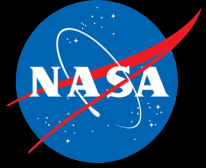




# EXPLORE

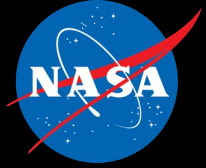
*Alison Park*  
Députy Tech Fellow – NASA Engineering and Safety Center  
Hawaii HTDC/NASA Mfg Tech Talk | Oct '24, 2023 | Virtual

**Additive Manufacturing at NASA**



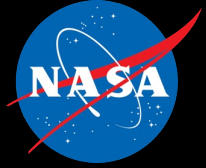
# Executive Summary of Today's Presentation

*Additive Manufacturing (AM) is certainly changing the space industry and providing new opportunities to travel to low earth orbit and explore our universe. New design opportunities – not previously possible – for new high performance metal alloys, light-weighting, managing thermal, structural, and dynamic loads are being enabled by AM. This presentation will showcase the vast portfolio of NASA's AM activities in the last 12 years; transportation from Earth to Destination, Habitat at Destination, Lander from Station to Surface, and Science mission spacecrafts. NASA's technical excellence is being leveraged heavily in the AM community thru collaborative projects, partnership agreements, tech transfer program. Challenges as well as opportunities will be discussed.*



# Topics

- What is Additive Manufacturing (AM)
- When does it make big impacts in using AM and what are the current challenges
- What's NASA doing in AM
- What's Space Industry is doing in AM
- What are NASA's roles in context of AM
  - How NASA's AM tech excellence is being leveraged via partnership opportunities



# Speaker Introduction

## Alison Park – Deputy Tech Fellow at NASA

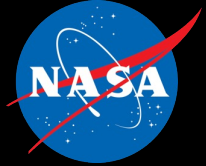


Works at NASA Chief Engineer's Office – NASA Engineering and Safety Center

Responsible for safe implementation of Additively Manufactured Hardware for critical NASA missions – AM Qualification/Certification and Flight Rationale

Being involved in Additive Technology Innovation and Maturation activities around the agency

Big fan of sharing knowledge, working together for rapid (but safe) implementation of AM technology

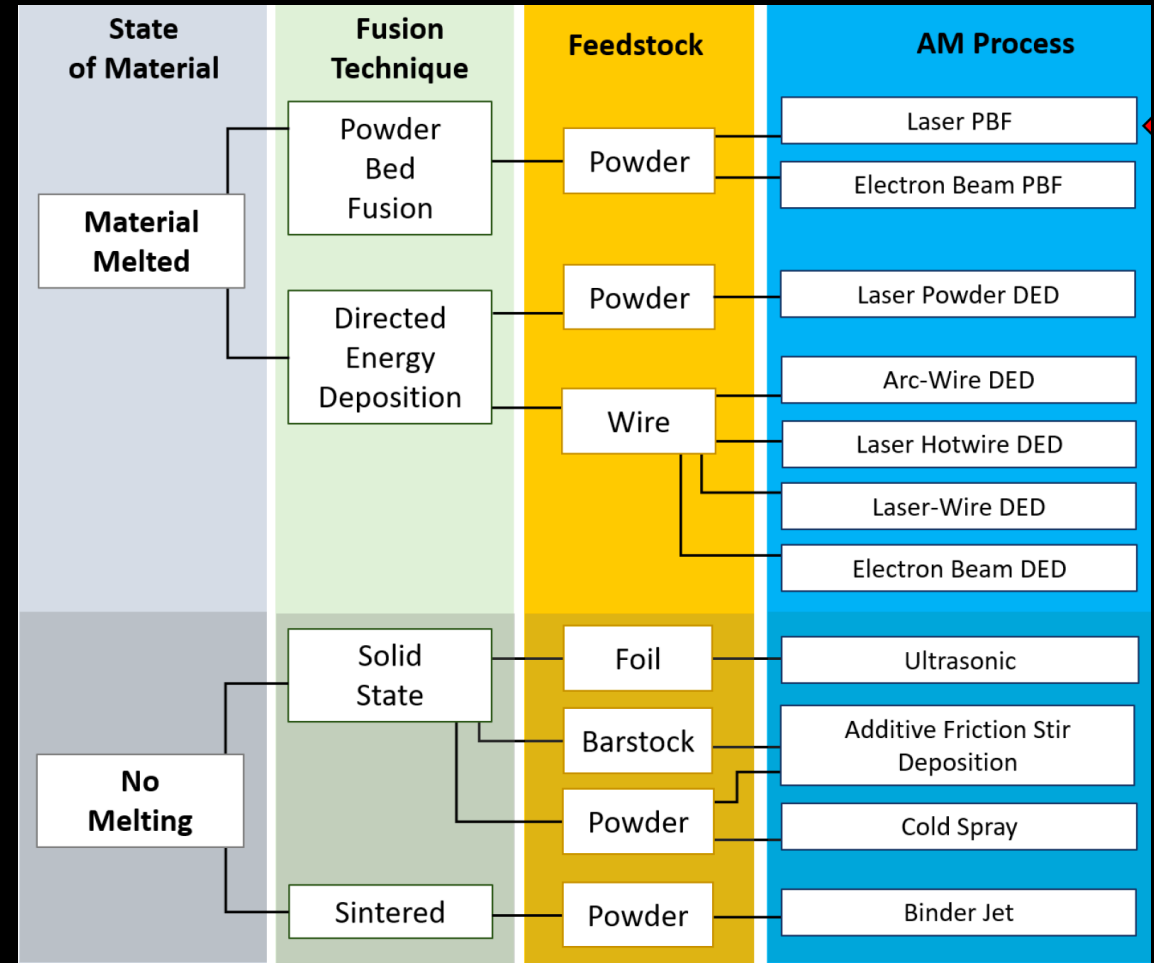


# Additive Manufacturing (AM)

## Definition:

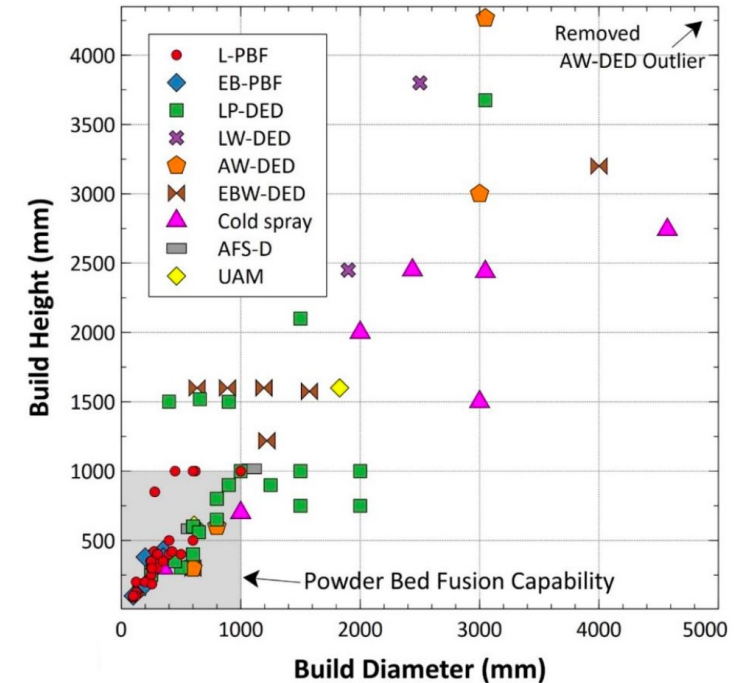
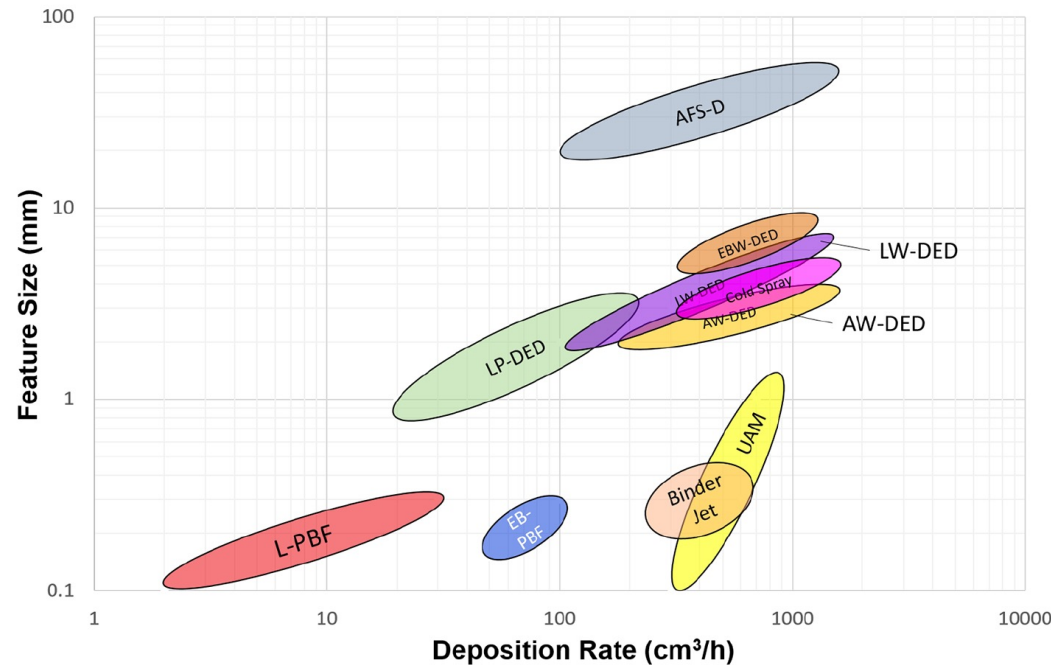
Process of joining materials to make parts from three dimensional model data, usually layer upon layer

AM processes =  
Material feedstock +  
Energy Source



Excerpt from "Metal Additive Manufacturing for Propulsion Applications"  
AIAA Progress in Astronautics and Aeronautics Book Serie  
P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

# Things to consider to pick the right AM Process



Complexity of Features

Scale of Hardware

Material Physics

Cost

Material Efficiency

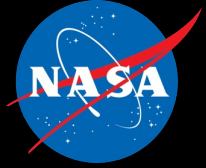
Speed of Process

Material Properties

Internal Geometry

Availability

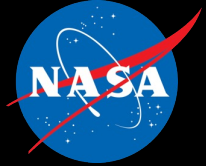
Post Processing



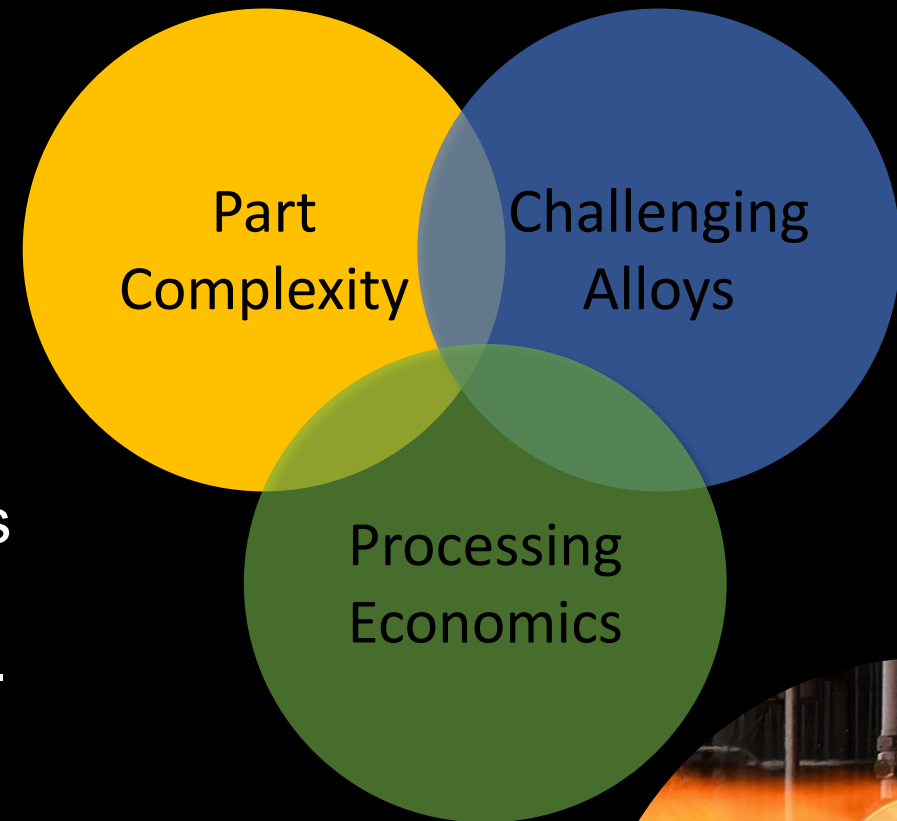
# When to Use Additive Manufacturing

- ~~• You have a fully designed part~~
  - ~~• You need it to be good~~
  - ~~• You need it to be cheap~~
  - ~~• You need it quickly~~
- Recipe for Disappointment
- You need to prototype and/or iterate a *lot*
  - You need an *extremely* optimized part (i.e., topology optimization)
  - You can't easily make the part using legacy "subtractive manufacturing"
  - You need a part with a high "buy to fly" ratio
  - You literally *can't* make it any other way
  - You want to decrease part count

# The Case for AM in Rocket Propulsion



- Metallic AM can provide significant advantages for lead time and cost over traditional manufacturing for rocket engines.
  - Lead times reduced by 2-10x
  - Cost reduced by more than 50%
- Complexity is inherent in liquid rocket engines and AM provides new designs, part consolidation, 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.



Excerpt from "Metal Additive Manufacturing for Propulsion Applications"  
AIAA Progress in Astronautics and Aeronautics Book Series  
P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

# Examples of NASA's AM Dev Work for Rocket Propulsion



## Main Fuel Valve

Part reduction: 5 to 1  
Successfully tested



## Fuel Turbopump

Schedule reduction by 45%  
Part reduction: 40 to 22  
Tested to 90,000 RPM



## Combustion Chamber

Schedule Reduction: > 50%  
Bimetallic L-PBF/DED  
Tested to 100%



## Regen Nozzle

## Oxidizer Turbopump

### Bypass Valve

Part reduction: 5 to 1

## Main Oxidizer Valve

Part reduction: 6 to 1  
Successfully tested



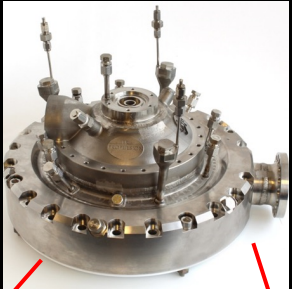
## Oxidizer Turbopump

Part reduction: 80 to 41  
Tested to 40,000 RPM.



## Injector

Cost Reduction: 30%  
Part reduction: 252 to 6  
Eliminated braze joints  
Tested to 100%



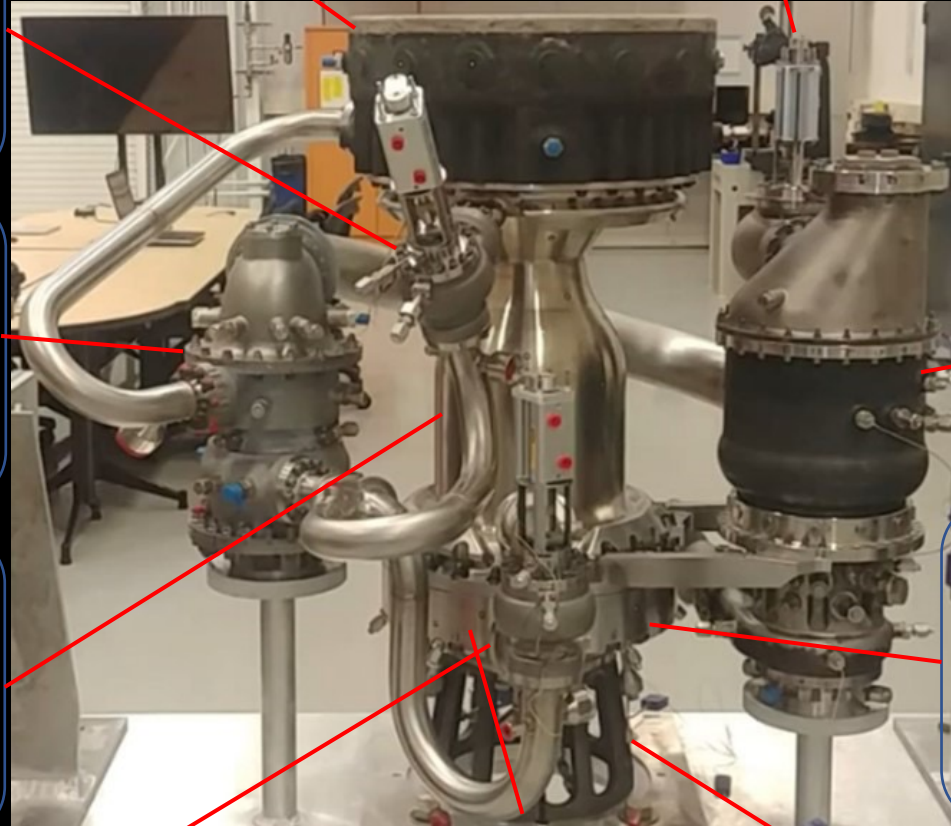
## Mixer

Part reduction: 8 to 2

## Coolant Control Valve

Part reduction: 5 to 1

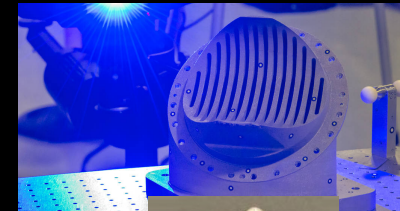
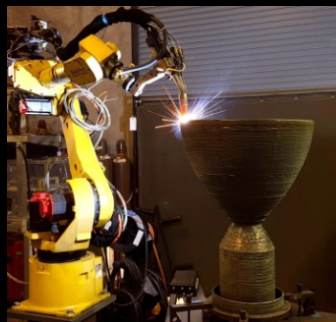
## Thrust Structure



# Examples of NASA's AM Dev Work for Rocket Propulsion



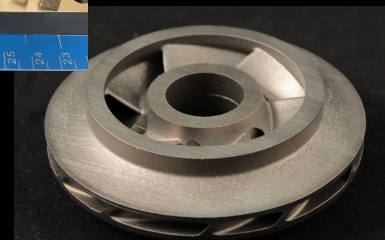
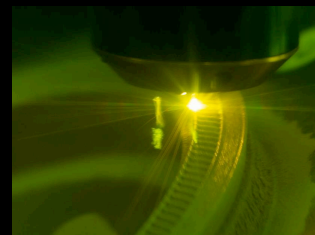
Laser Powder Directed  
Energy Deposition  
(LP-DED)



Laser Powder Bed Fusion  
(L-PBF) GRCop42. *Courtesy  
Dr. Dave Ellis (NASA GRC).*



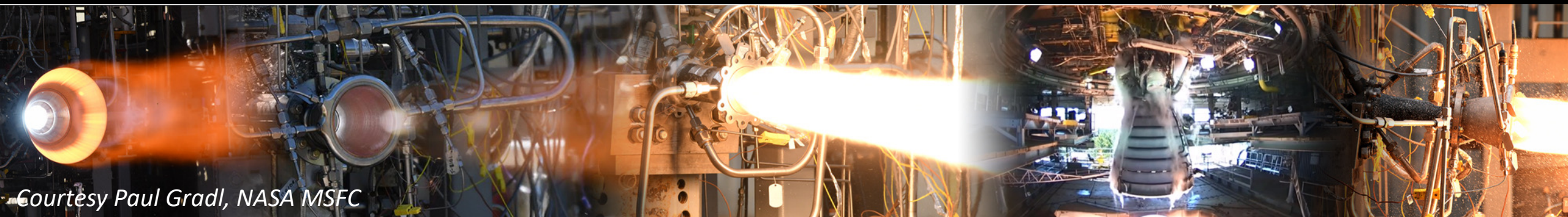
Hybrid bi-  
metallic AM



L-PBF AM turbomachinery.



GRX-810 combustor. *Courtesy  
Dr. Tim Smith (NASA GRC).*



*Courtesy Paul Gradl, NASA MSFC*

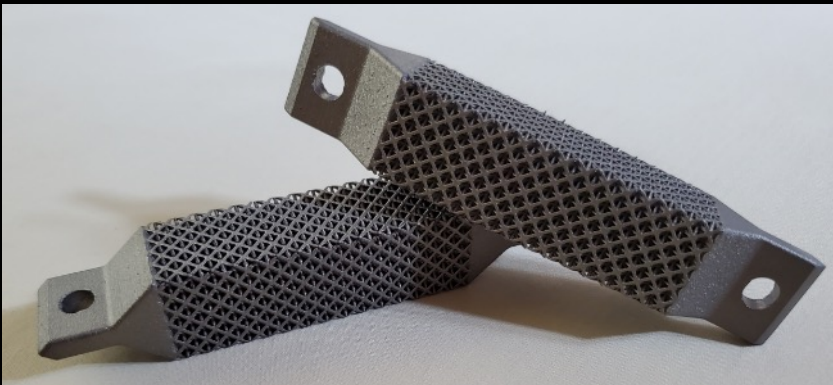
# NASA's AM Dev Work for Cryogenic Fluid Management (CFM)



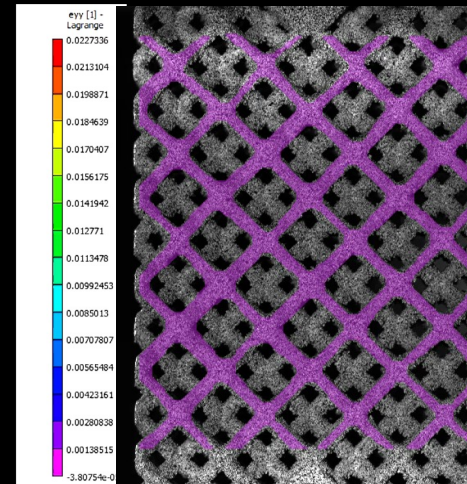
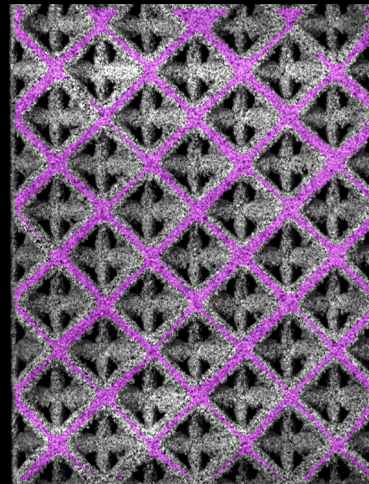
- Long-Duration Propellant Storage
  - LH<sub>2</sub> at 20 K.
  - LOX at 90 K.
- Component Optimization
  - Heat Exchangers
  - Augmented Injectors
  - Tanks with integral cooling channels
  - Galleries
  - Sponges
  - Lattice Struts



L-PBF AM IN718 TVS Augmented Injector. *Courtesy Travis Belcher (NASA MSFC).*

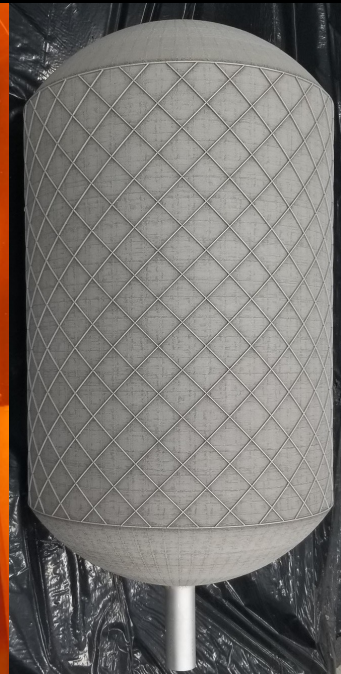
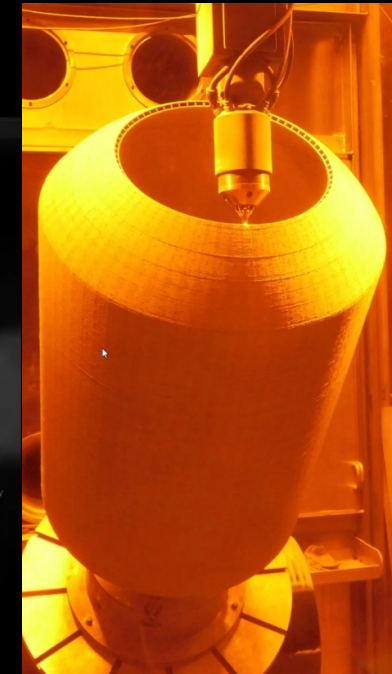


L-PBF AM Ti6Al4V Cryo Lattice Struts. *Courtesy Travis Belcher (NASA MSFC).*



**Node** strain localization of Octet-Truss-30%RD (left) and **Strut** strain localization of Rhombic Dodecahedron (20 %RD),  $\alpha = 4$  mm, IN718 in SR+HIP+SA condition.

*Courtesy Dr. Kavan Hazeli (University of Arizona).*



LP-DED AM A6061-RAM2 propellant tank with integral cooling channels. *Courtesy RPM Inc.*

# NASA's AM Dev Work for Nuclear Power Systems



- Heat Pipes

- L-PBF AM Ni- or Nb- base
- Surface conformal
- Integrated wicking structures

- Stirling Alternator

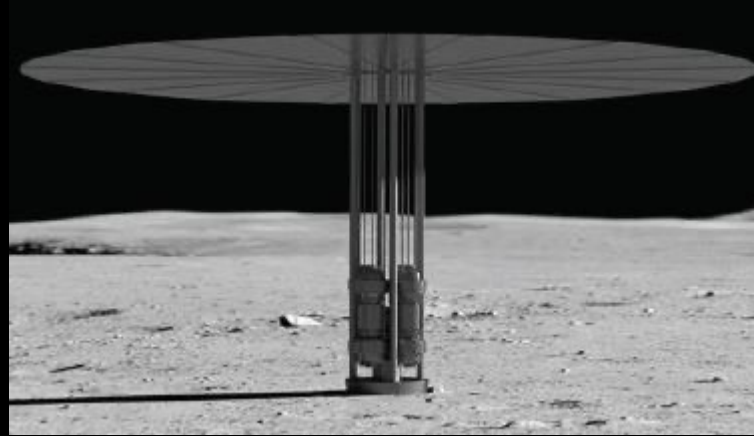
- Lattice Regenerator from L-PBF AM Tungsten

- Fuel

- Additive Friction Stir Deposition (AFS-D) of depleted U-8wt%Mo

- Shielding

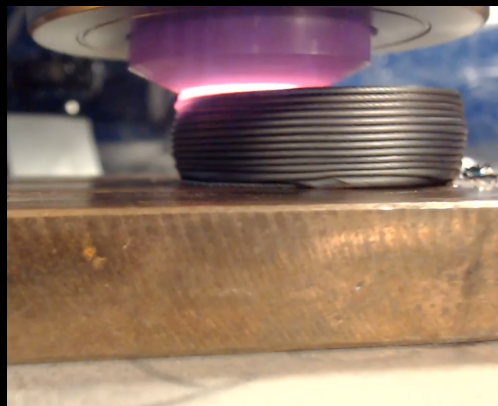
- Multi-material
- Hybrid AM
- Multi-physics topology optimization



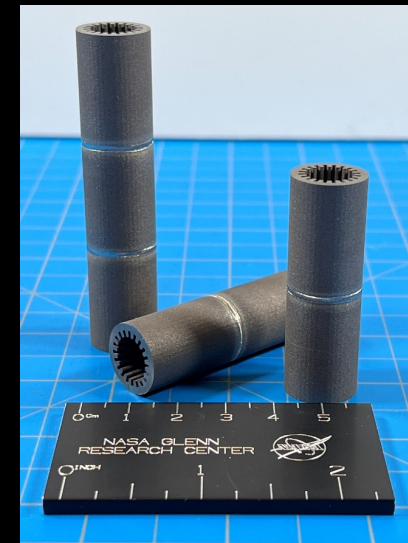
10 kWe surface power reactor concept



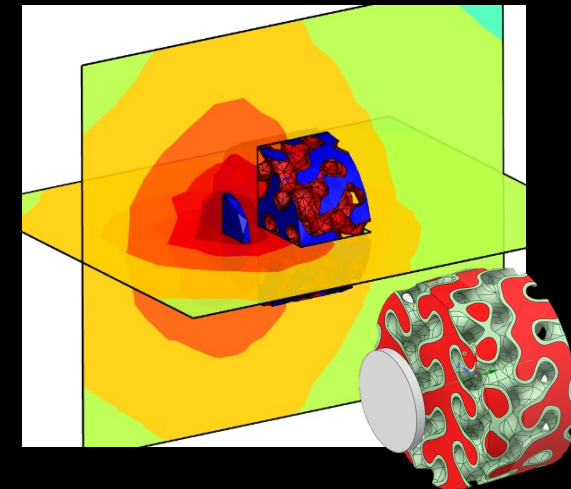
L-PBF AM IN718 integrated heat pipe funnels



AFS-D of dU-8Mo.



L-PBF AM C103 heat pipe segments. *Courtesy Dr. Justin Milner (NASA GRC).*



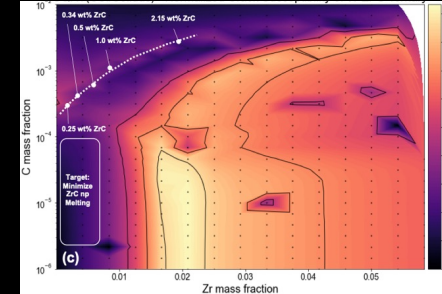
Hybrid AM shield topology optimized for neutron/ $\gamma$ -ray radiation attenuation, loads, and active cooling. *Courtesy Dr. Jarvis Caffrey (NASA MSFC).*

# NASA's AM Dev Work in Refractory Metal AM

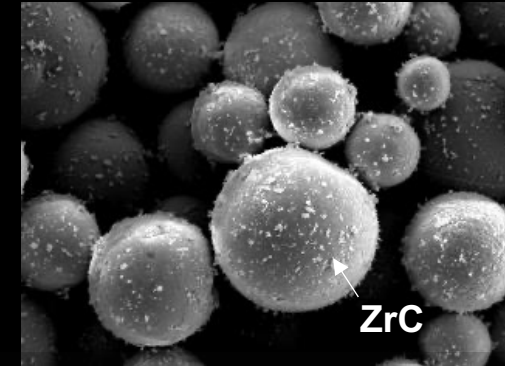
- Refractory metals for extreme high temperatures
  - Reaction Control System (RCS): chambers
  - Space Nuclear Power & Propulsion: clad, structure, heat pipes
  - Hypergolic / green propulsion: chambers and catalyst.
  - Electric propulsion: grids
  - Hypersonics: wing leading edges

- Development Areas:

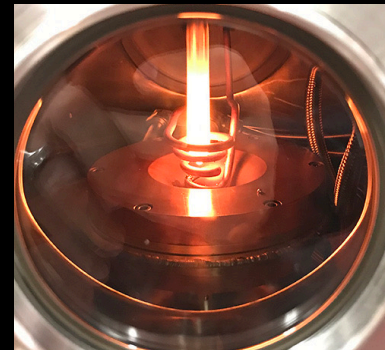
1. ICME, Simulation, Modeling
2. Feedstock Production
3. Parameter Development / Part Prod.
4. Heat Treatment & Joining
5. Novel Non-Destructive Evaluation
6. Surface Finishing & Coatings
7. Property Characterization
8. Component Test



Crack susceptibility modeling.  
 Courtesy Carly Romnes (Univ IL, Urbana-Champaign).



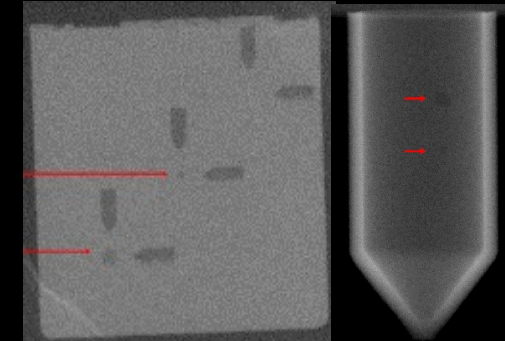
Mo with ZrC nano-powder. *Courtesy Dr. Fernando Reyes (NASA MSFC).*



EIGA of Mo44Re rod.



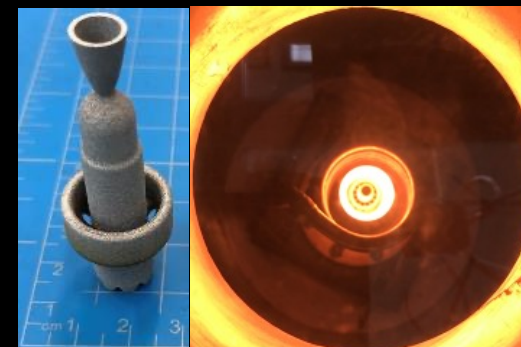
LP-DED AM C103 development.  
 Courtesy Univ. of Texas, El Paso (UTEP).



Neutron radiograph of L-PBF W with engineered defects. *Courtesy Phoenix.*



L-PBF AM Mo RCS Chamber

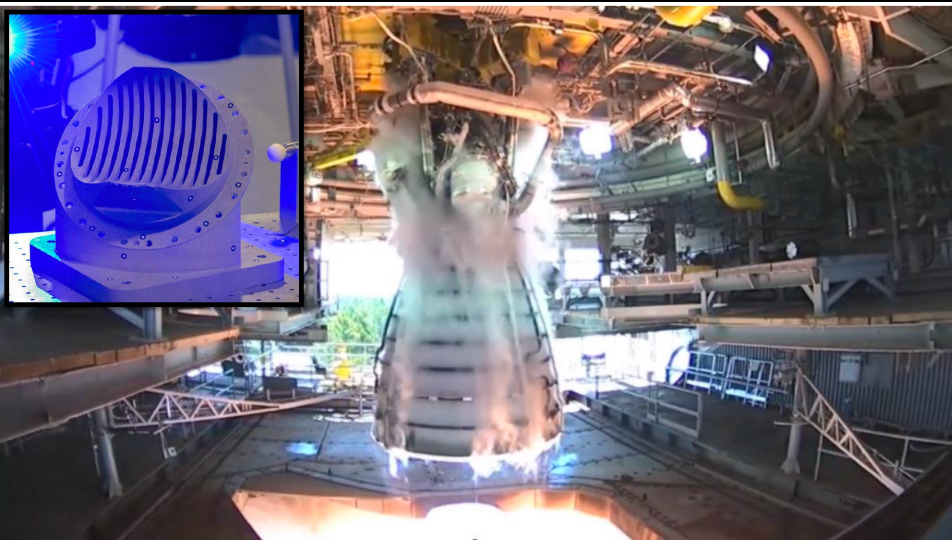


L-PBF AM W chamber test at 1900 °C.  
 Courtesy Dr. Jamelle Williams (NASA MSFC).



L-PBF AM C103 Nozzle Extension.  
 Courtesy Brandon Colon, UTEP.

# Great Insertion of AM in Spaceflight – Commercial Space



Credit: GE  
GE Aviation fuel nozzle (L-PBF)

Titanium pylon rib for F-15 replacements using DED (2003)



Credit: Norsk Titanium

Ti6Al4V propellant tank using electron beam wire DED

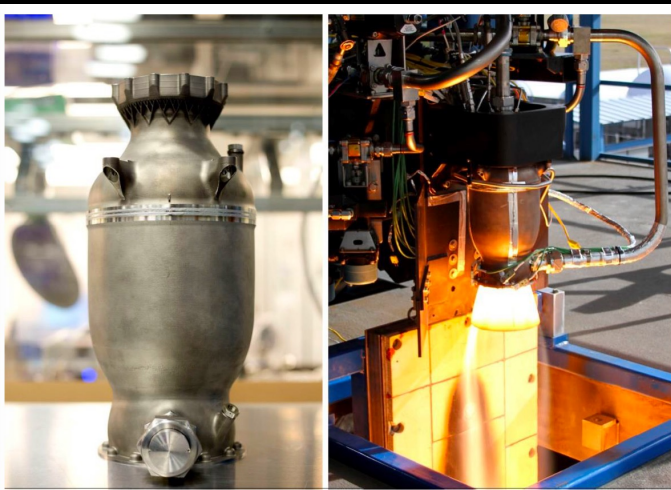


J-2X Rocket Engine Gas Generator Duct:  
a) Traditional tooling, b) L-PBF part



Credit: Lockheed Martin

Excerpt from Online AM Training "Metal Additive Manufacturing for Propulsion Applications"  
AIAA Progress in Astronautics and Aeronautics Book Serie  
P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

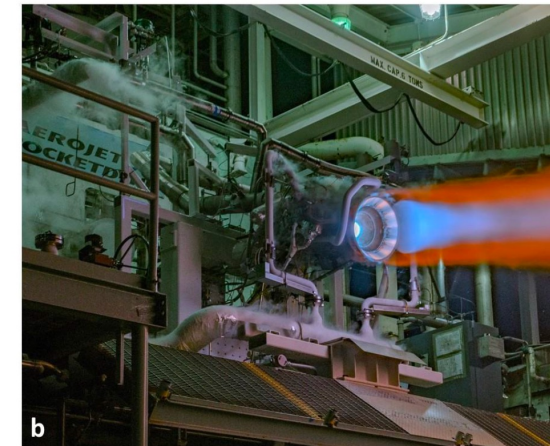


Credit: SpaceX

SpaceX SuperDraco Inconel 718 combustion chamber using Inconel 718 L-PBF

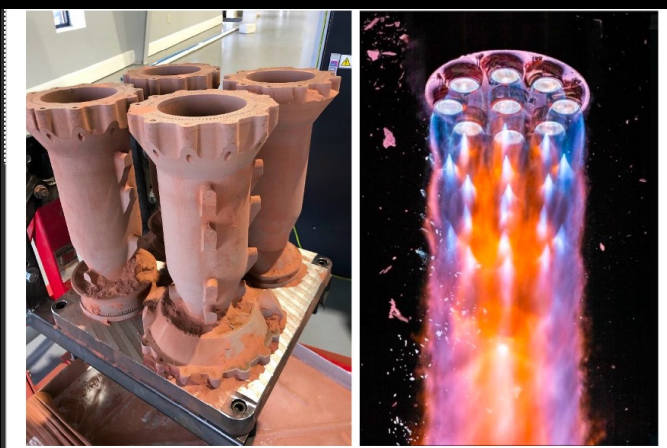


a



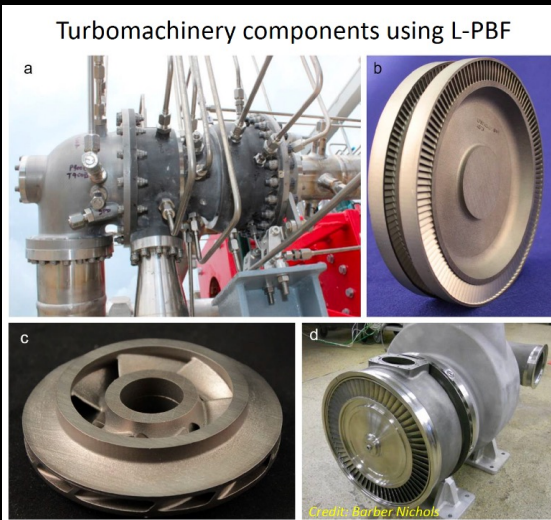
Credit: LG Harris Aerojet Rocketdyne

Aerojet Rocketdyne RL-10CX All-additive thrust chamber assembly



Credit: Relativity Space

Relativity Space – DED for tanks and L-PBF engine components, including NASA alloy GRCo-42



Turbomachinery components using L-PBF

Credit: Barber Nichols

Excerpt from Online AM Training "Metal Additive Manufacturing for Propulsion Applications"  
 AIAA Progress in Astronautics and Aeronautics Book Serie  
 P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).



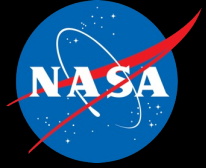
Credit: Rocket Lab / Andrews Burns and Simon Moffatt

Rocket Lab Rutherford engine using L-PBF Inconel 718 combustion chamber



Credit: Vast / Launcher

Launcher Space L-PBF CuCrZr 1 meter height combustion chamber



# In-Space Manufacturing (ISM)

## On-Demand Manufacturing & Recycling of Plastics

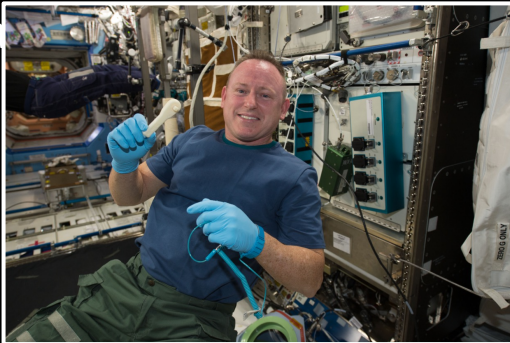
- 3D printing and recycling system designed to repeatedly recycle plastic materials into feedstock for manufacturing in the microgravity environment of the ISS.

## On-Demand Manufacturing of Metal

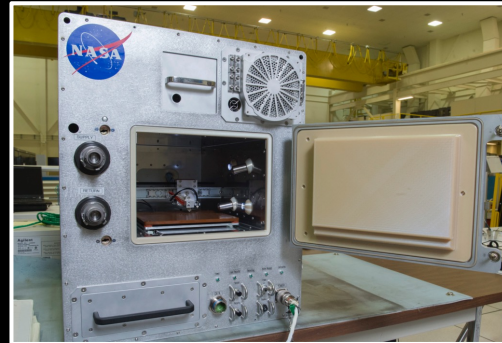
- Additive and subtractive manufacturing systems for creating metal parts on demand.

## On-Demand Manufacturing of Electronics

- Ability to fabricate electronics during missions, such as crew and structural monitoring systems



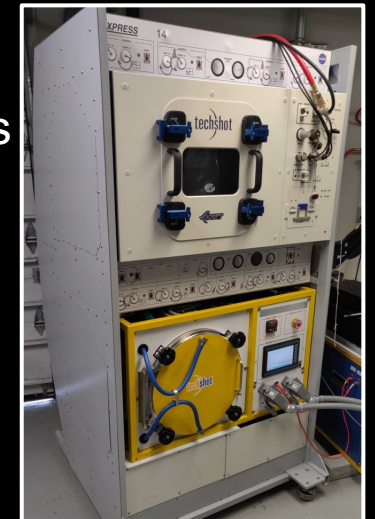
*First 3D printer in space, 2014  
ISS Demonstration*



*Refabricator ISS  
Demonstration*



*Redwire Commercial ISS Additive  
Manufacturing Facility (AMF)*



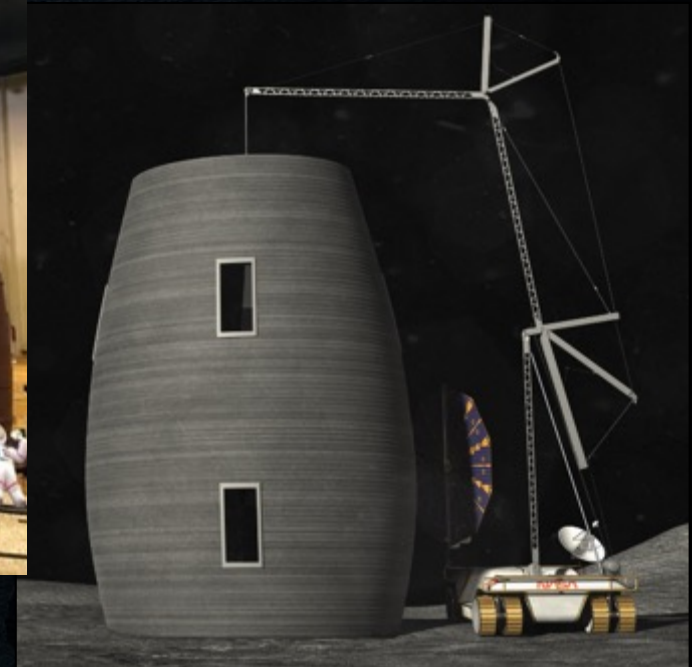
*Techshot Fabrication  
Laboratory*

# Moon-to Mars Planetary Autonomous Construction Technology (MMPACT)

Develop, deliver, and demonstrate capabilities to:

- Protect crew and hardware
- Build infrastructure
- Construct landing pads, habitats, shelters, roadways, berms and blast shields using lunar regolith-based materials

Partners: ICON, SEArch+, USAF, Defense Innovation Unit, Texas Air National Guard



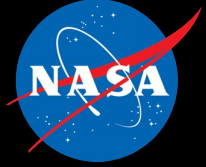


NASA is moving from Low Earth paradigm to Deep Space paradigm

Additively manufactured parts are already being used for NASA programs in critical applications – “ready to fly”

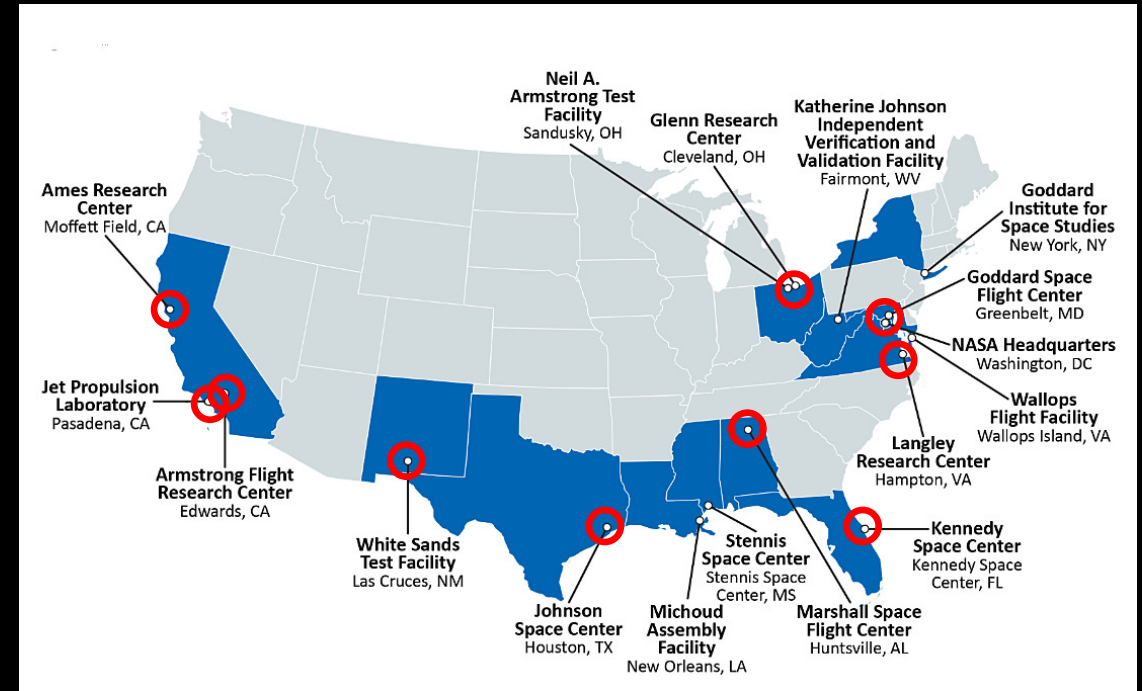
- Transportation from Earth to Destination
- Stations at Destination
- Lander from Station to Surface
- Spacecraft for Science Missions
- Sample Return from Mars

Human exploration of space, especially deep space, requires extreme reliability

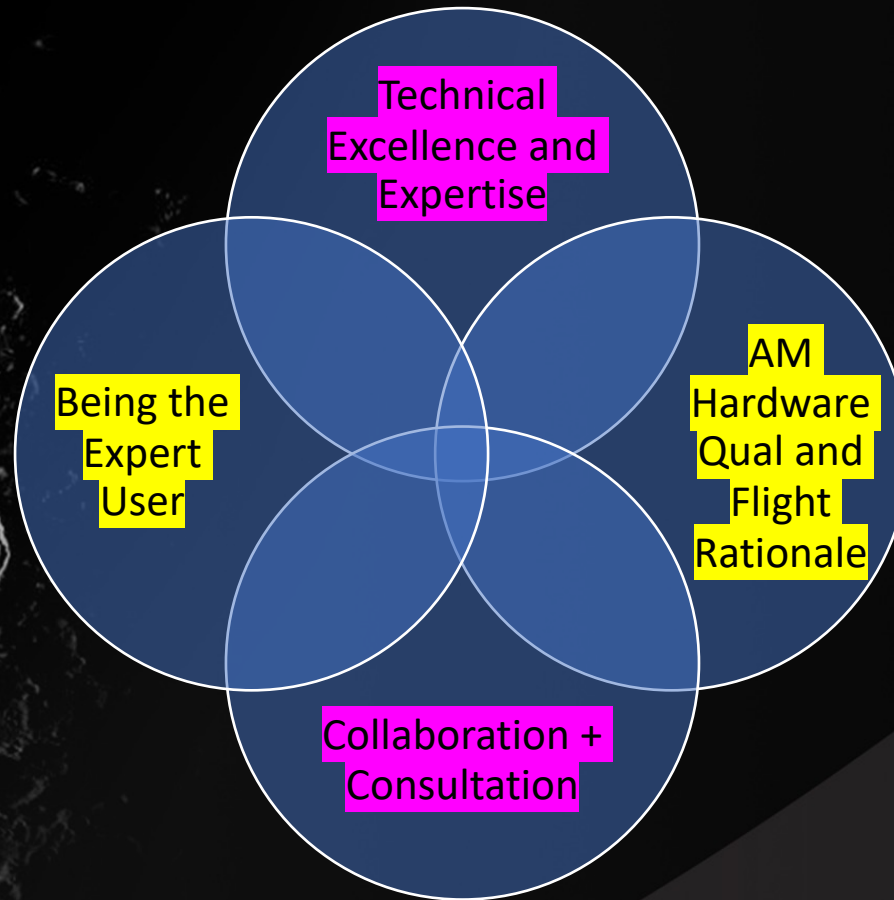
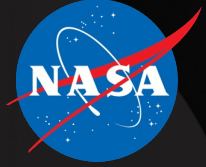


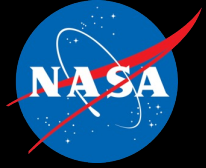
# Additive Manufacturing at NASA

- Human-rated spaceflight
  - JSC, KSC, MSFC
- Space Science
  - GSFC, JPL
- Aeronautics
  - LaRC, GRC, ARC
- “NASA is an user of AM” means...
  - NASA engineers utilizing AM processes to make hardware = NASA has the design authority
  - NASA procuring sub-system (rocket engine) or system (lunar lander spacecraft) from a commercial vendor/partner = NASA does not have the design authority; vendor does
- End goal → **Safe and successful missions**



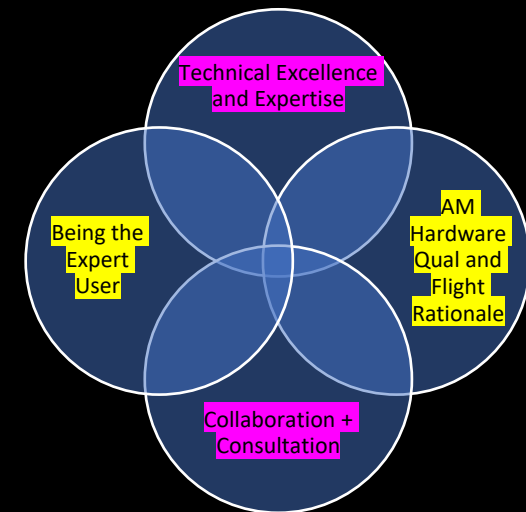
# NASA's Roles in Additive Manufacturing



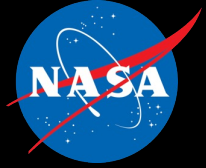


# NASA's Roles in AM

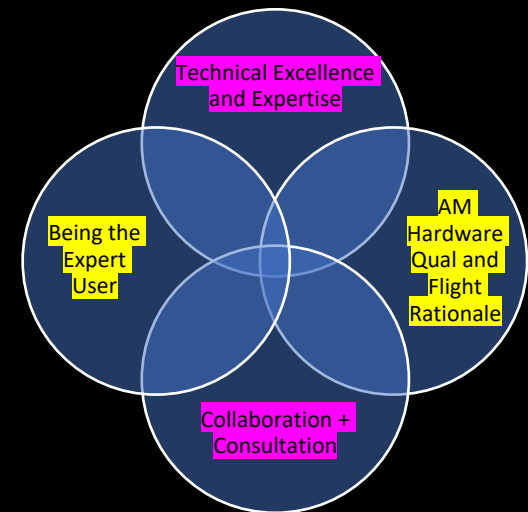
- Technical Excellence and Expertise
  - Propulsion systems and component development enabled by AM
  - Novel Alloy Development – refractory, MEA, OSD, GRCop
  - Extreme environment material characterization
    - Very cold and hot temperature
    - Hypergolic compatibility
    - Flammability
    - Corrosion
- Integrated Computational Materials Engineering
- Damage Tolerance
- Failure Analysis
- "In Space Manufacturing"
- Lunar construction demo
- AI enabled AM Design



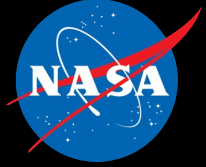
# NASA's Roles in AM



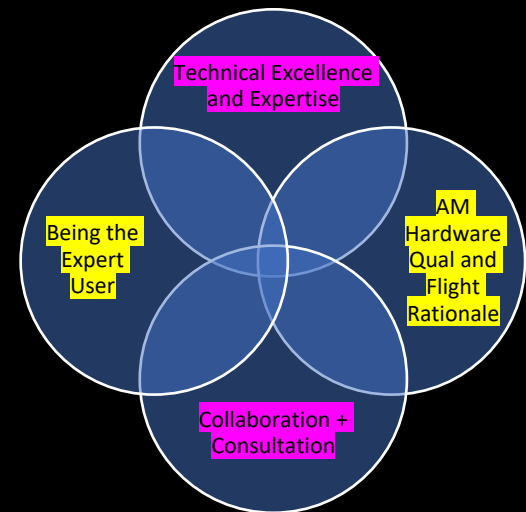
- AM Hardware Qual and Flight Cert Rationale
  - NASA-STD-6030 and 6033
  - When these are cited in your NASA program, you get to "sit down" with us to negotiate on the tailored version of 6030 and 6033 to meet the intent of the requirements
  - BUT, we'd like to get to know you earlier than that
  - Active engagement with commercial space industry as well as other US Government Agencies with AM Policy governing body
  - Risks are defined clearly and communicated to Tech Authority



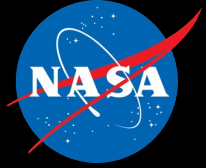
# NASA's Roles in AM



- Being the expert user for in-house applications
  - Robust AM process selection
  - Printer vendor management
  - Design for AM
  - Generative Design
  - Structural Integrity
  - Non-Destructive Evaluation (NDE) Inspection



# NASA's Roles in AM

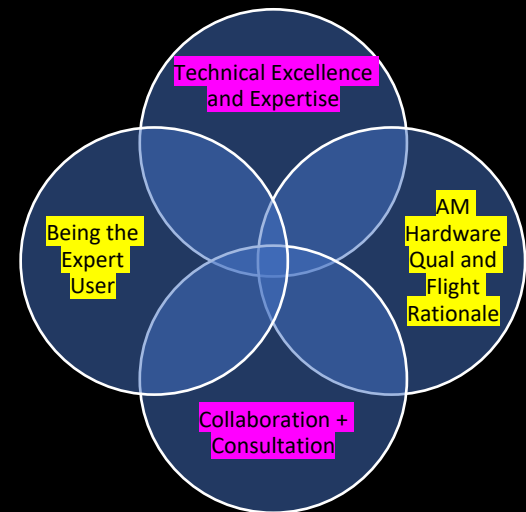


## • Collaboration

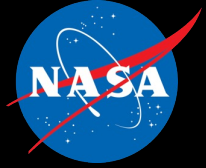
- AM Standard Development Organizations (ASTM, SAE/AMS, MIL-HDBK-5...)
- America Makes, ANSI, NIST, ASTM COE...
- Powder producers, machine makers, software companies, surface treatment, NDE, in-situ monitoring, machining house...
- Academia around the world
- Space Tech Mission Directorate
  - NASA STRI (Space Technology Research Institute) - Model based AM Qual kicking off 4Q 2023
  - NASA Tech Transfer (GRX-810 alloy)

## • Consultation and Knowledge Transfer

- NASA STMD - Tipping Point, CAN, ACO, Space Act Agreement



# NASA STMD – Space Tech Research Institute 2023



## Institute Overview



### ***What's an STRI?***

*Long-term sustained investment in research and technology critical to NASA's future. Highlights include:*

- **Empowered** university-led team
- Specific research objectives with **credible expected outcomes** in 5 years
- Talented, **diverse**, cross-disciplinary and fully **integrated** team
- Low to mid TRL

### *Award Details*

- Expected duration: **5 years**
- Award amount up to **\$3M per year**
- Institutes expected (and *empowered*) to implement their own review internal processes
- NASA oversight – annual reviews and brief quarterly status reports

### ***Research Areas***

1. A furthered understanding of **materials-processes-structure-property relationships** for AM through advanced computational toolsets coupled with innovative experiments, laying the foundation for accelerated product certification.
2. Development of **uncertainty-quantified, physics-based models and simulations** to understand the factors that can affect the formation, distribution, and the effects of process-induced defects and to address other principal sources of variability.
3. Integration and application of methodology, software tools, artificial intelligence (AI), machine learning (ML), and/or databases, etc., based on computational and experimental tools to a **model-centric certification approach**.

itters

**Awarded to Team led by A.D. (Tony) Rollett (Carnegie Mellon's U), PI & Somnath Ghosh (Johns Hopkins U)**

# NASA led book on Metal Additive Manufacturing



## Metal Additive Manufacturing for Propulsion Applications

Edited by  
Paul R. Gradl, Omar R. Mireles,  
Christopher S. Protz, and Chance P. Garcia



PROGRESS IN ASTRONAUTICS AND AERONAUTICS

Timothy C. Lieuwen, Editor-in-Chief  
Volume 263

P. R. Gradl, O. Mireles, C.S. Protz, C. Garcia. (2022).

*Metal Additive Manufacturing for Propulsion Applications.*

AIAA Progress in Astronautics and Aeronautics Book Series

<https://arc.aiaa.org/doi/book/10.2514/4.106279>

Online version and hardcopy available

AM processes are an enabling technology and revolutionizing the propulsion industry. AM-related advancements in new industries, supply chains, design opportunities, and novel materials are increasing at a rapid pace.

The goal of this text is to provide an overview of the practical concept-to-utilization lifecycle in AM for propulsion applications.

