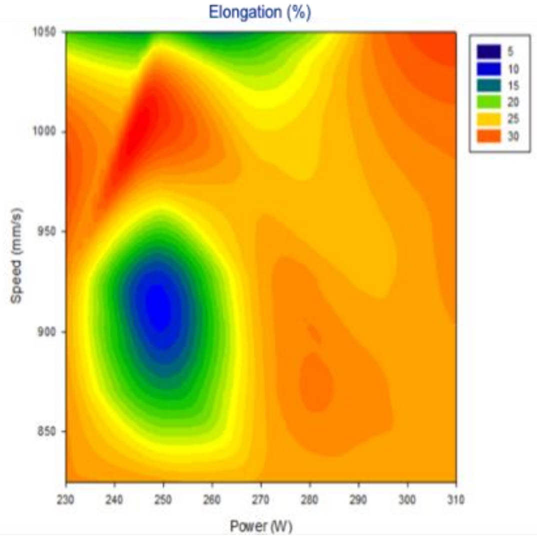

## GRCop-42 and GRCop-84 for different applications:

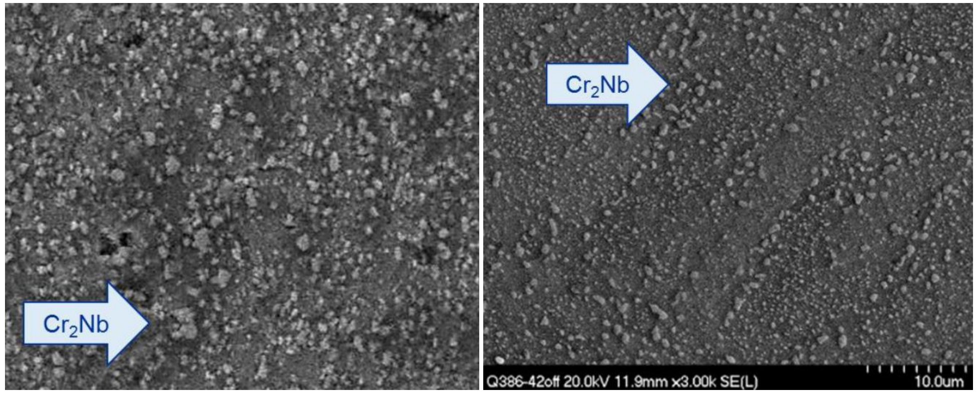
- GRCop-42 has improved thermal conductivity (5-8%)
- GRCop-84 has higher strength and better LCF properties
- GRCop-42 has simplified powder atomization based on powder supplier comments
- GRCop-42 less costly fabrication build times based on increased layer height



# Process Development of GRCop-alloys using L-PBF

- AM of GRCop-alloys using layer-by-layer SLM/L-PBF process
- **Challenges with AM of Copper-alloys:** High reflectivity and high conductivity
- Power and speed build parameters were varied on material samples and evaluated to determine optimal properties for given set of parameters
- Inclusion of the finer particles below the preferred (typical SLM) mesh size resulted in better density and material properties
- Stability of GRCop-42 weld pools allowed 50% thicker layers of powder to be deposited to facilitate (~20%) faster build times
- Similar build feature resolution and standard AM SLM build “rules of thumb”

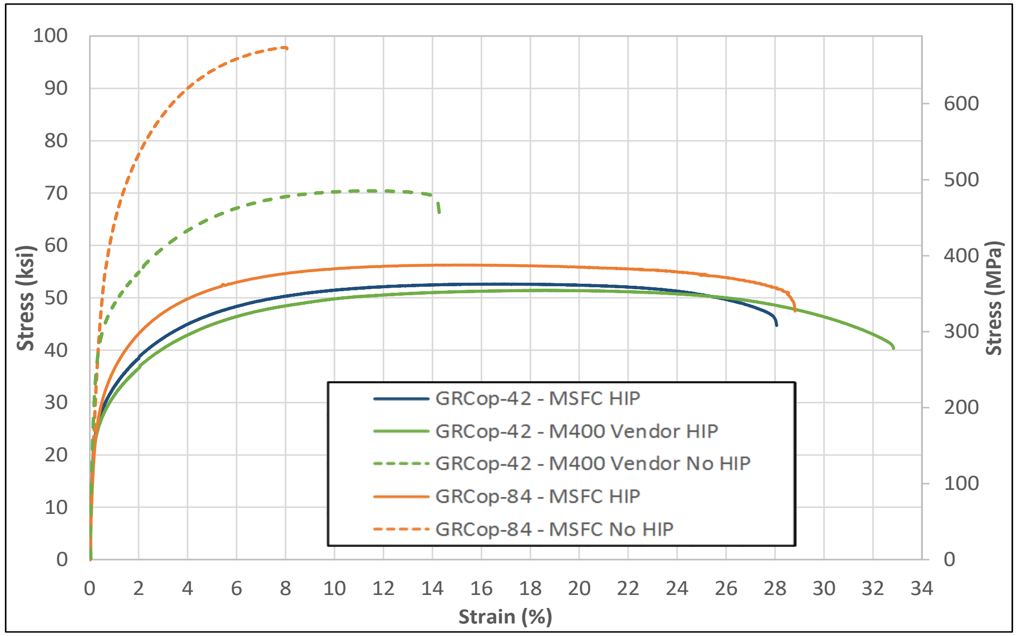


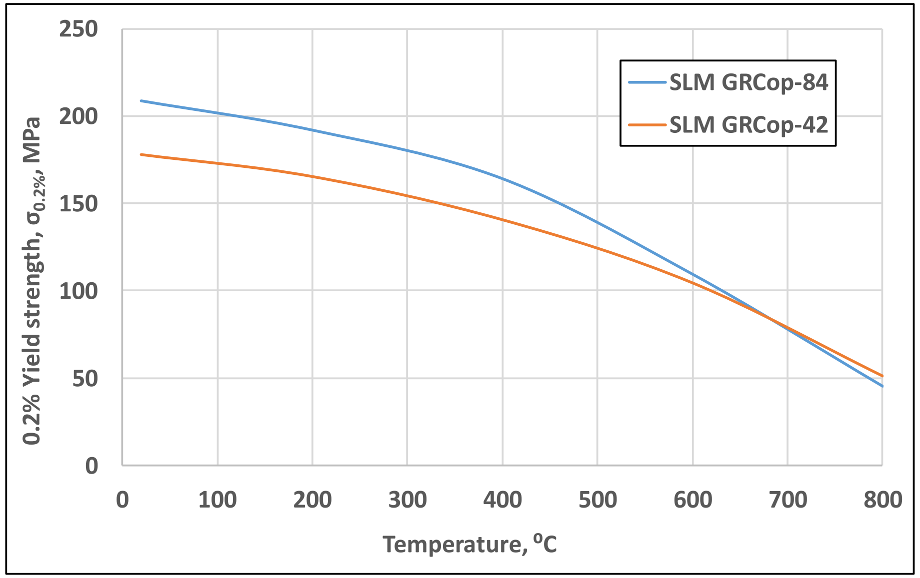



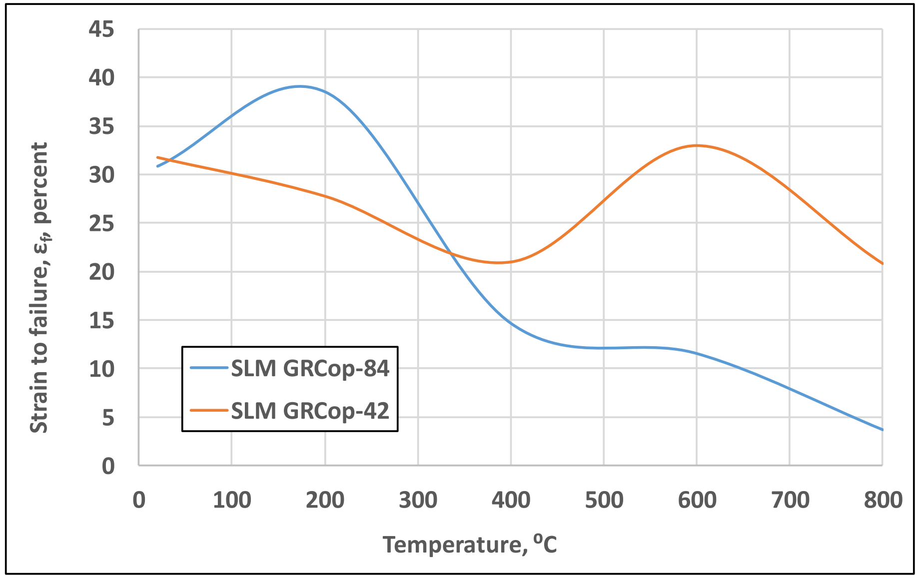

GRCop-84 SEM (Left) Wrought, (Right) SPM

# Mechanical Properties of GRCop-84 and GRCop-42

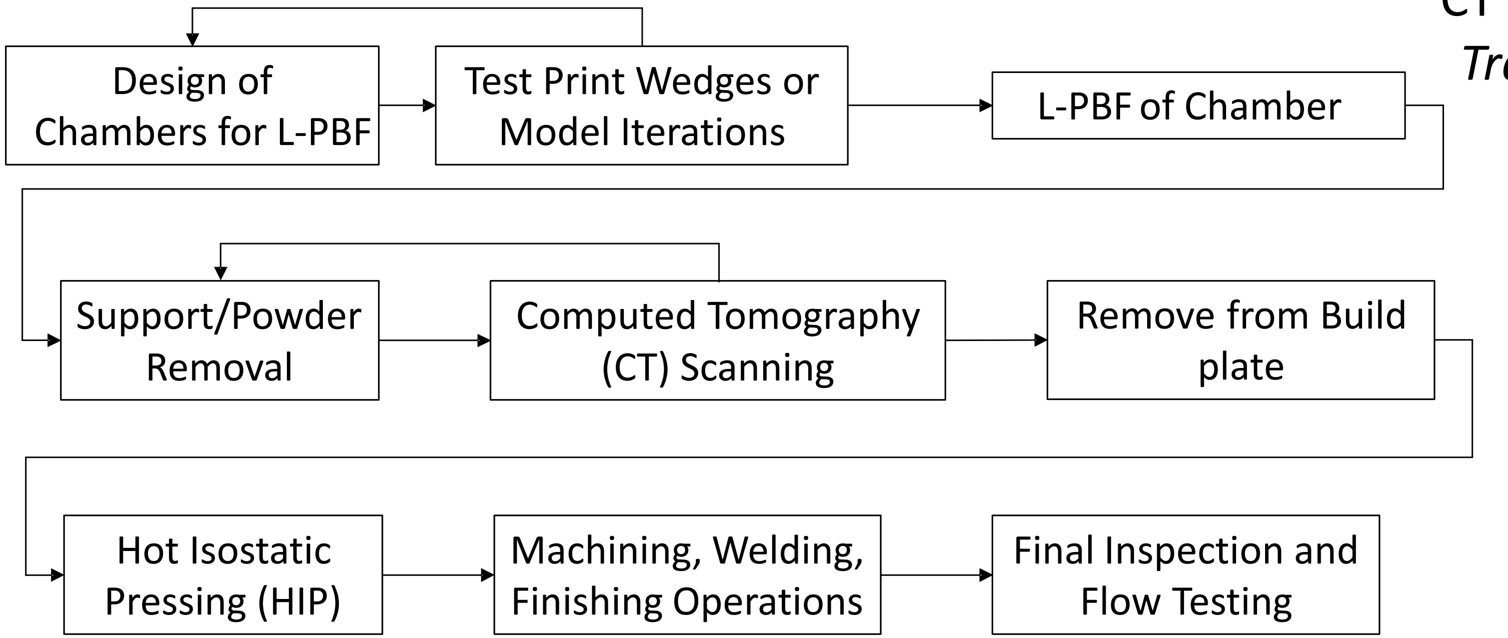
- Demonstrated repeatability of GRCop-84 and GRCop-42 on various machines (Concept M2, EOS M290, EOS M400)
- Identical post-processing including Hot Isostatic Pressing (HIP)
- HIP reduces strength but increases elongation to desired values
- Surface roughness studies completed



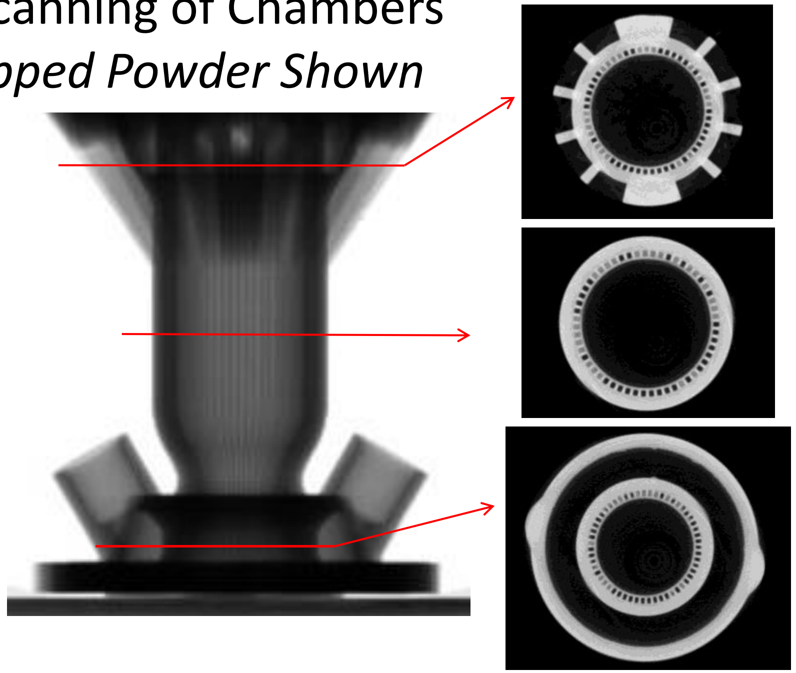



# Post-processing of L-PBF GRCop-alloy Chambers




CT Scanning of Chambers
*Trapped Powder Shown*

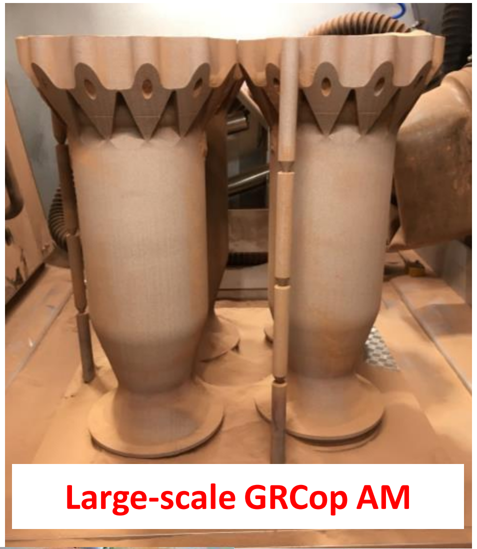


- Successful L-PBF development should place <u>considerable emphasis on post-processing</u>
  - Several chambers scrapped due to trapped powder
- Order of post-processing critical to success
- Hot Isostatic Pressing (HIP) successfully developed

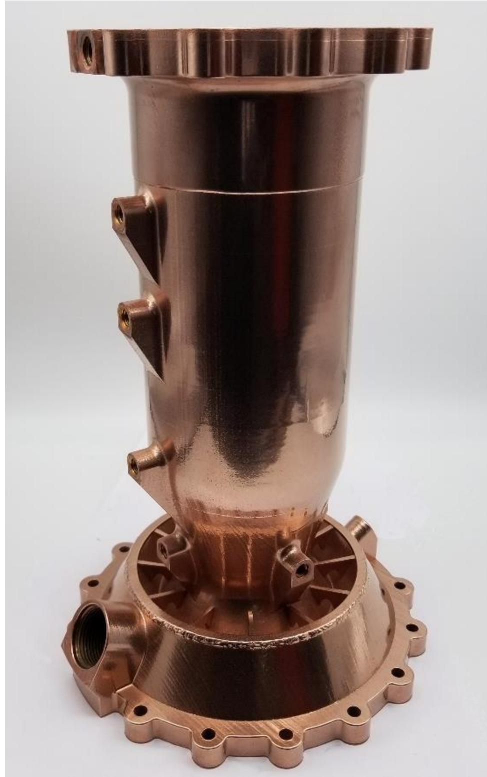
# L-PBF GRCop-alloy Combustion Chambers

Multi-Alloy Additive

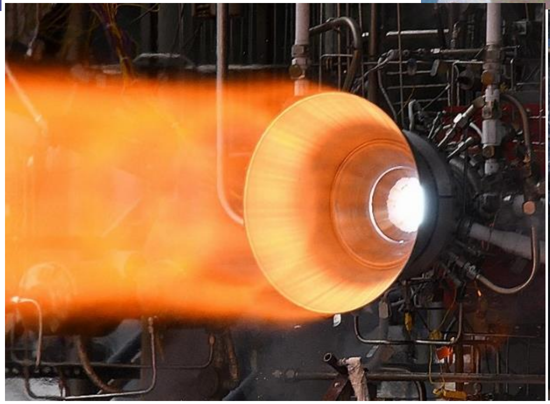
Combine L-PBF and DED

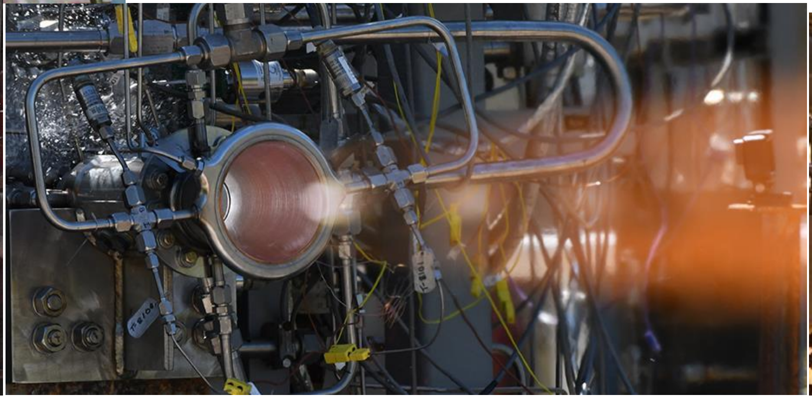


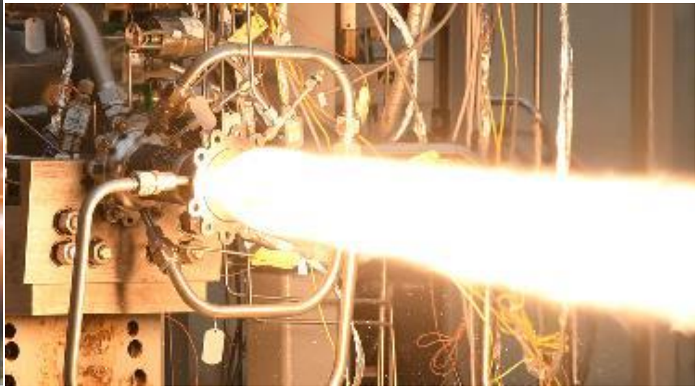
Large-scale GRCop AM



~16” Dia





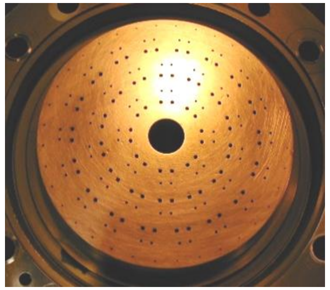


# Hot-fire Testing

# Overview of Injector Manufacturing

## Flow Elements / Faceplate



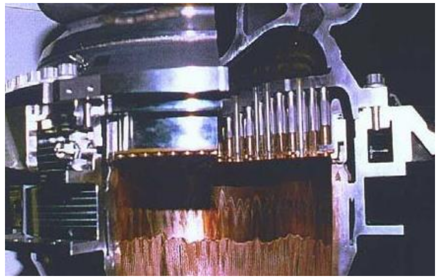


- Multi-axis Machining
- Multi-axis Grinding
- Electro discharge Machining (EDM)
- Laser-Powder Bed Fusion (L-PBF)
- Laser Drilling
- Photochemical Etching
- Electrochemical Milling (ECM)
- Post-processing / Polishing
- Wrought (Forged / Barstock / Plate)
- Platelets

## Manifolds and Subassemblies


- Forging
- Machining
- Powder Metallurgy
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Laser Powder Bed Fusion( L-PBF)
- Platelets
- Coldspray
- Casting
- Hydroforming

## Final Assembly

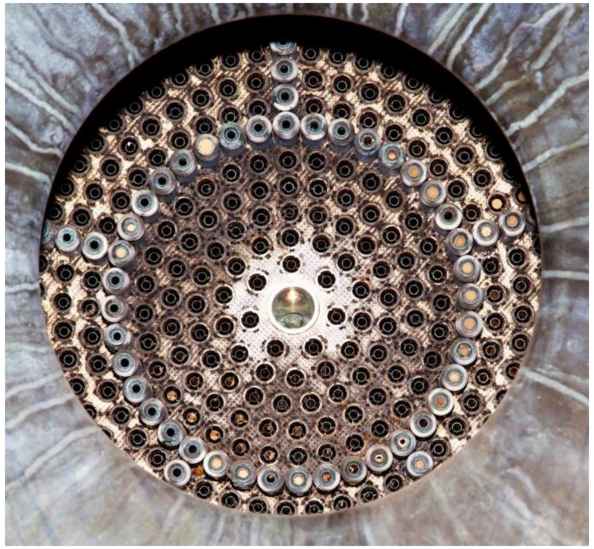


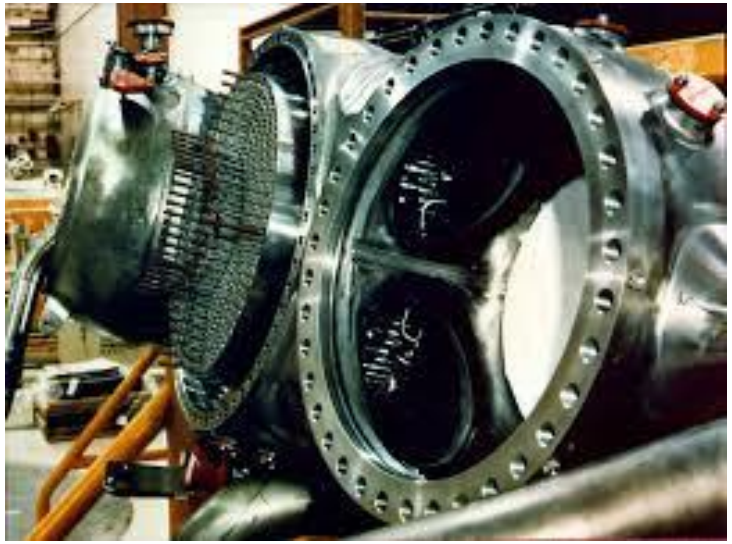

- Brazing
- Welding – TIG, EB, Laser, Inertia
- Laser Powder Bed Fusion (L-PBF)
- Electroplating
- Multi-axis Machining
- Electro discharge Machining (EDM)
- Post-processing / Polishing
- Rigimesh Permeable Faceplates
- Directed Energy Deposition
  - Blown Powder Laser
  - Laser Wire Direct Closeout
  - Arc-based Wire
- Ultrasonic
- Diffusion Bonding
- Platelets
- Casting
- Coatings

# Injector, Traditional Fabrication Examples

*All pictures courtesy NASA archives unless noted

Traditional machining of impinging injector on F-1 engine





Shear Coaxial, Machined and Brazed (SSME/RS-25)

Rigimesh Faceplate

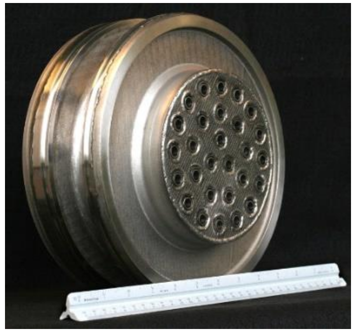
Impinging, Machined (Credit: BU RPG)

RL-10 Traditional Coaxial

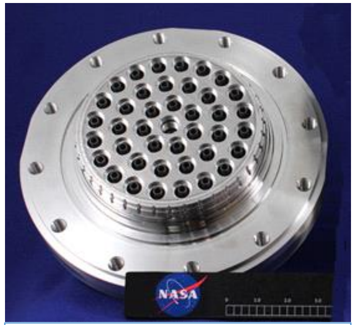
# Examples of Additively Manufactured Injectors

100lbf LOX/Propane Nanolaunch Injector. Built 2012. Tested 2013.

1.2K LOX/Hydrogen Injector First Tested in June 2013. >10,000 seconds hotfire

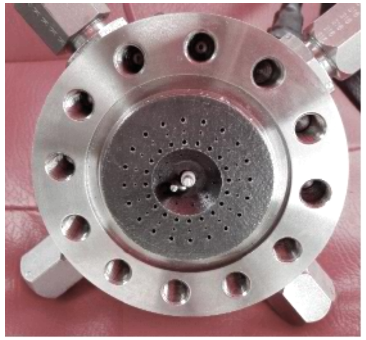


20K LPS Subscale Injector. Tested August 2013



Methane 4K Injector with printed manifolds, parametric features. Tested Sept 2015.

35K AMDE Injector with Welded Manifolds, Tested 2015

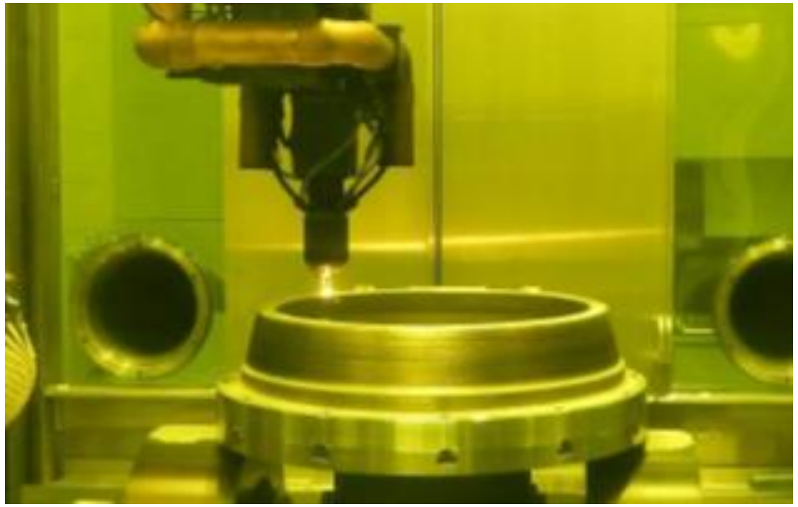
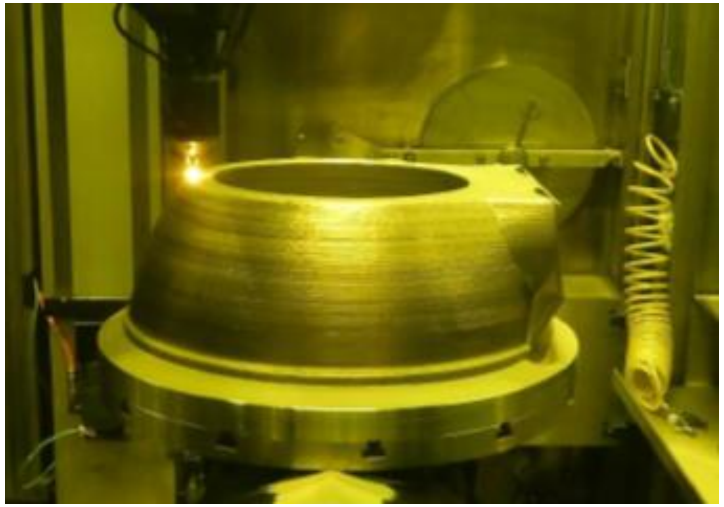
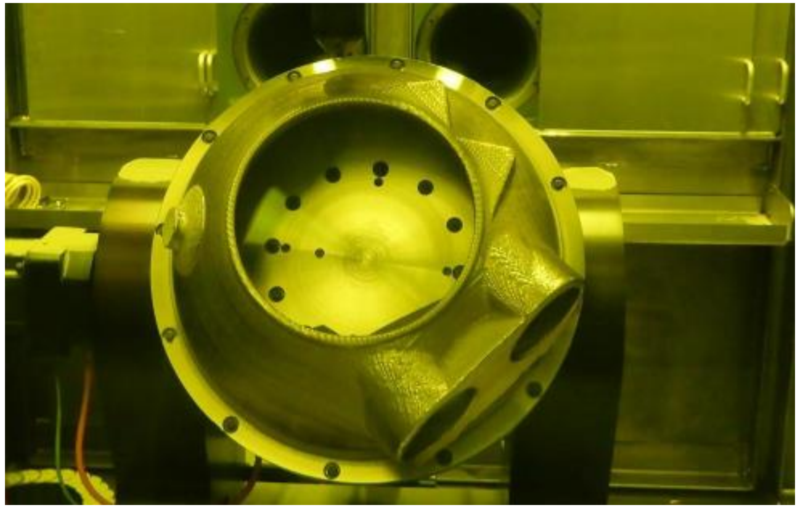
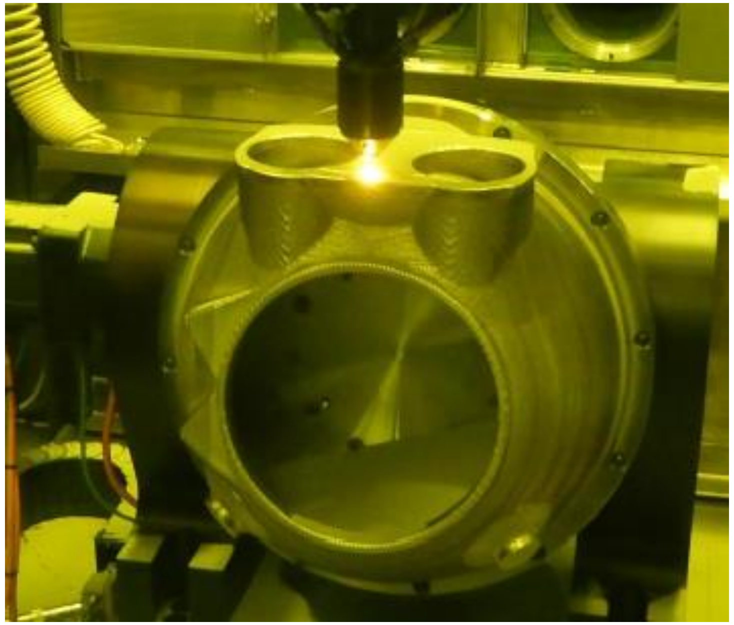
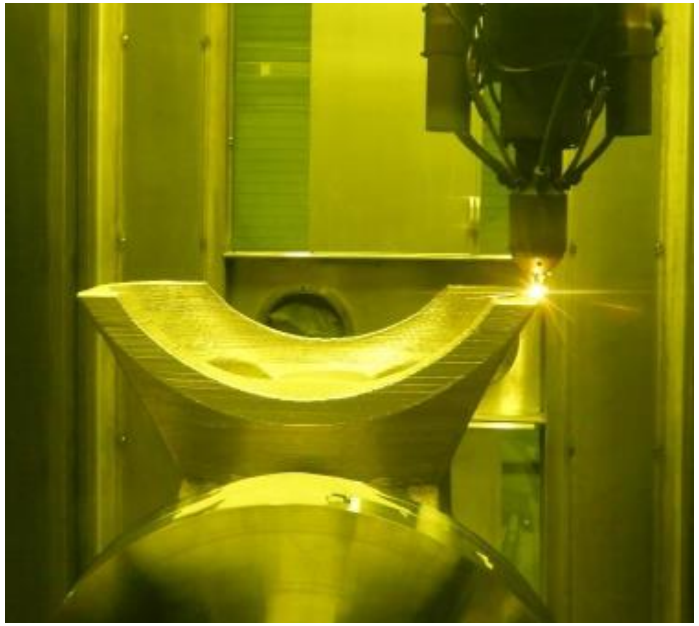


LOX/Methane Gas Generator Injector, Tested Summer 2017

- MSFC has developed and tested a total of 25+ unique AM injectors between 2012-2020
  - Materials: Inco 625, Inco 718, Monel K-500, GRCop-84/42, JBK-75
  - Element Types: swirl coax, shear coax, impinging
  - Number of Elements: ranging from 6 to 62+
  - Diameters: ranging from 1.125” to 7.5” +
  - Hundreds of hot-fire tests performed with AM injectors
- To date, all MSFC injector designs have been manufactured with L-PBF process.
- Advantages of AM application to injectors:
  - Reduction of part count, braze/weld operations, cost, and schedule
  - Allows non-conventional manifolding schemes and element designs
- Challenges of AM fabrication of injectors:
  - Feature size resolution (particularly radial to the build direction)
  - Excessive surface roughness
  - Removing powder prior to heat treatments (even stress relief) is both necessary and challenging

Ref: Brad Bullard, Jim Hulka, Chris Protz, Sandy Greene, Greg Barnett, Jessica Wood

# Injector Powerhead (RS25)
# Development of Blown Powder DED Inconel 718


RPM Innovations (RPMI) under NASA SLS Artemis Program

# Overview of Turbomachinery Manufacturing

## Rotating Components

**Final Geometry**
- Multi-axis Machining
- Multi-axis Grinding
- Electro discharge Machining (EDM)
- Electrochemical Milling (ECM)
- Laser-Powder Bed Fusion
- Post-processing / Polishing

**Starting Stock**
- Forging
- Powder Metallurgy
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Coldspray
- Casting

## Housing / Casings (Volutes, Diffusers)

**Final Geometry**
- Multi-axis Machining
- Electro discharge Machining (EDM)
- Laser-Powder Bed Fusion
- Post-processing / Polishing

**Starting Stock**
- Forging
- Casting
- Powder Metallurgy
- Directed Energy Deposition
  - Blown Powder Laser
  - Wire-based Laser
  - Arc-based Wire
- Coldspray
- Molded Composites

## Assembly

- Manual and Auto TIG Welding
- Coatings
- Thermal Assistance
- Pressing Operations
- Manual and furnace brazing
- Multi-axis Machining
- Drilling
- Laser Powder Bed Fusion (L-PBF)
- Electroplating
- Directed Energy Deposition
- Diffusion Bonding

Ref: Chris Hill, Derek O’Neal, Matt Marsh

# Turbomachinery – Traditional Manufacturing and Assembly

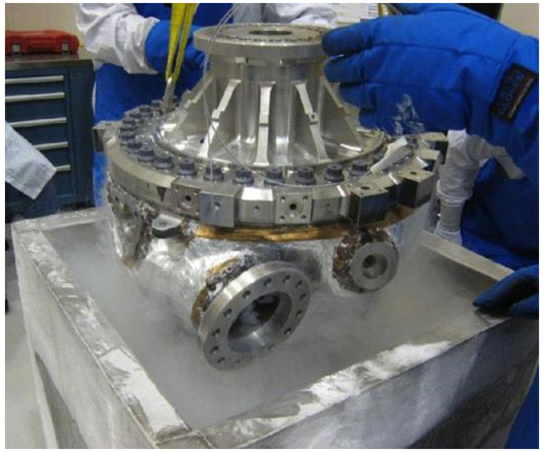
RS-25 Fuel Pump Discharge Housing, Cast and machined (Courtesy: Metalex/NASA)

RS-25 LOX Pump Forward Inducer, machined
Courtesy: Metalex/NASA

Turbopump Assembly
Courtesy: Barber-Nichols

RS-25 Fuel Pump 2nd Stage Impeller, Forged and Machined (Courtesy: Metalex/NASA)

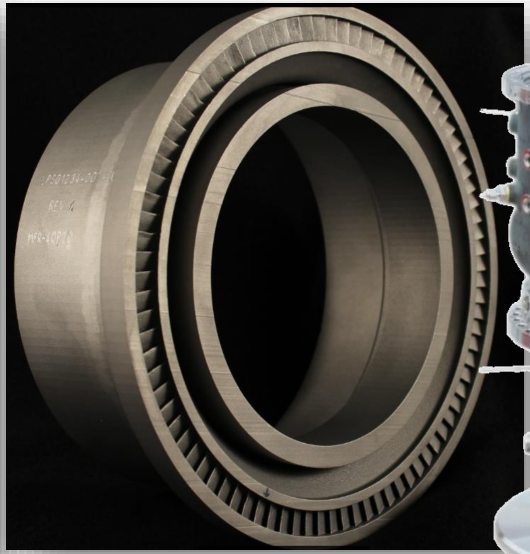
RS-25 Fuel Pump Discharge Housing, cast and machined (Courtesy: Metalex/NASA)

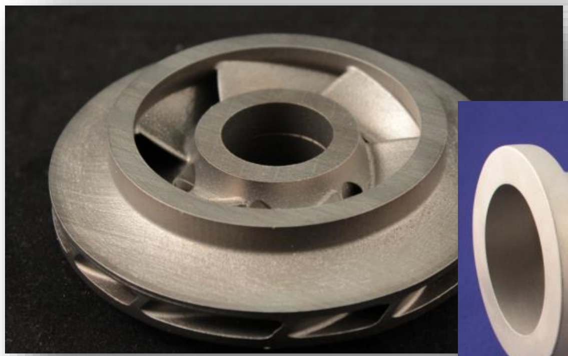


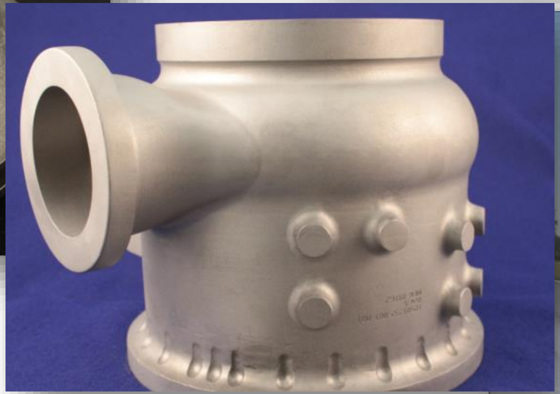
J-2X Fuel Housing Assembly and Test
Courtesy: Aerojet Rocketdyne/NASA

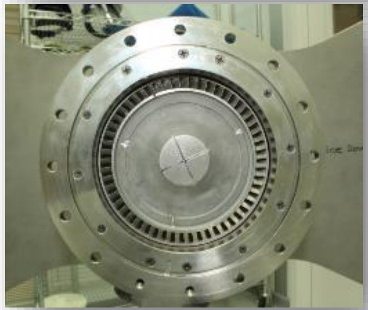
Machined A-286 Housing
NASA/Derek O'Neal

# Examples of Additively Manufactured L-PBF Turbomachinery





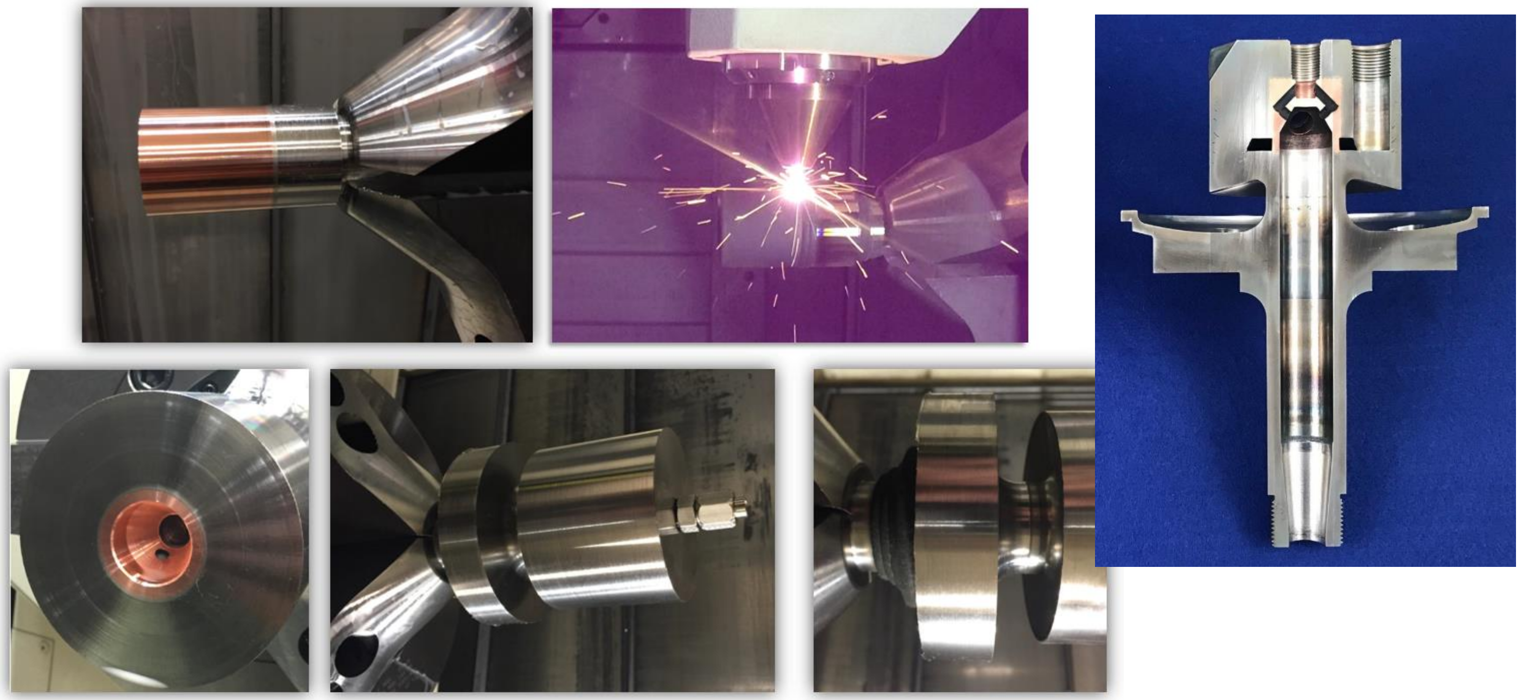




Ref: Derek O'Neal, Chris Hill, Marty Calvert / NASA MSFC

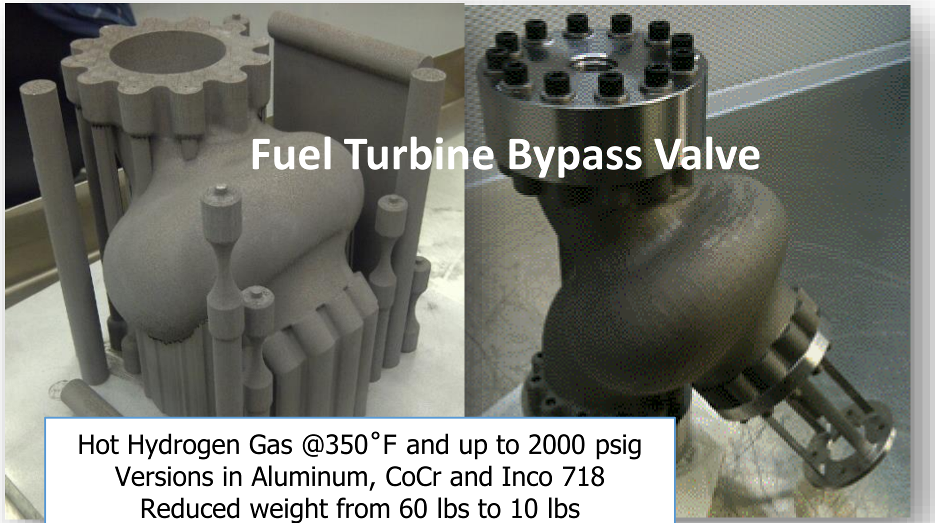
# Bimetallic Components – Ignition Systems and Chambers

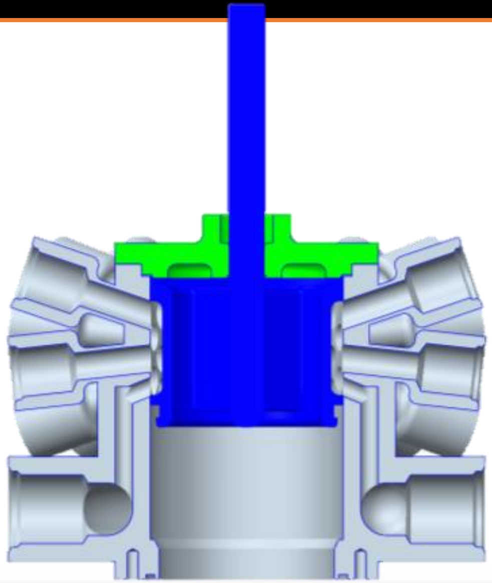
- NASA has developed bimetallic combustion chambers using Copper-alloy liners and Inconel structural jacket (GRCop-84 to Inconel 625)
  - L-PBF to fabricate the liner and DED for structural support
  - Similar processes used for Spark Ignition Systems with bimetallic but using wrought material and DED (C-18150 to Inconel 625)

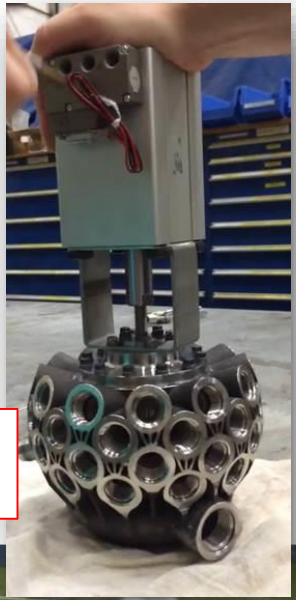


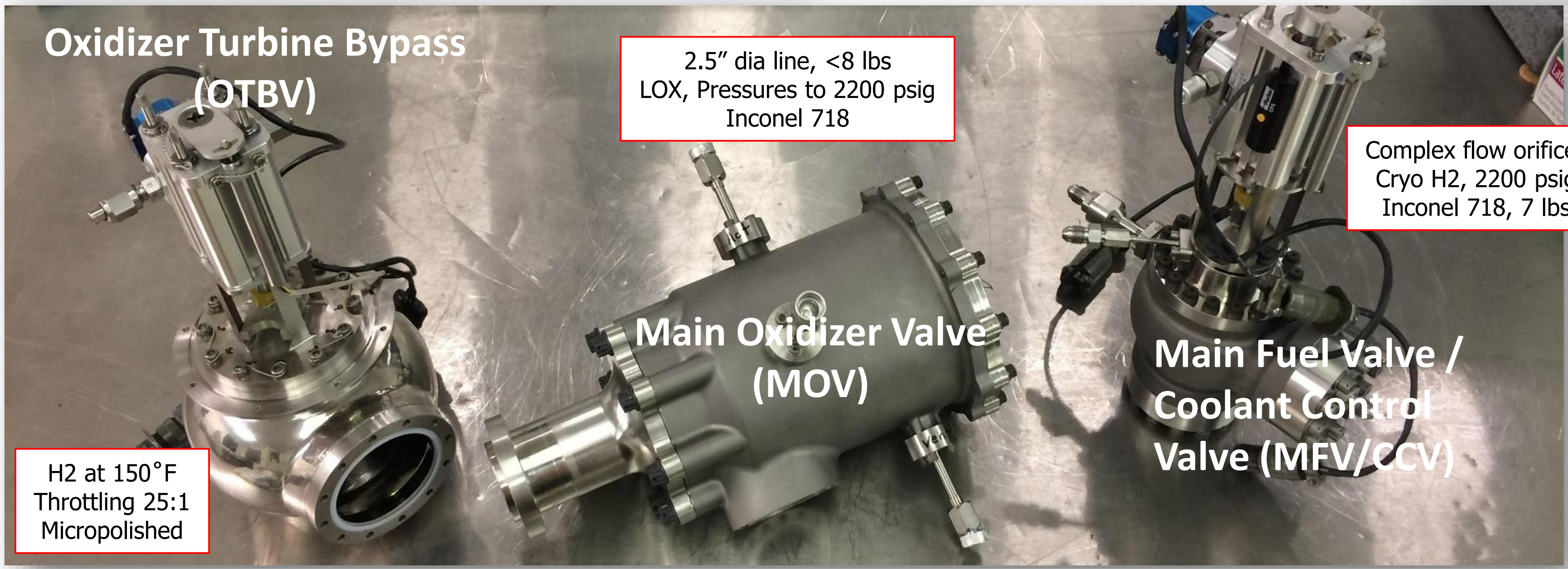
Ref: Chris Protz, Robin Osborne / NASA MSFC

# Additively Manufactured Valves



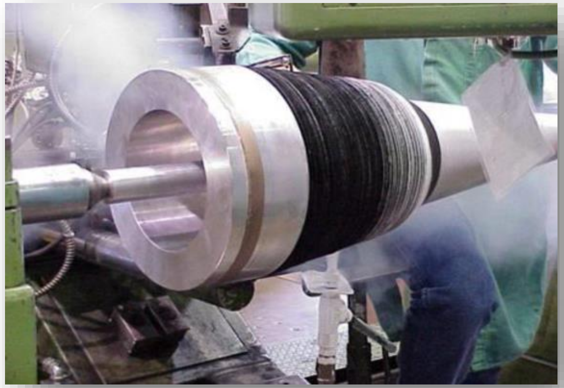


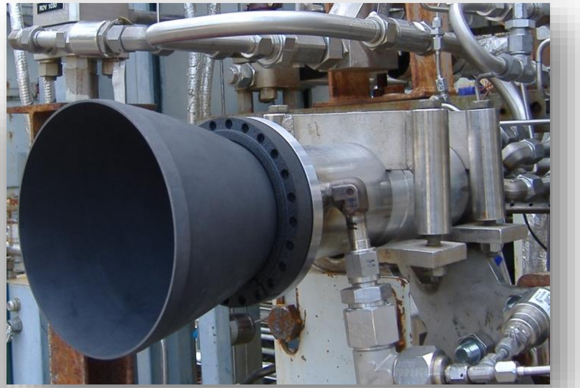


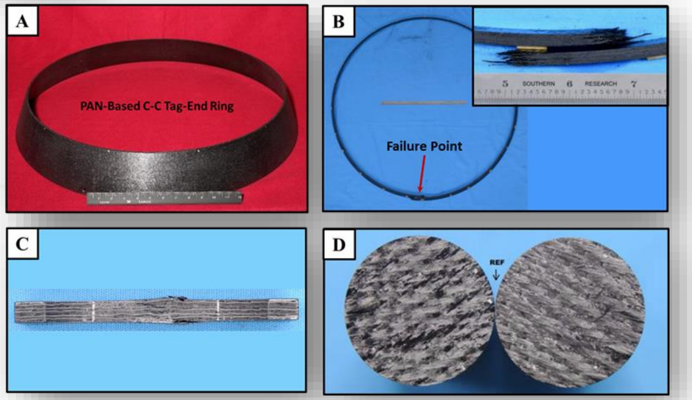
Ref: Jim Richard, Dave Eddlemen, Travis Davis / NASA MSFC

# High Temperature Nozzle Extensions
## Composite and Metallic

- High temperature materials can be used for un-cooled or film cooled nozzles as heat fluxes are reduced in higher expansion ratio thrust chamber assemblies
- Composite materials (C-C, C-SiC, CMC) and Refractory Metals are most often used
  - Composites have benefits of weight reduction, improved thermal margins, and potential cost reduction
  - Detailed understanding of properties under relevant conditions required
- Temperatures can exceed 3500°F

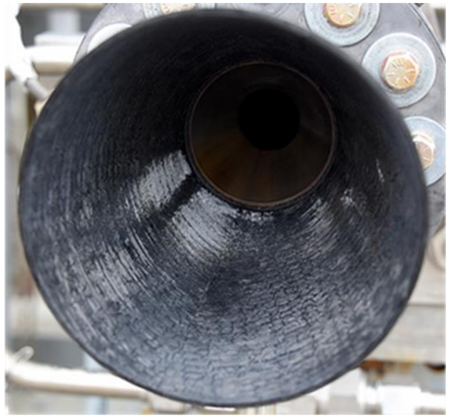




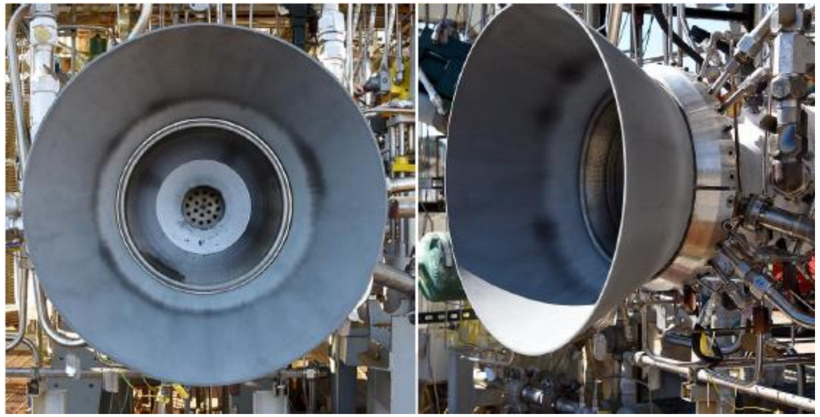


# Composite Nozzle Extensions

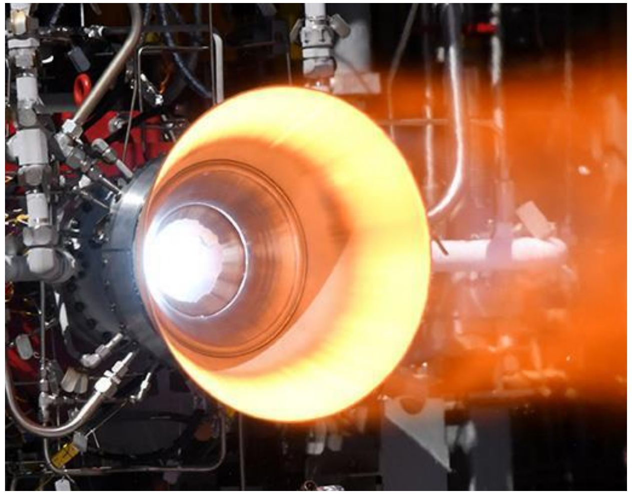
- Various Carbon and refractory materials being explored and coatings to prevent oxidation
  - Carbon-Carbon (C-C)
  - Silicon-Carbide (SiC)
  - Carbon-Silicon/Carbide (C/SiC)
  - Refractory-based coatings with Zr, $MoSi_2$, Hf, $ZrB_2$
  - Secondary coating processes and matrix enhanced
- Development testing completed in LOX/$H_2$, LOX/$CH_4$, and LOX/RP-1



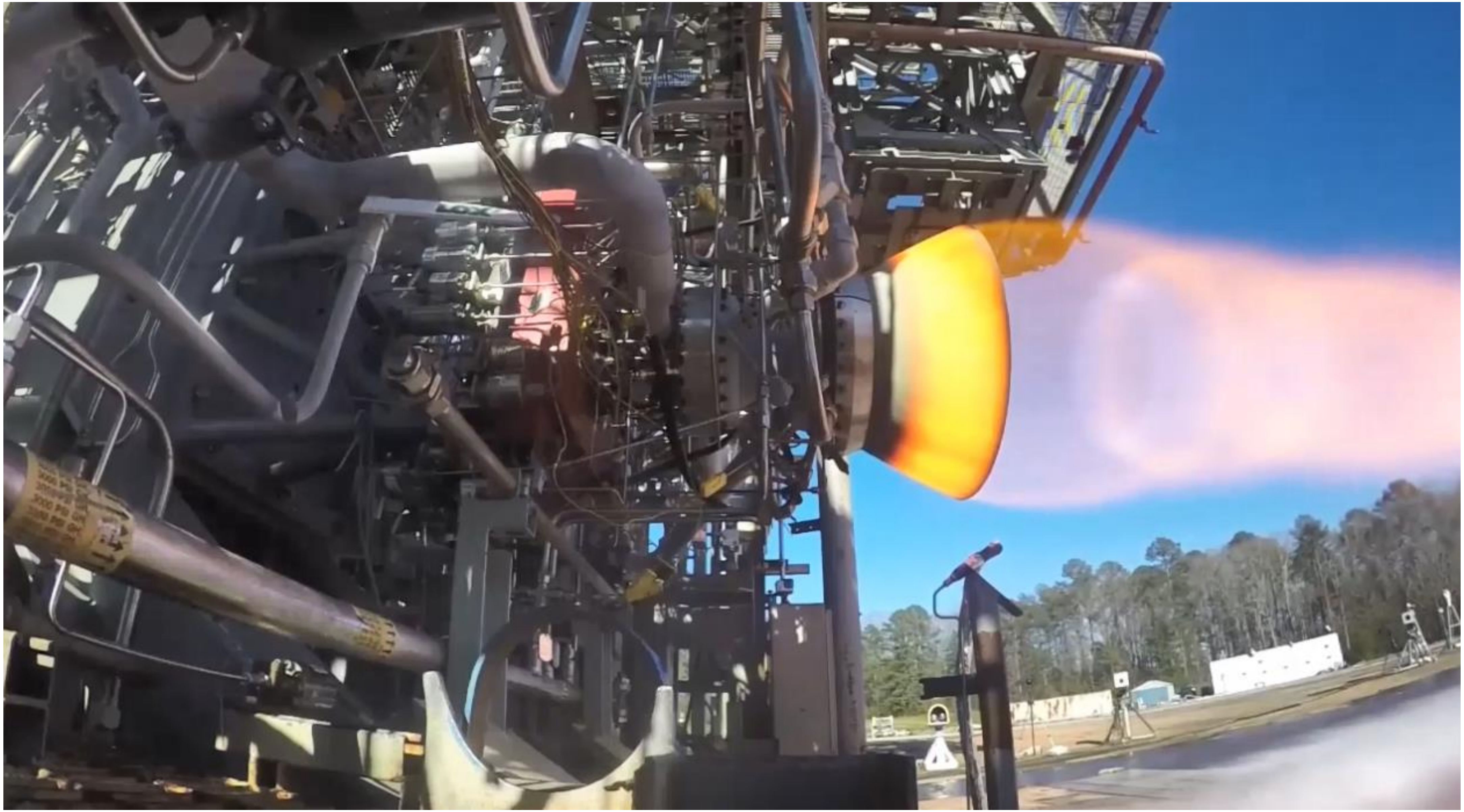
2.5D needled C-SiC, PIP densification, uncoated



T-300 6K Fiber with ACC-6 condition SiC conversion coating



# Composite Nozzle Extensions



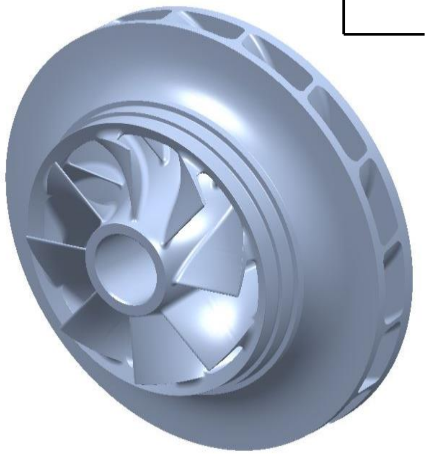
# Generic Process Flow of AM Components

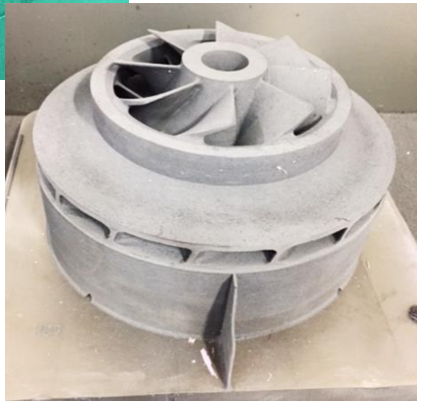
**Model Design, Generation and Tool Pathing** → **Additive Manufacturing Process** → **Post-Processing** → **Part in service**

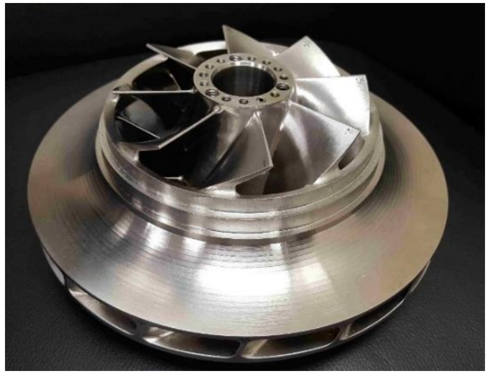
**Material Feedstock** → **Additive Manufacturing Process**

Model Design, Generation and Tool Pathing:
- Part Design
- Analysis
- Build Layout
- Support Generation
- Model Slicing
- Toolpath

Post-Processing:
- Powder Removal
- Heat Treatments
- Support Removal
- Build Plate Removal
- Inspections
- Final Machining
- Cleaning
- Polishing
- Welding
- Brazing



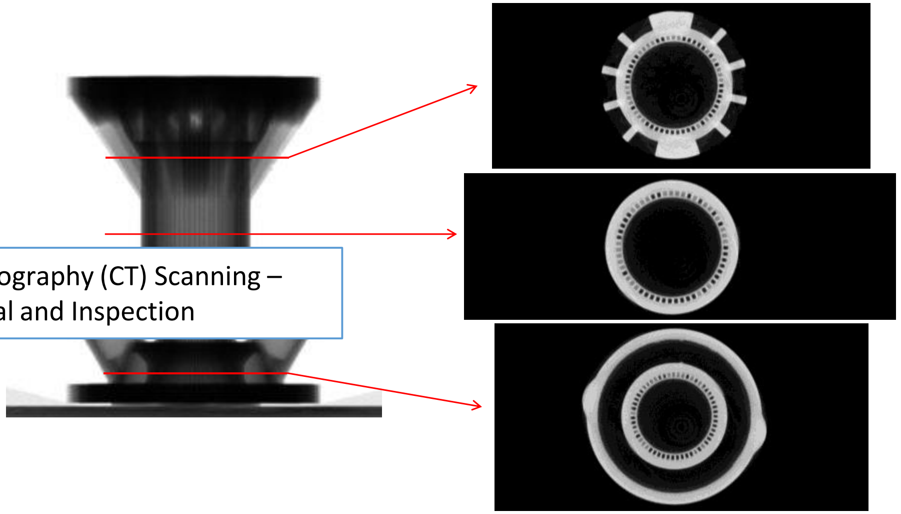




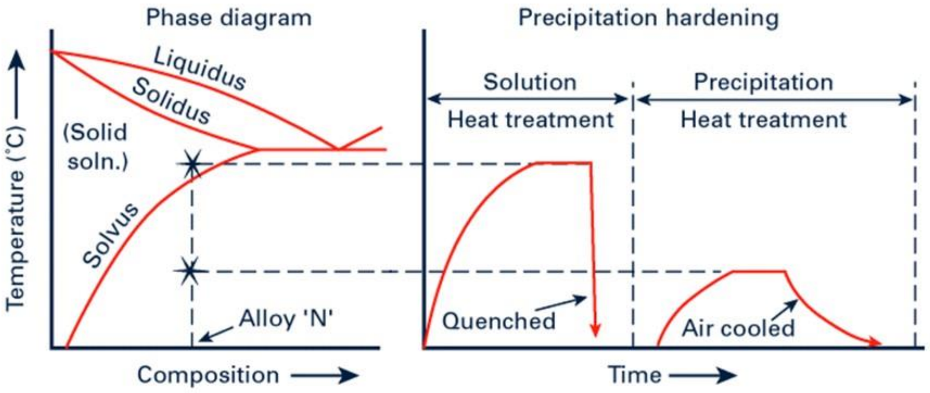
All Pictures Courtesy: Southwest Research Institute (SwRI)

# Advanced Manufacturing Post-Processing

- Additive manufacturing techniques **must** consider the entire process for parts to be successful – the print is only a portion of the process
  - De-powdering and confirmation
  - Heat Treatments including HIP
  - Inspections
  - Build plates removal
  - Cleaning of Parts
  - Joining (welding/brazing)
  - Machining operations
  - Polishing



Computed Tomography (CT) Scanning – Powder Removal and Inspection



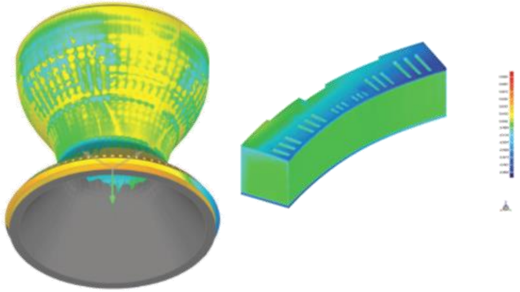

General phase diagram showing heat treatments.

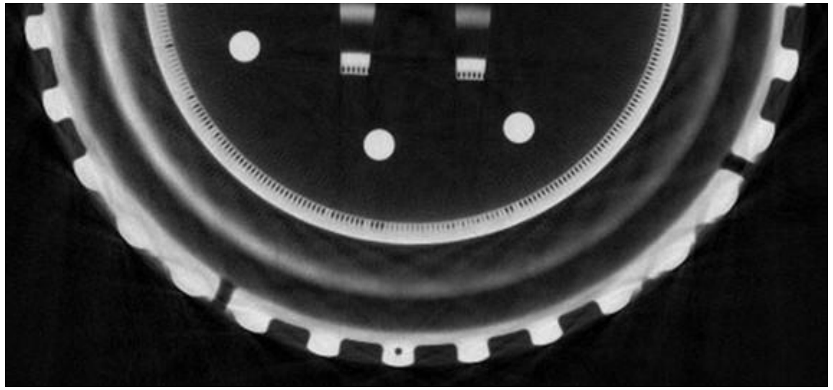
# Non-Destructive Evaluation (NDE)

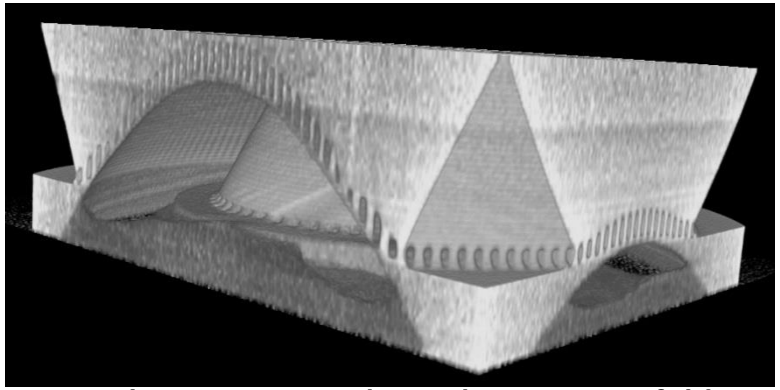
- Structured Light Scanning
  - Surface mapping
  - Geometric distortion/deviation
  - Limited spatial resolution
  - Equipment expensive but operation relatively inexpensive
- X-ray radiography & CT
  - Detect trapped powder
  - Large flaws
  - Limited spatial resolution (excludes micro-focus CT)
  - Material determines scan time/resolution
  - Expensive & time consuming
- Other
  - Visual / Borescope
  - In-situ
  - Ultrasonic
  - Penetrant
  - Infrared

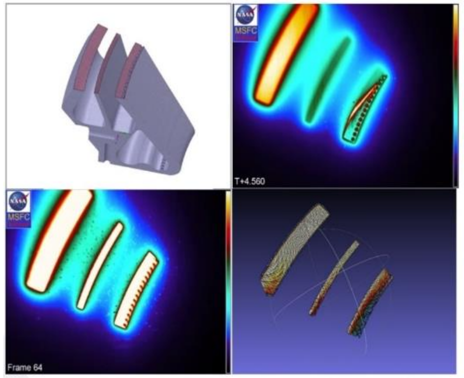

Visual Borescope

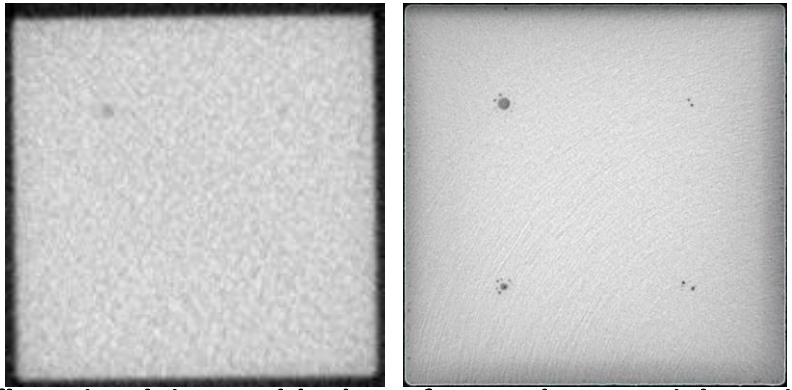

Structured Light Scanning


CAD-scan data comparison

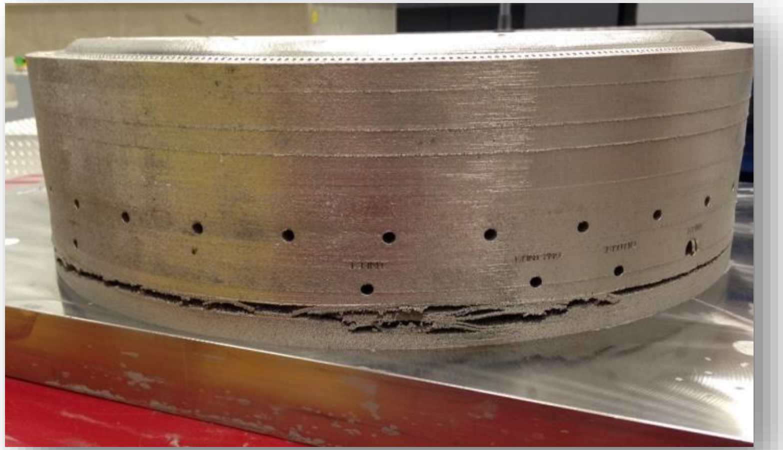

Radiograph showing powder filled channels


CT showing trapped powder in a manifold

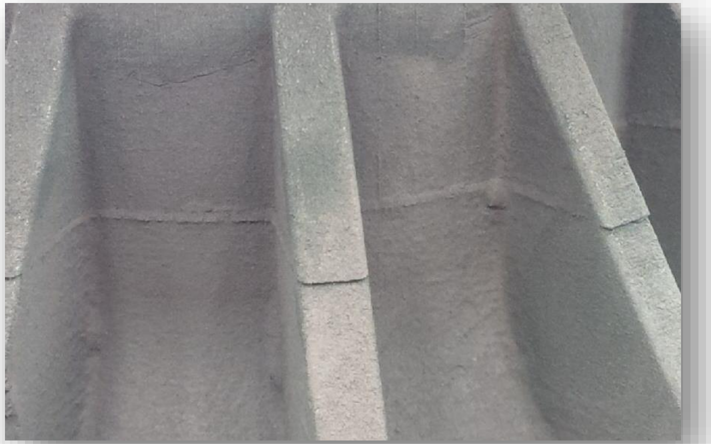

In-situ Inspections


Known flaws in AlSi10Mg block. Left: Regular CT. Right: Micro-CT

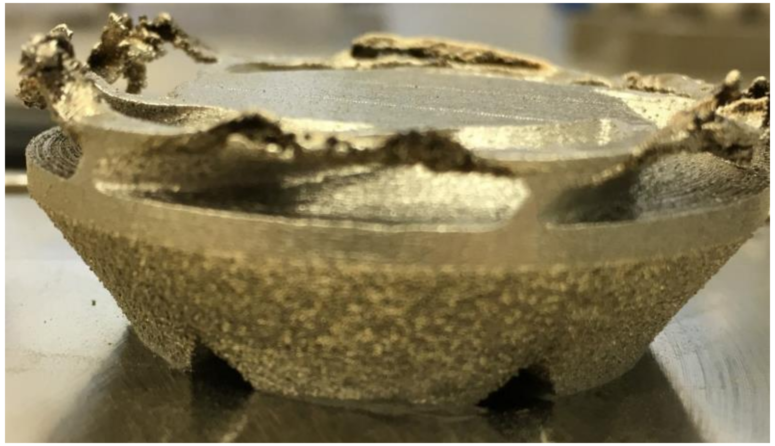
# Additive Manufacturing is not easy…

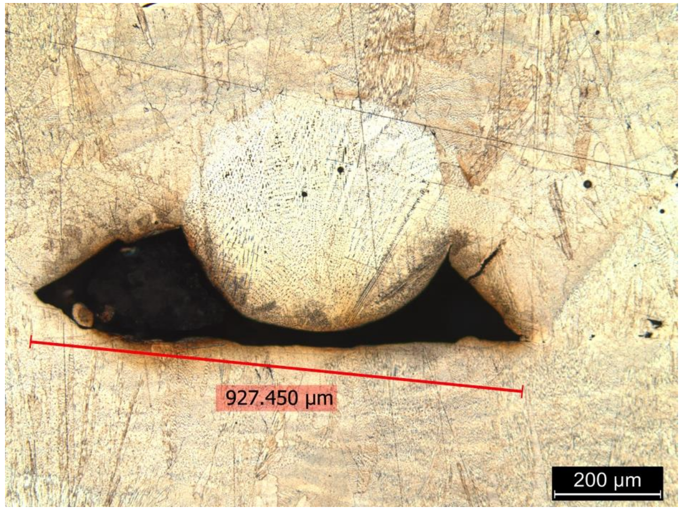


Cracking from Residual Stresses during build

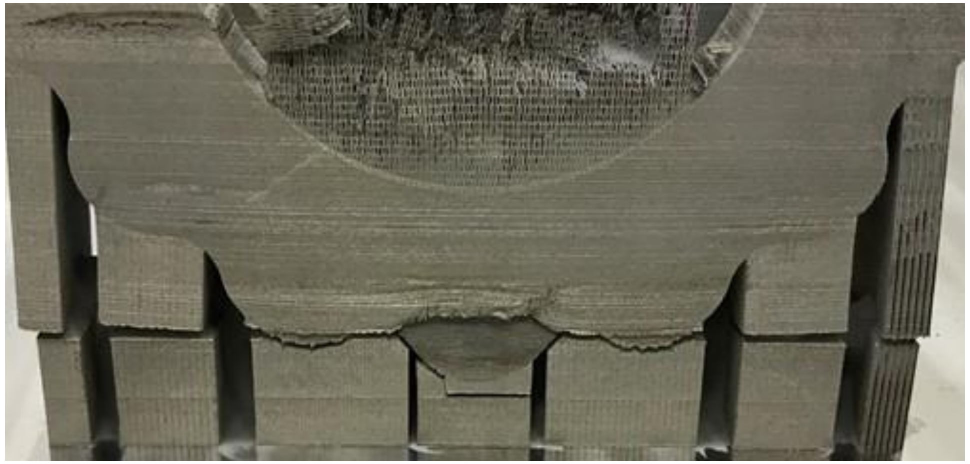


Restart line observed post-build

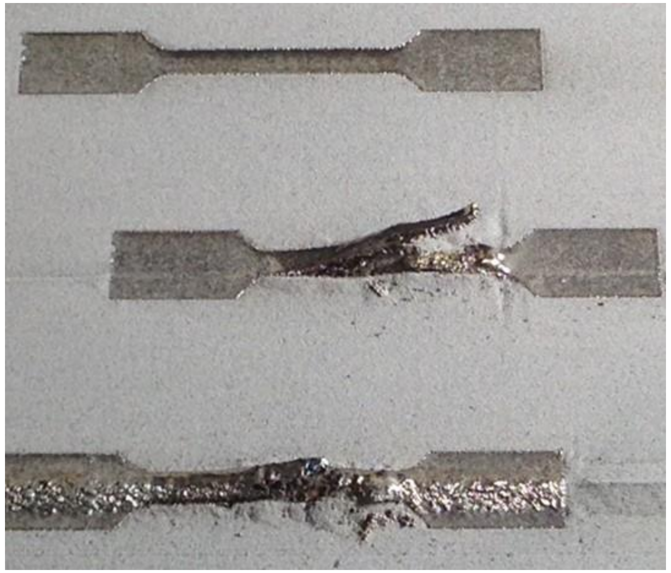





Lack of Fusion



Residual stress induced failure.

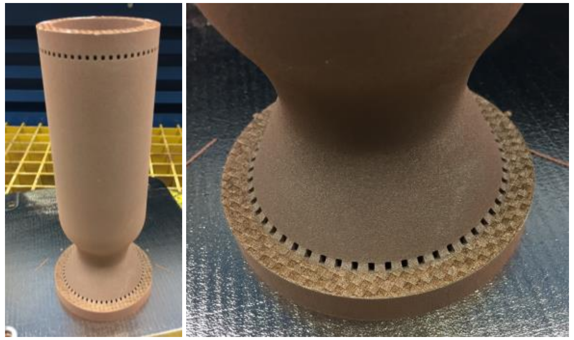


Part separation from support structure

# AM Surface Roughness and Polishing

## A significant hurdle in additive manufacturing is the surface roughness of internal and external surfaces

- Fatigue Performance significantly impacted
- Flow performance impacted, but can also result in heat transfer augmentation
- Various techniques are feasible: shot peen, chemical milling, abrasive machining (slurry), chemical mechanical polishing, electropolishing, laser polishing, ultrasonic, controlled corrosion



### Response to Surface Roughness in Channels

| Surface Roughness | Pressure Drop | Hotwall Temperature | Total Heat Load |
|---|---|---|---|
| ↑ | ↑ | ↓ | ↑ (small) |

*Ref: Sutton, Rocket Propulsion Elements*

### Response to Surface Roughness of Hotwall

| Surface Roughness | Pressure Drop | Hotwall Temperature | Total Heat Load |
|---|---|---|---|
| ↑ | – | ↑ | ↑ |

*Ref: Sutton, Rocket Propulsion Elements*

# NASA Certification of Additive Manufacturing

- Standardization is essential for consistent and reliable production of flight critical AM components.
- NASA has chosen to develop internal standards to meet immediate needs while also participating in open industry AM standard development activities
- Status of NASA AM standardization
  - MSFC-STD-3716 & MSFC-SPEC-3717 issued
    - Issued October 2017
    - L-PBF only
  - Agency wide standard, NASA-STD-6030 (AM Requirements for Crewed Spaceflight Systems)
    - Includes approach for L-PBF and DED
  - Agency wide specification, NASA-SPEC-6033 (Additive Manufacturing Requirements for Equipment and Facility Control)
  - NASA-STD-6030, target release is early fall 2020


NOT MEASUREMENT SENSITIVE

National Aeronautics and Space Administration

MSFC-STD-3716
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

Standard for Additively Manufactured Spaceflight Hardware by Laser Powder Bed Fusion in Metals

DRAFT 1 – April 10, 2017

This official draft has not been approved and is subject to modification.
DO NOT USE PRIOR TO APPROVAL

CHECK THE MASTER LIST — VERIFY THAT THIS IS THE CORRECT VERSION BEFORE USE

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED


METRIC/SI (ENGLISH) SENSITIVE

National Aeronautics and Space Administration

MSFC-SPEC-3717
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20
MSFC TECHNICAL STANDARD

Specification for Control and Qualification of Laser Powder Bed Fusion Metallurgical Processes

DRAFT 1 – July 13, 2017

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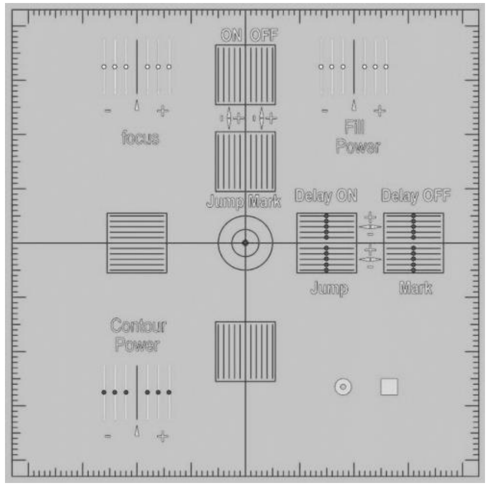
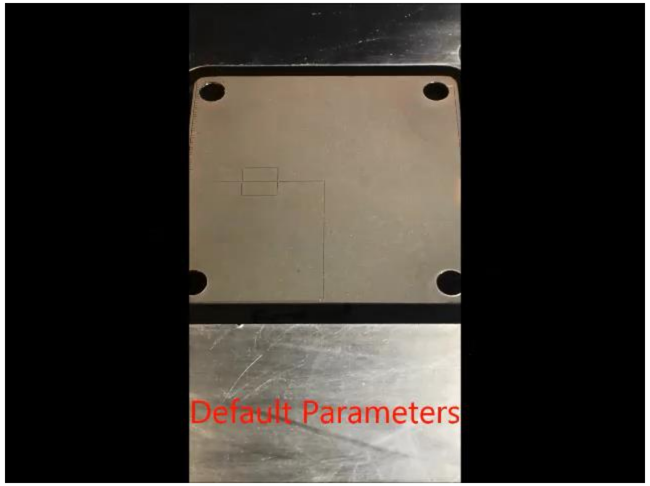
Process specification: From powder to acceptance




Machine repeatability

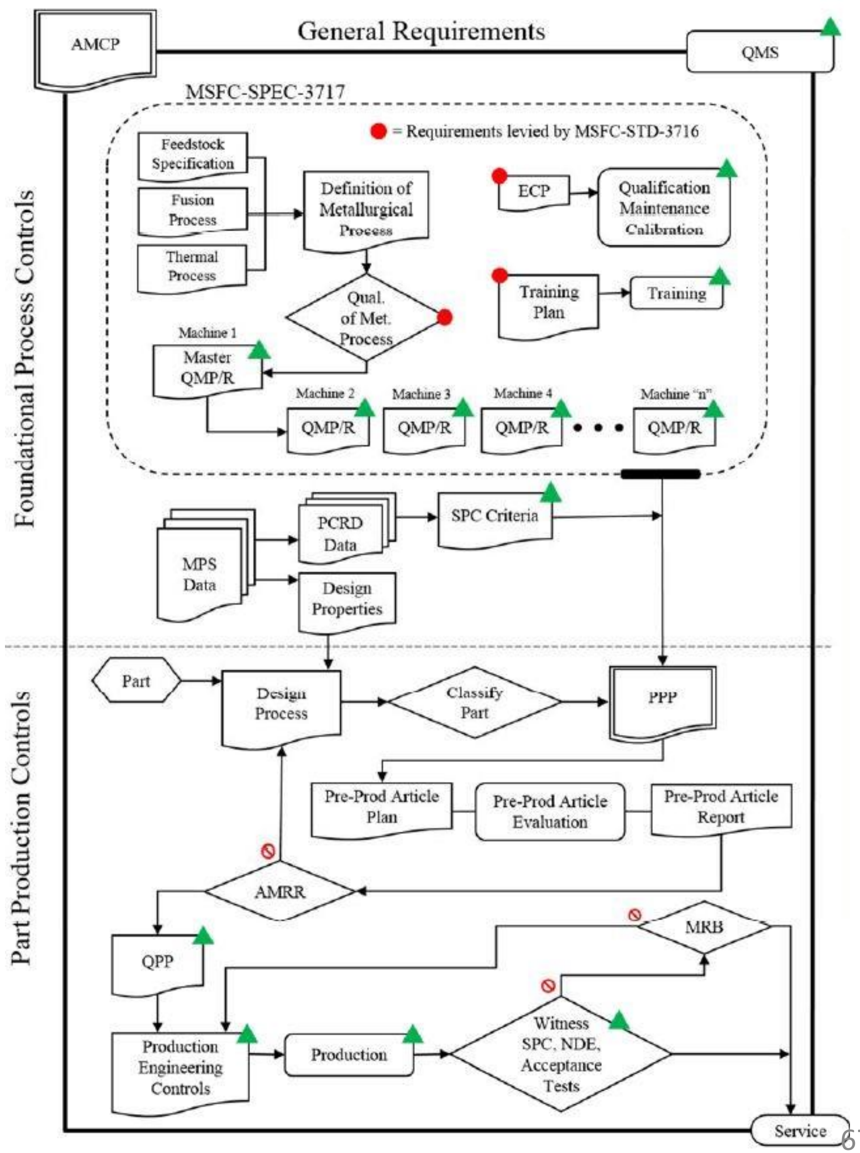
# NASA Standards for Additive Manufacturing

## Key aspects of NASA AM requirements

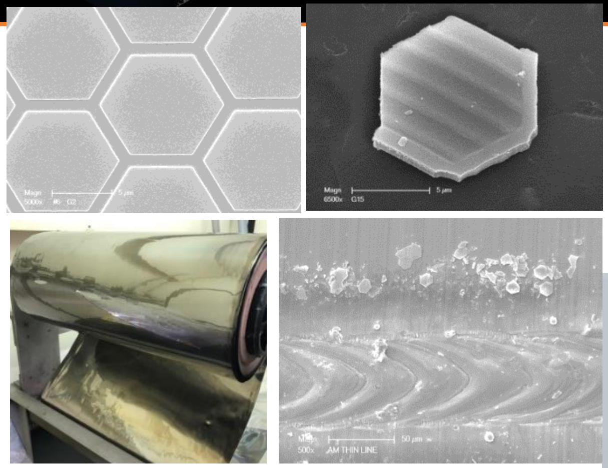
- Overarching and foundational controls
  - AM Control Plan
  - Quality Management System
  - Equipment and facility control,
  - Personnel training
  - Machine/process qualification
  - Material property methodology for AM
- Part production controls
  - Part classification
  - Part production plans
  - Pre-production articles
  - Qualified Part Process

## Ingredients for AM Qualification and Certification

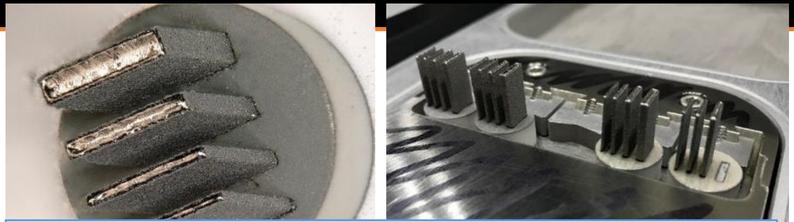
- *Understanding* and *Appreciation* of the AM process
- *Integration* across disciplines and throughout the process
- *Discipline* to define and follow a plan



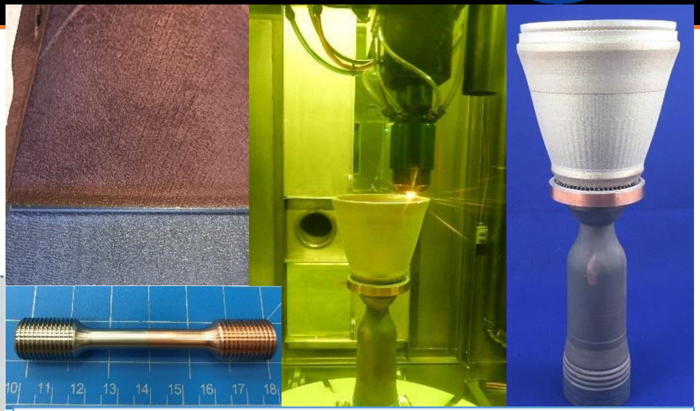
# Advances in Additive Manufacturing



Engineered platelets to replace powders. Courtesy SwRI

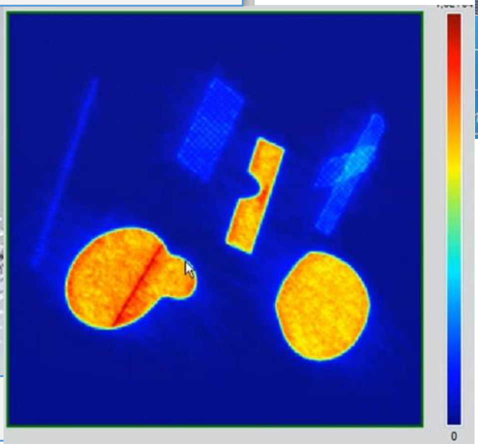


**Hermetic metal-ceramic bonds.** Courtesy SwRI

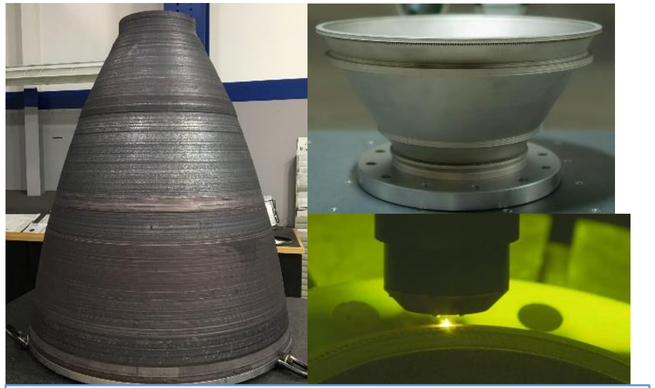


**Multi-alloys and hybrid techniques**

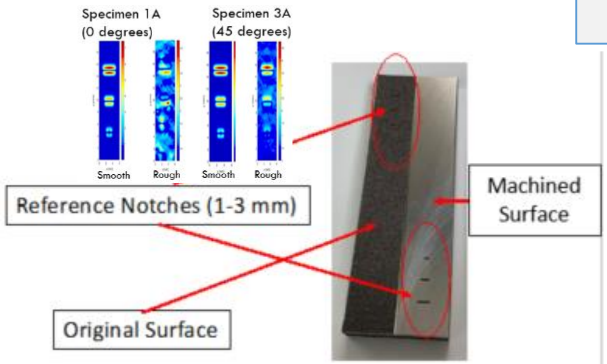
**High density ceramic AM.** Courtesy Lithoz.



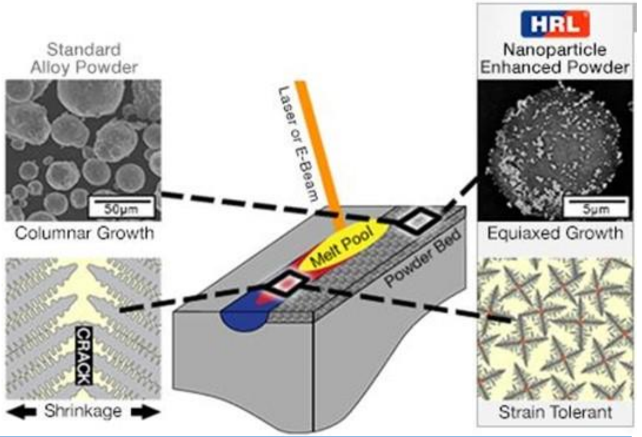
**In-Situ Process Monitoring.** Courtesy EOS.



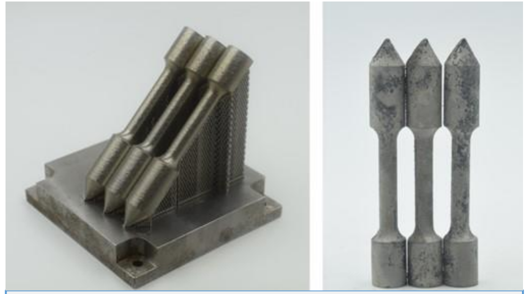
**Increased scale and resolution**




**Advanced NDE application for qualification (Eddy Current Testing shown).** Courtesy SwRI




**Non-weldable alloys.** Courtesy HRL.



**Support structure etching.** Courtesy CO. School of Mines.

**LPBF of shape memory alloys.** Courtesy SwRI

# Continued Development at NASA with Advanced Manufacturing

**Bimetallic Deposited Manifolds**
Vendor Development and Optimization

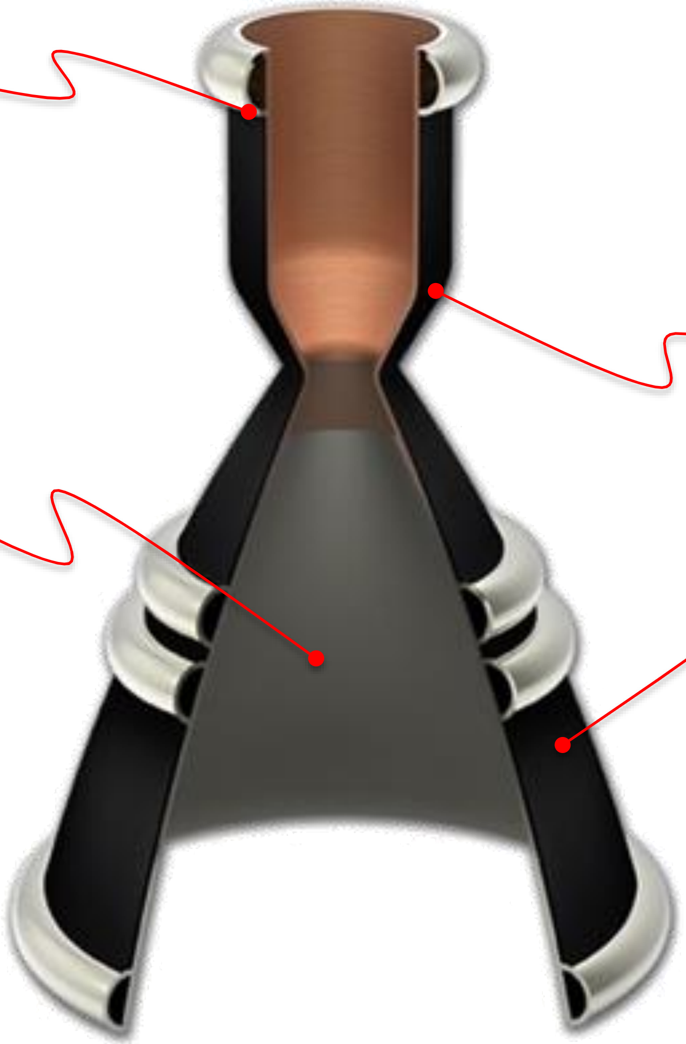
- Develops commercial supply chain
- Reduces Cost
- Optimizes weight based on selective material deposition

**Integrated Large Scale Freeform**
Manufacturing Deposition Regen-Cooled Nozzle

- Rapid Fabrication for Increased Scale
- Reduces cost and schedule (50%)
- Removes all joints
- Increases reliability
- Reduces complexity

Design and Process Modeling Tools Enable an Integrated Optimized Design

- Reduces design cycles by 60%



**3D printed Copper Chamber** (derived from LCUSP Program)

- Proven Technology
- Advances Commercial Supply Chain

**Composite Overwrap**
Thrust Chamber Assembly

- Reduces overall cost and schedule
- Increased performance
- Builds upon COPV Technology

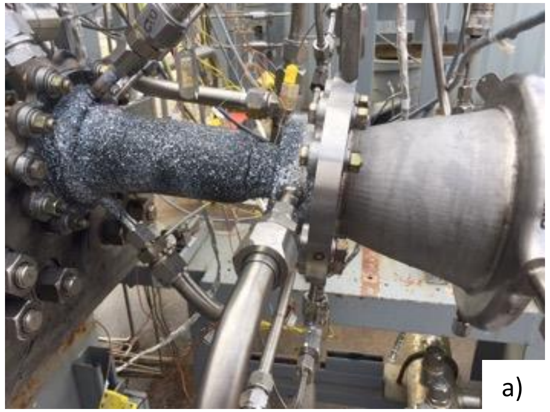
Demonstrate Subscale and Large Scale Hot Fire testing of Multi-material Chamber

- Allows for infusion and increases TRL

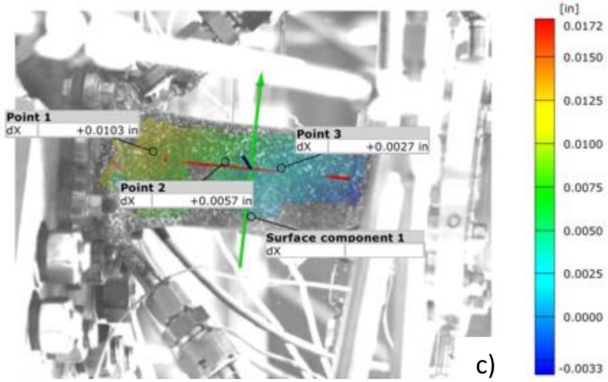
**Industry Involvement in Key Technologies through Public-Private Partnerships**

# Continued Development at NASA with Advanced Manufacturing

NASA is continuing development of combining advanced manufacturing technologies to allow for optimization of multi-materials and weight reductions

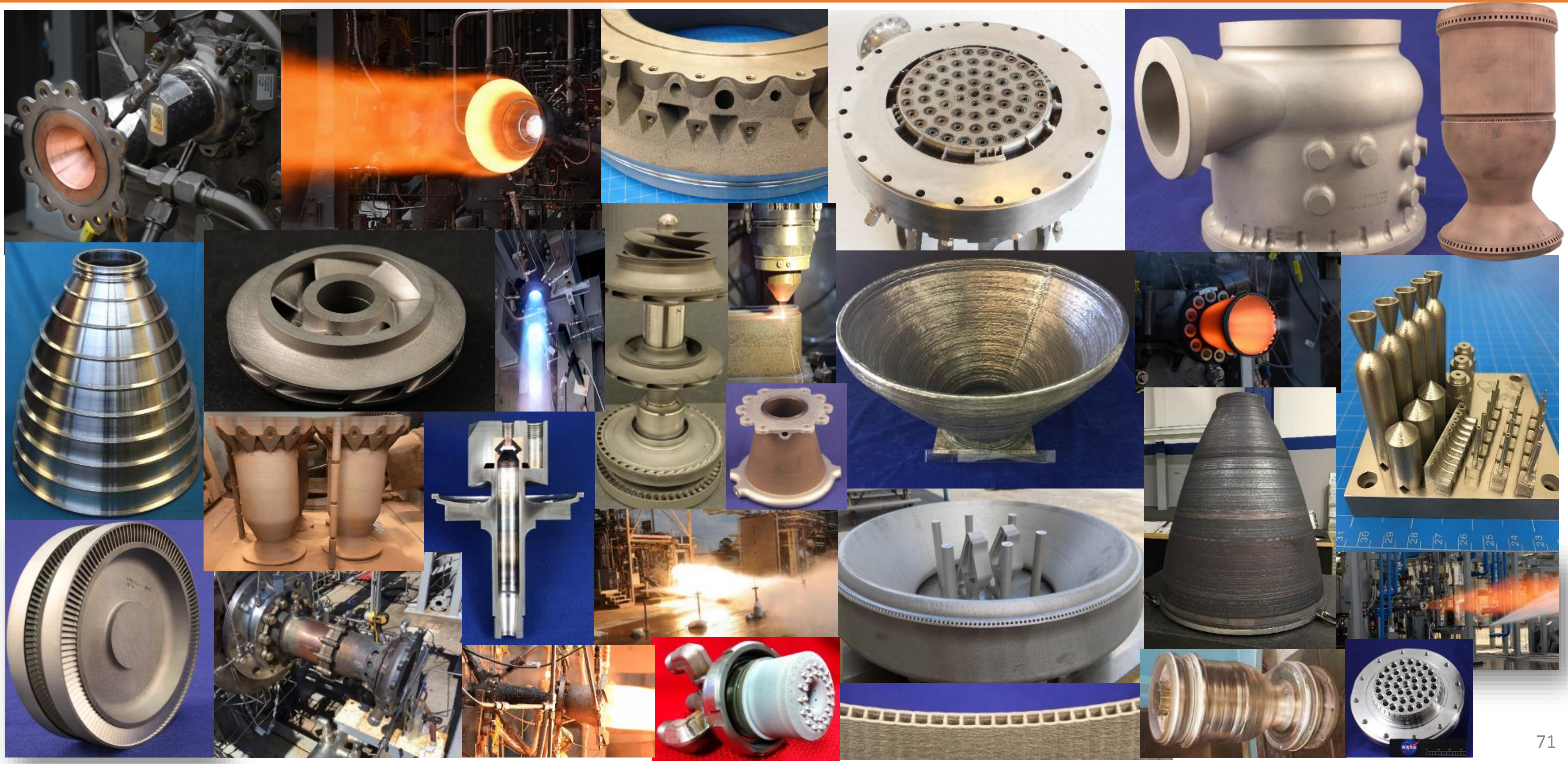




a) Hot-fire testing of composite overwrap chambers and DED nozzles
b) Bimetallic additive manufacturing
c) Advanced imaging technologies to evaluate test performance

# Examples of Additive Propulsion Components



# Additive Manufacturing Questions to Consider
## For Powder-based AM Processes

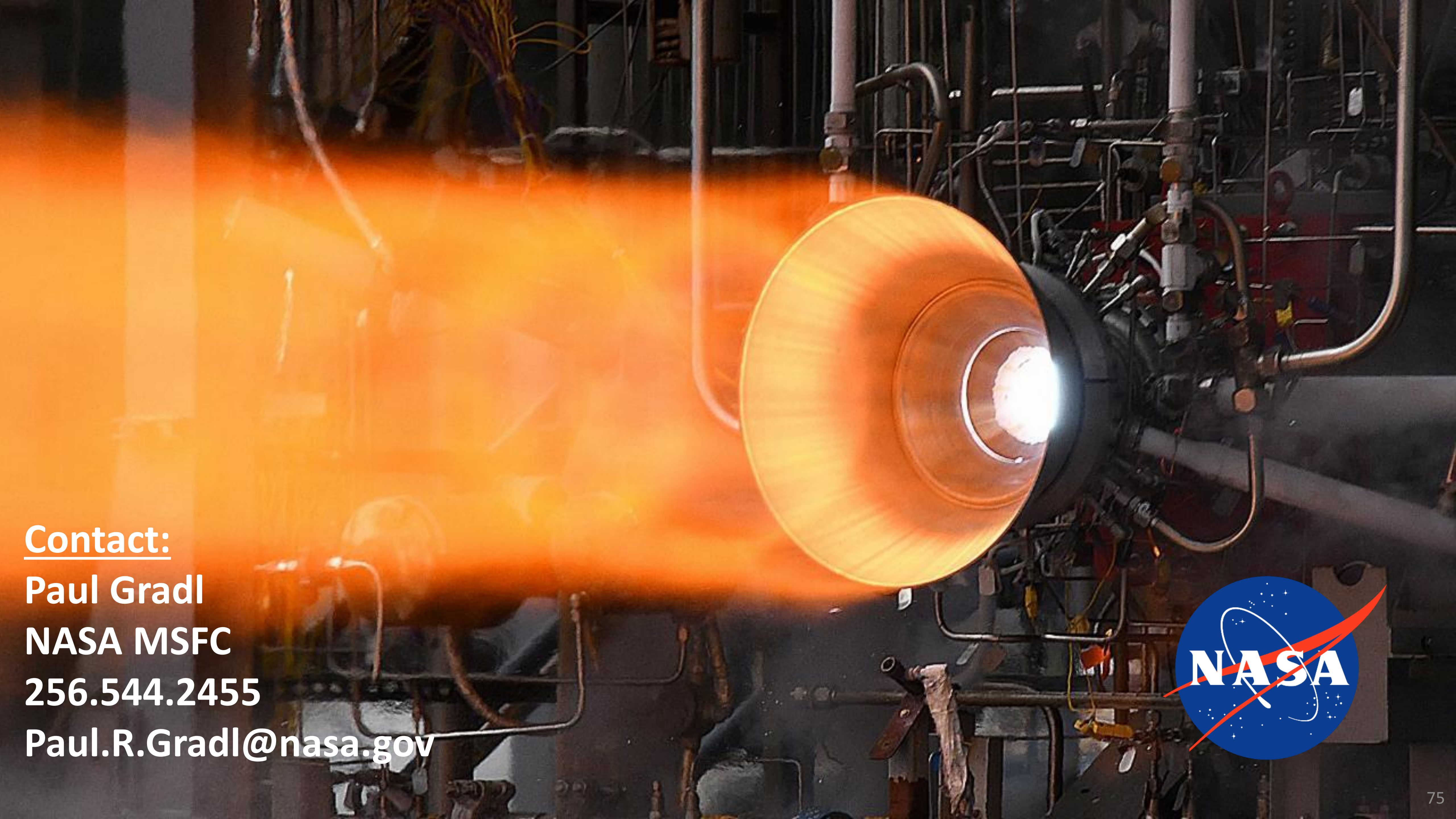
- Should this part be printed or traditionally manufactured?
- What process will be used?
- Is the print accuracy adequate for the design?
- What is the build orientation?
- How am I going to remove all the powder?
- How do I verify powder removal?
- Will support structure be used in the build?
- Are there downstream operations that require fixturing or tooling to integrate in the print design?
- What kind of post machining needs to occur after the print?
- How is this part being removed from the build plate?
- Will there be any material processing after the print?
- What type of material properties do I require?
- What inspections are required to verify integrity of design?

# Summary

- Additive manufacturing and advanced manufacturing must be traded with other manufacturing processes for component designs
- AM has significant advantages for components with complex internal features and for reduction of parts
  - Injectors and combustion chambers are a good use of AM
- High performance materials can still be maintained in design as the AM technology has advanced (ie. copper for chambers)
- Materials must be properly evaluated specific to the design, machine, configuration to have a thorough understanding of design allowables
- Certification of new processes must meet the approach and rigor relative to the design environment and functionality of the design

# Current Focuses in Additive

- Large scale, small feature DED processes
  - Focus on blown powder DED, also investigating WAAM, coldspray
  - Continue development on laser wire DED for channel closeout
  - Materials include: NASA HR-1, JBK-75, GRCop-alloys, new alloys
- Large scale DED processes for forging and casting replacement
  - Manifolds, liners, ducts, complex geometry to reduce machining
- Bimetallic and multi-metallic deposition with a variety of processes
  - Combining L-PBF and DED, and other processes (coldspray)
- New alloy development and/or with new processes (L-PBF and DED)
  - Refractory, Superalloys for specific environments
- Full material characterization and property development (L-PBF and DED)
- Certification of AM processes for flight applications

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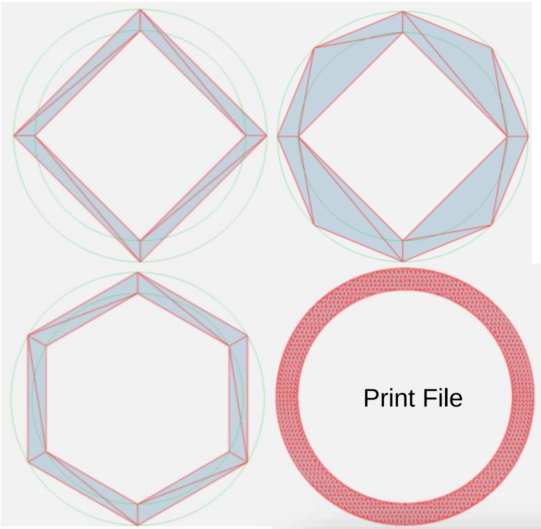
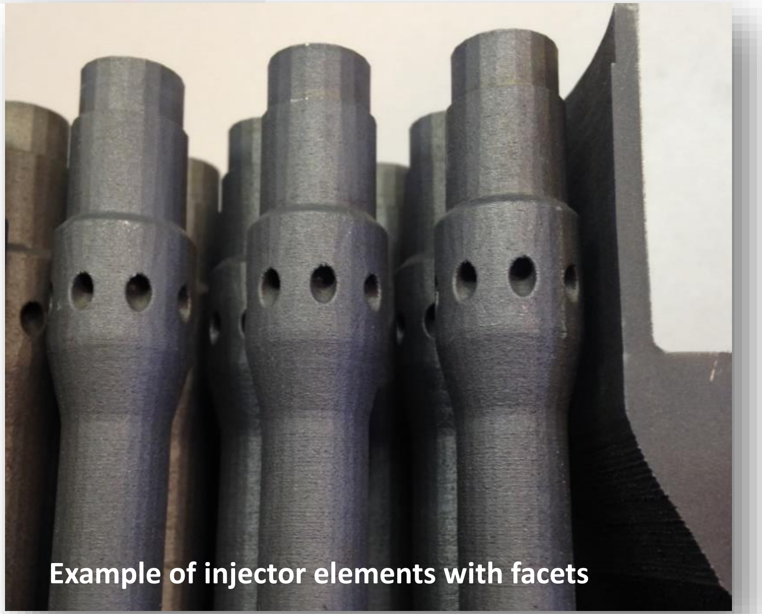
Carpenter
Various MSFC engineering and technician support

# Considerations in Design and Printing

- The printer is going to (attempt to) print geometry based on the CAD model
- Most 3D printers use .stl files (stereolithography)
  - .stl files are flat triangles used to approximate CAD geometry
  - The .stl file is sliced into layers to generate the laser toolpath / code
- Have observed significant differences in surfaces, although based on geometric features
- Finer resolution files are significantly larger and machines can be limited on toolpath code

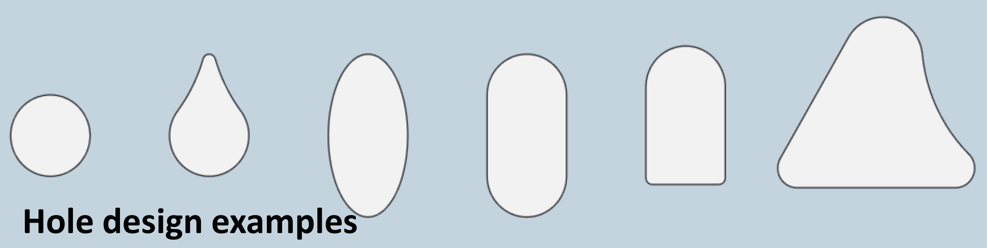
Same CAD file with different export parameters





Example of injector elements with facets

# Considerations in Design and Printing

- Angled feature designs are limited (measured from horizontal)
  - Features <45º normally require support
  - Features >45º normally do not require support
  - Consider features in all dimensions
- Holes cannot be printed as true holes if larger diameter
  - Largest unsupported hole ~ .250”
  - Smallest hole/feature ~.030”
- Overhangs can be created, but require supports (and subsequent removal)

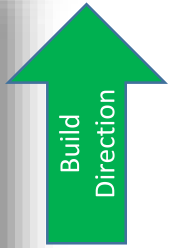

Hole design examples

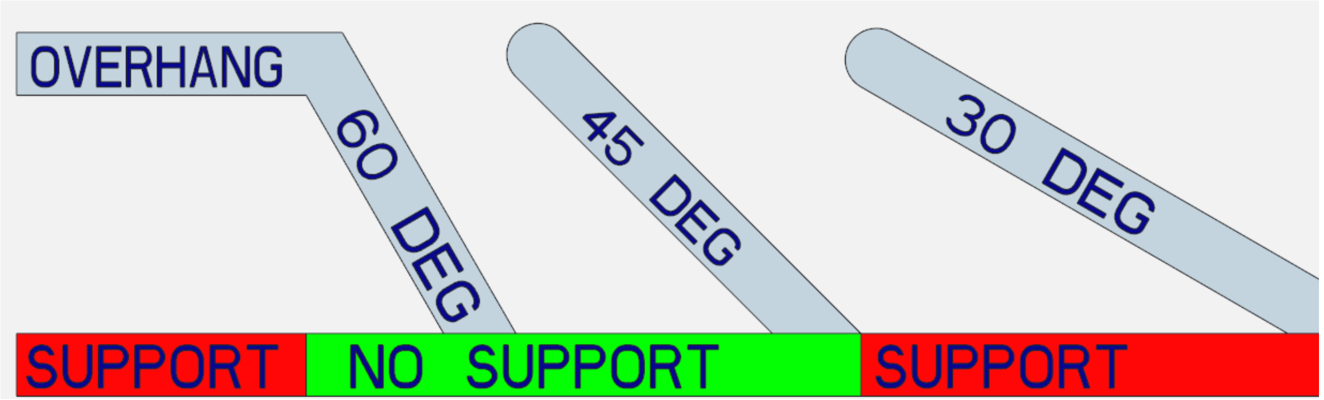

Hole examples


Hole examples


Manifold design


Design support needed for flange

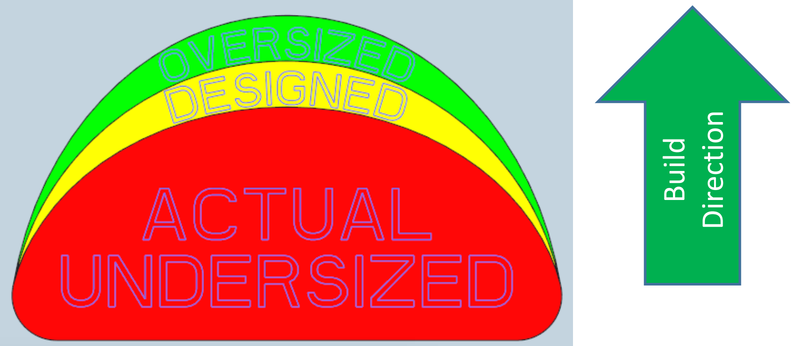


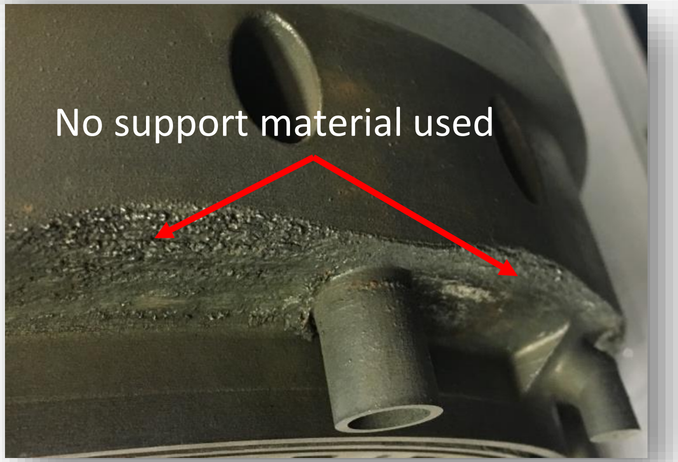
Angled wall design example

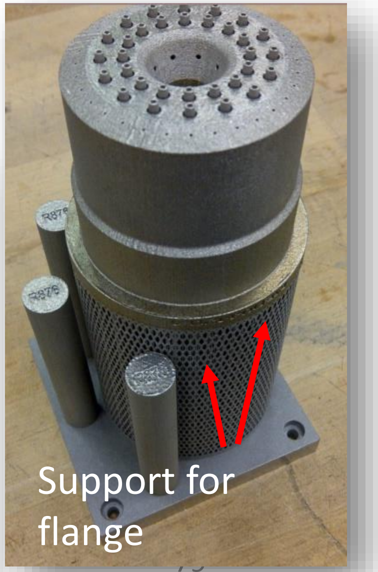
# Considerations in Design and Printing

- Design and analysis needs to consider surface finishes for internal and external features
- Internal passages may need to be oversized to account for burn-thru or undersized hole
- Support material should be understood in design phase
  - Placement of support material is important
  - How support material is removed is equally important
  - Ask your operator or vendor
  - Support material highly dependent on print orientation





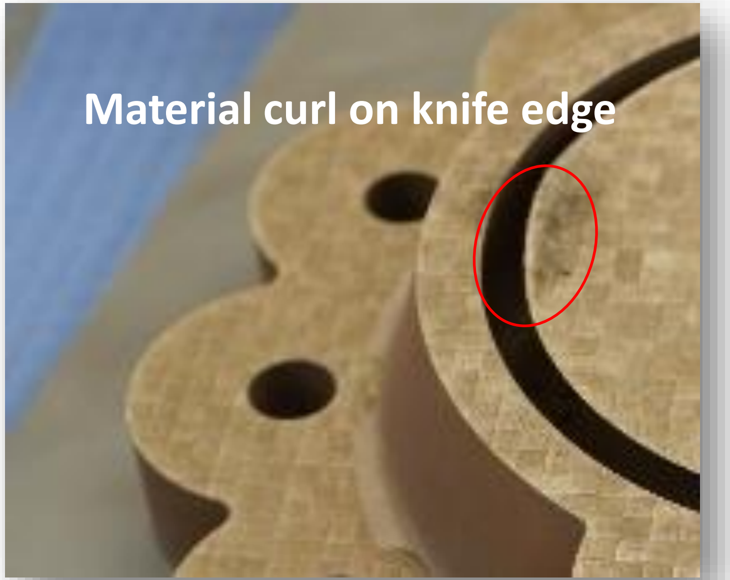


# Considerations during Pre-processing and Printing

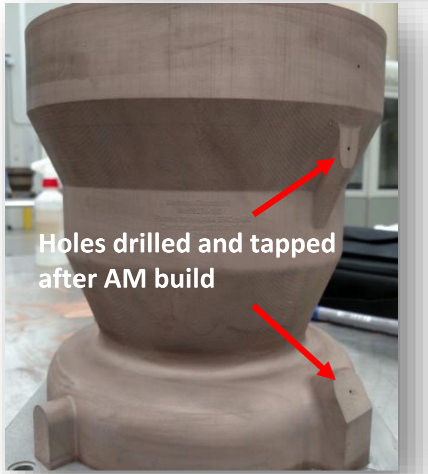
- Heat control is critical and can cause significant deformations or failures
  - May be driven by original design (too thick or thermal gradients too high across varying cross sections)
  - May be impacted by adjacent parts or witness specimens
- Material curl caused by coater arm damage
  - Based on knife edges during design
- Stops and starts are also common in 3D prints, causes knit lines
  - Refill of powder in dose chamber
  - Issue observed that requires visual

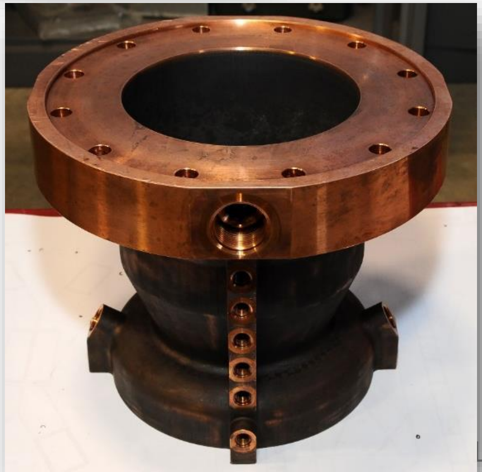




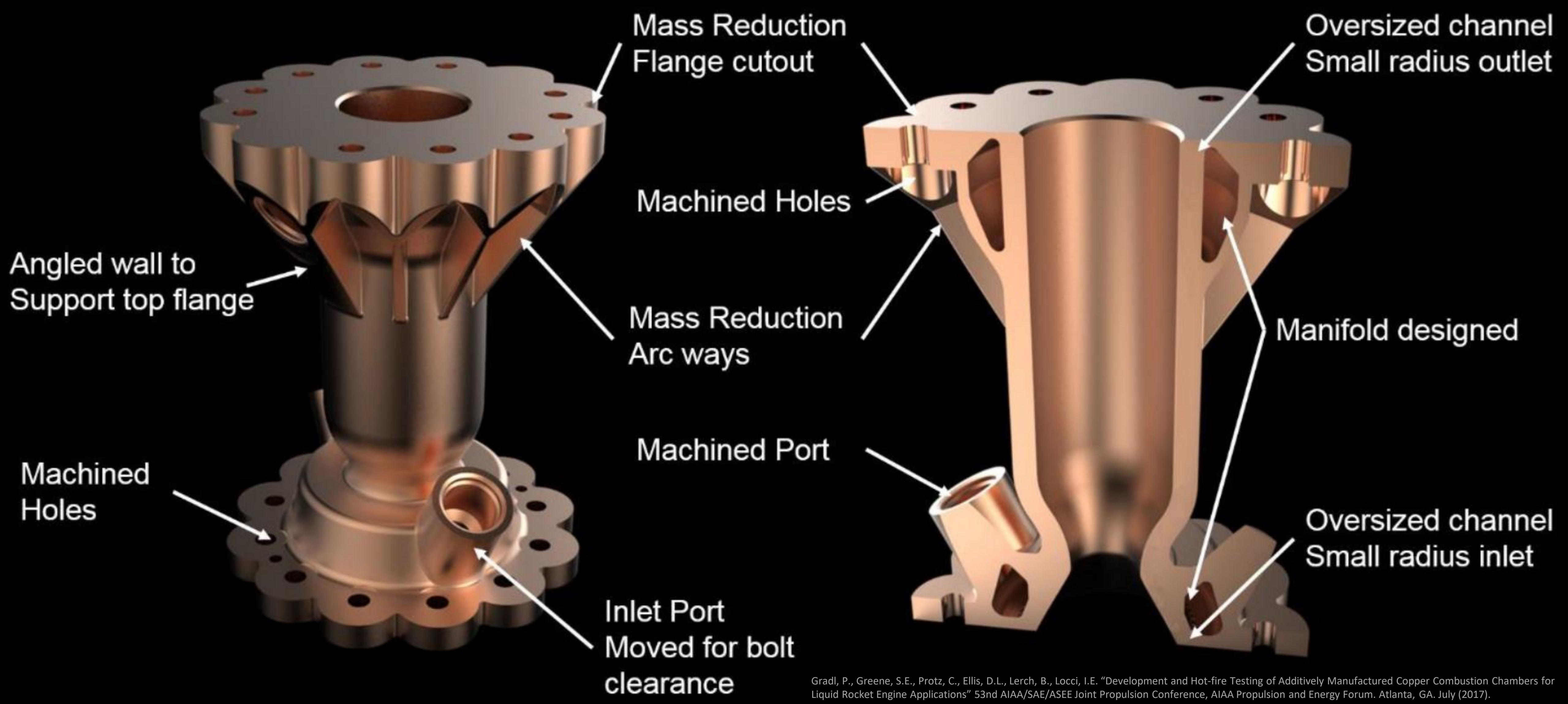
# Considerations during Design and Post-Processing

- **Geometric Dimensioning and Tolerancing (GD&T) needs to be considered during design for ease of post-processing**
    - Cylinders for better positional tolerance at feature level
    - Grooved for axial location
    - Flat surfaces for datums
    - Extra holes for powder removal
    - Additional stock material for critical features that will be post-machined
- **Holes only when required or in softer materials**
    - Existing printed holes can cause machine tools to "walk"
    - Do not print threads; post-machine
    - Undersize holes for reaming and tapping

# Sample Design of Chamber




Gradl, P., Greene, S.E., Protz, C., Ellis, D.L., Lerch, B., Locci, I.E. “Development and Hot-fire Testing of Additively Manufactured Copper Combustion Chambers for Liquid Rocket Engine Applications” 53nd AIAA/SAE/ASEE Joint Propulsion Conference, AIAA Propulsion and Energy Forum. Atlanta, GA. July (2017).

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