Additive Manufacturing: From Rapid Prototyping to Flight

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About Me

B.S. Physics from Eastern Kentucky University
M.S., Ph.D. Mechanical Engineering from Vanderbilt

Previously worked as a materials engineer at United Launch Alliance (ULA)

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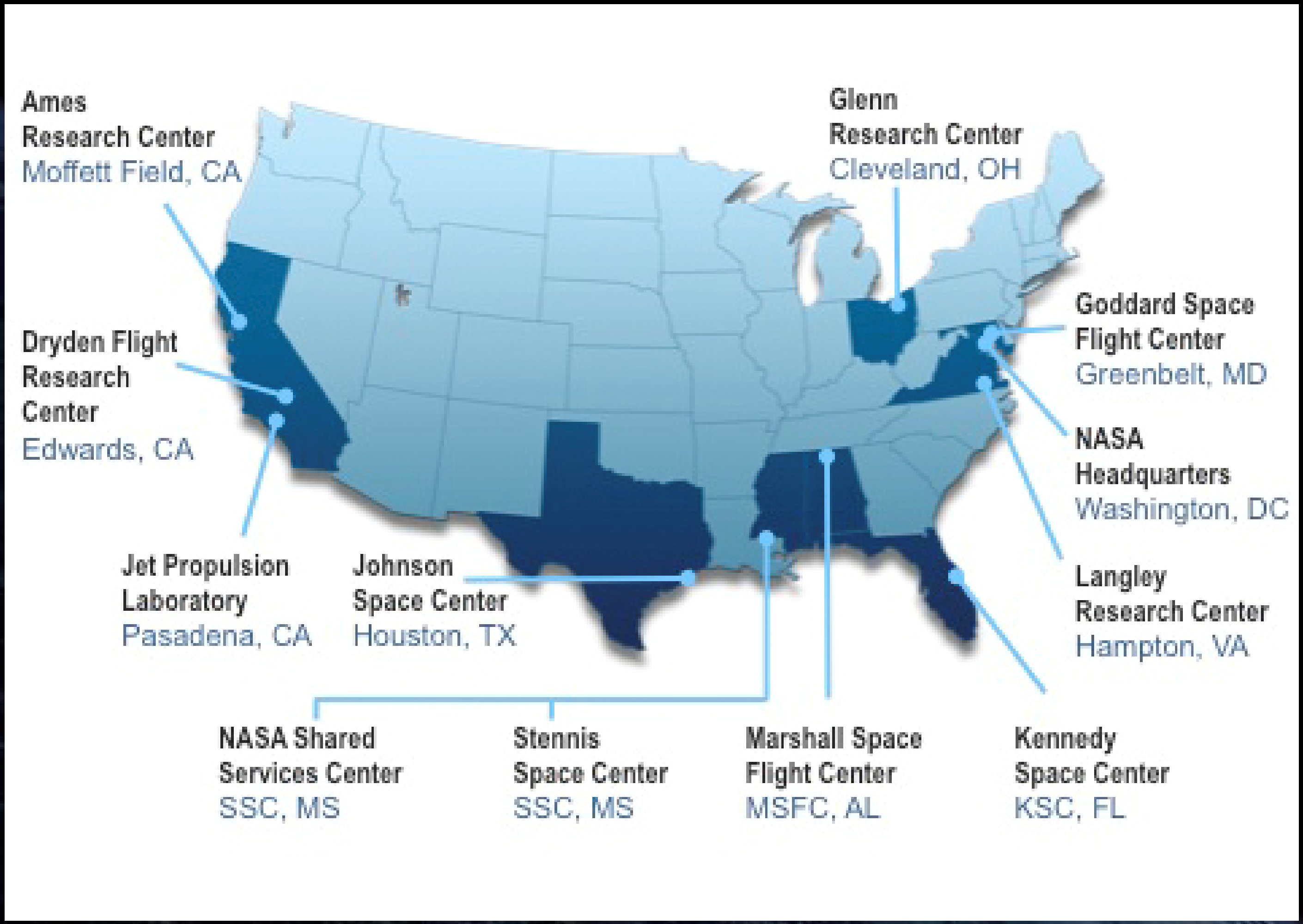
Then.....

KENNEDY SPACE CENTER
TRACIE

Living and working
on the new frontier of space

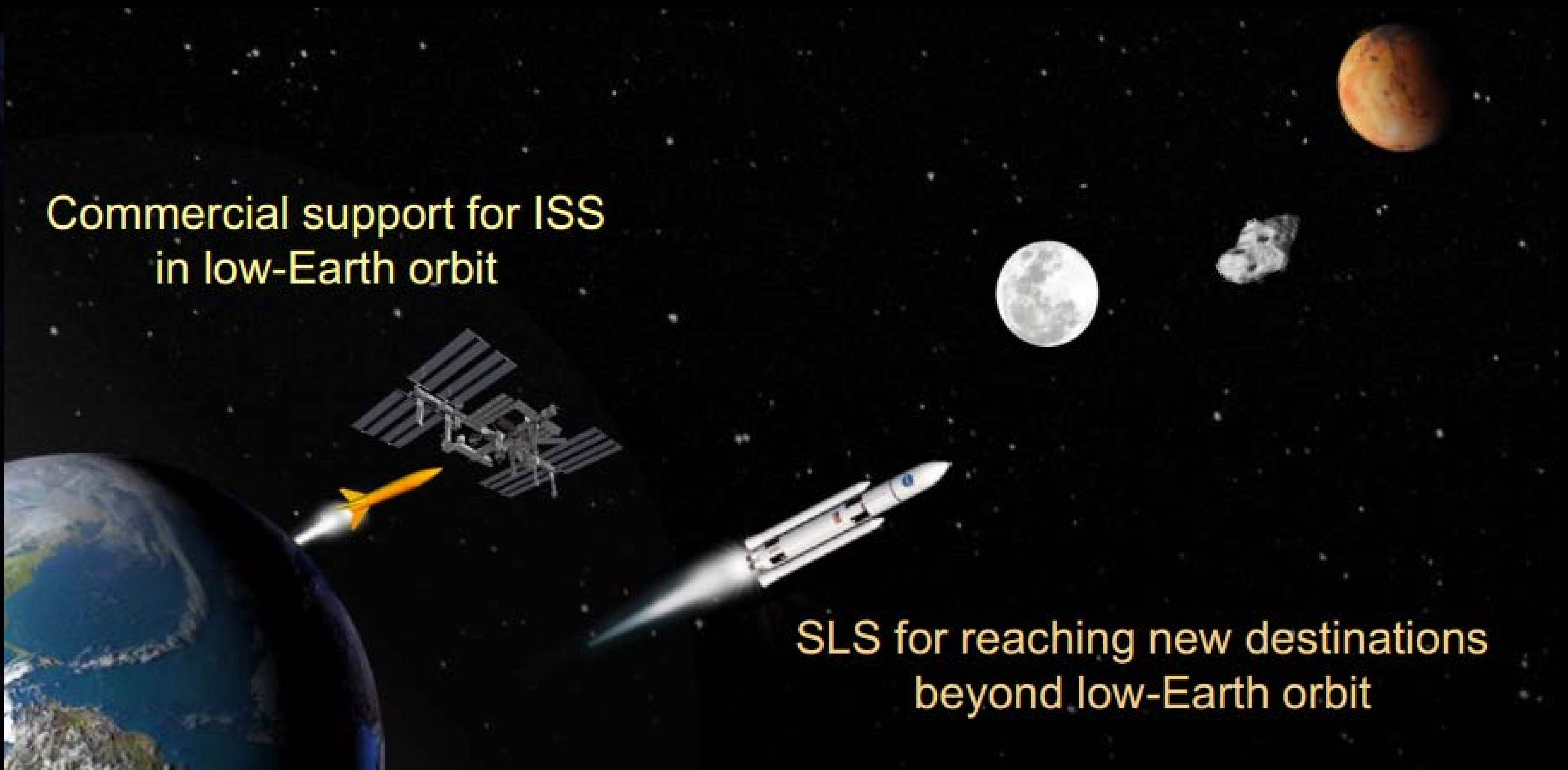
Now

NASA Field Centers



NASA's Four Core Mission Areas

Current Human Spaceflight Architecture



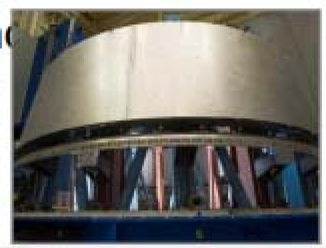
Space Launch System (SLS)

- Initial lift capacity of 70 MT, evolvable to 130 MT
- Carries the Orion Multipurpose Crew Vehicle (MPCV)
- First flight of SLS in 2018

Solid Rocket Booster Test

Friction Stir Welding for Core Stage

Shell Buckling Structural Test



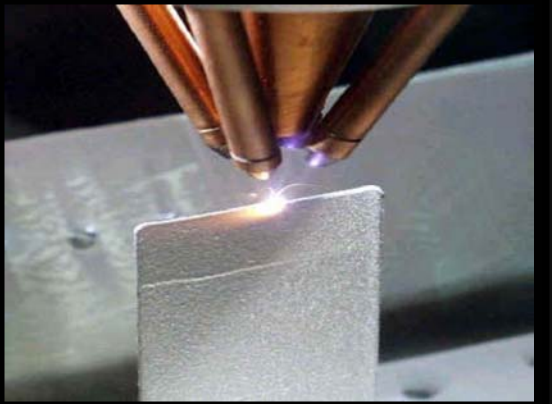
MPCV Stage Adapter Assembly

Selective Laser Melting Engine Parts

RS-25 Core Stage Engines in Inventory

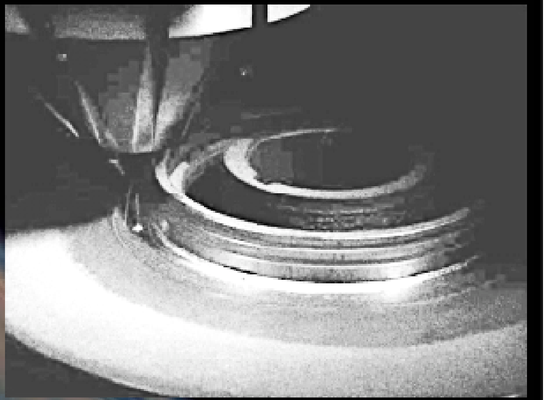
What is Additive Manufacturing?

-ASTM F42 defines AM as **"the process of joining materials to make objects from 3D model data, usually layer by layer, as opposed to subtractive manufacturing methodologies"**



-AM machine software slices a CAD model file into layers

-base material can be metallic, plastic, ceramic, composite, or biological

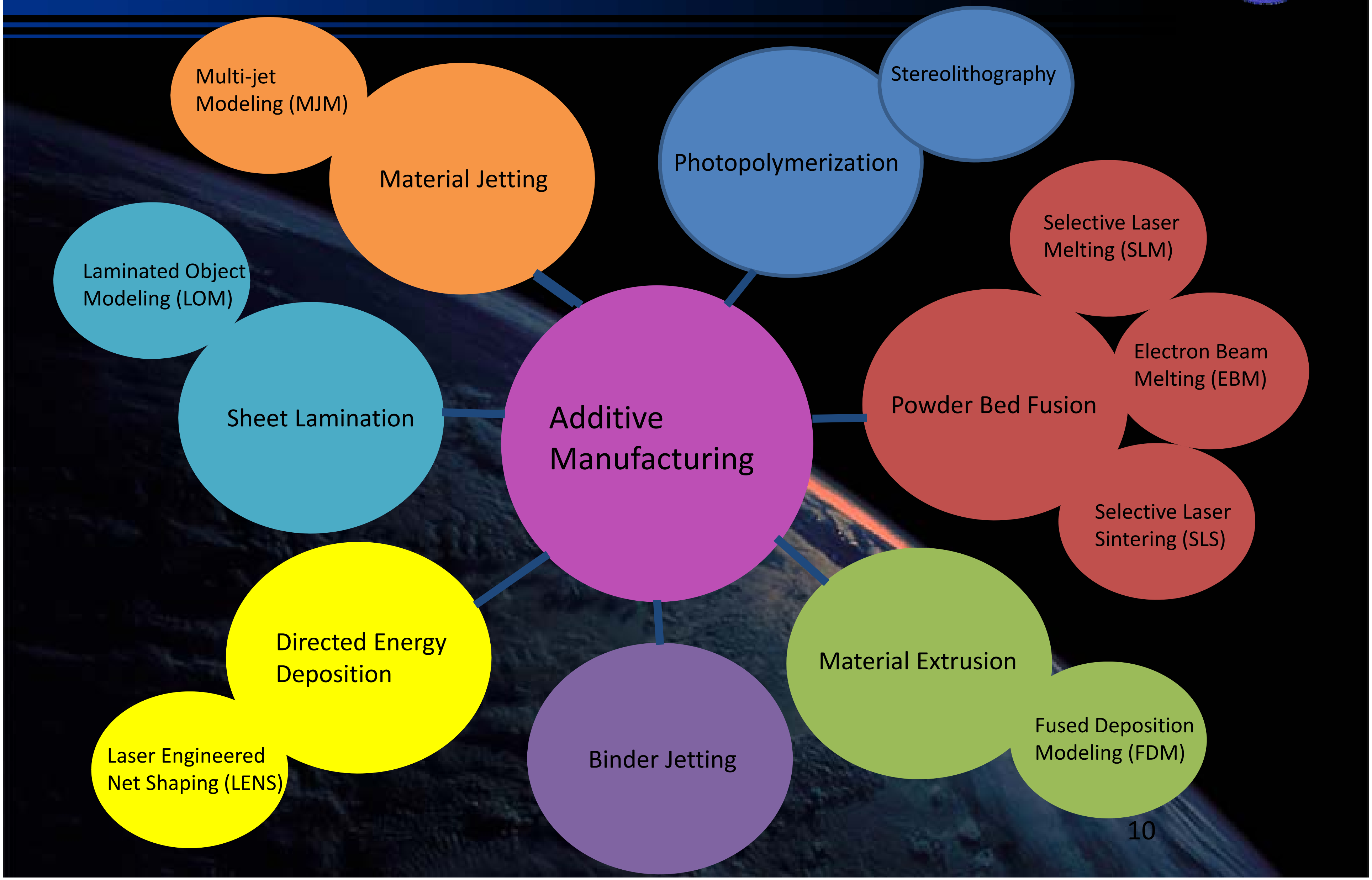


-2.2 billion dollar industry and U.S. is the world leader in industrial AM systems

-AM encompasses a broad range of processes

-distinguished by techniques used to deposit layers and the way in which the deposited layers are bonded together

What is Additive Manufacturing?



Why Additive Manufacturing?

-Aerospace components have complex geometries and are made from advanced materials

-Components are difficult, costly, and time-consuming to manufacture using conventional processes

-Aerospace hardware represents small batch, low-rate production

Why Additive Manufacturing?

Affordability

-reduced part count

-fewer critical welds and brazes

-reduced tooling

-schedule and cost savings

Performance

-optimized internal flow passages

-minimized leak paths

-lower mass

Design for Manufacturing → Manufacturing for Design

History of Additive Manufacturing at NASA MSFC

-NASA MSFC has 20+ years of experience with AM technologies

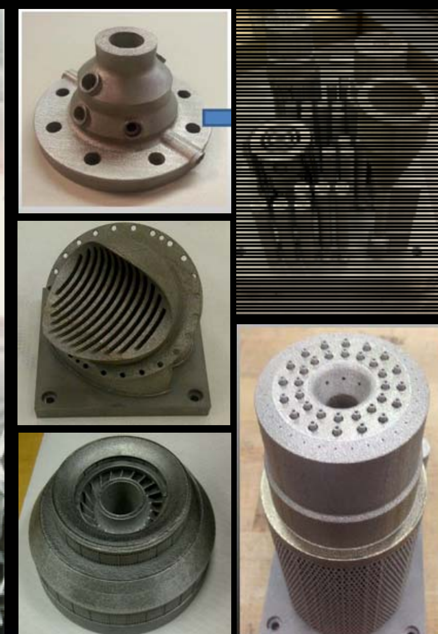
-initial focus in early 1990s on rapid prototyping

-National Center for Manufacturing Sciences (NCMS)

-first metallic system: laser engineered net shape parts

-currently focused on Electron Beam Melting (EBM) and Powder Bed Fusion (PBF) technology for production of propulsion hardware

-also focused on using AM to build parts in-space



Additive Manufacturing at MSFC

For space

Short term

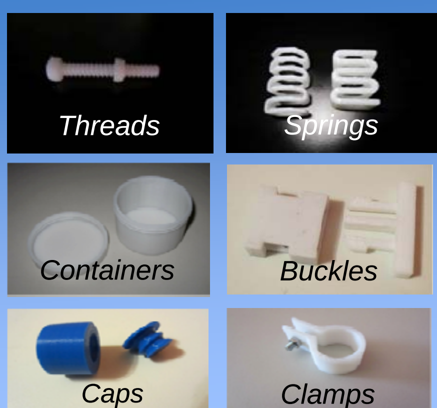
Long term

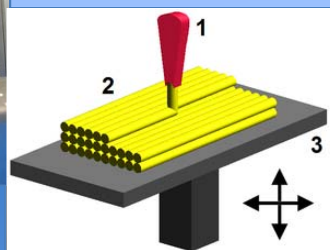
In space

3D Printing in Space

The 3D Print project will deliver the first 3D printer on the ISS and will investigate the effects of consistent microgravity on melt deposition additive manufacturing by printing parts in space.

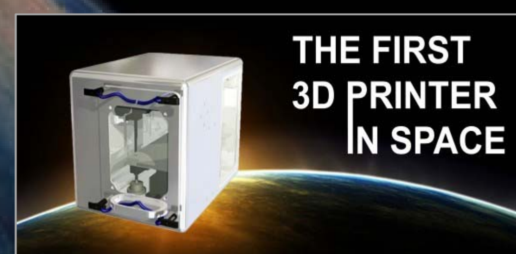
Potential Mission Accessories



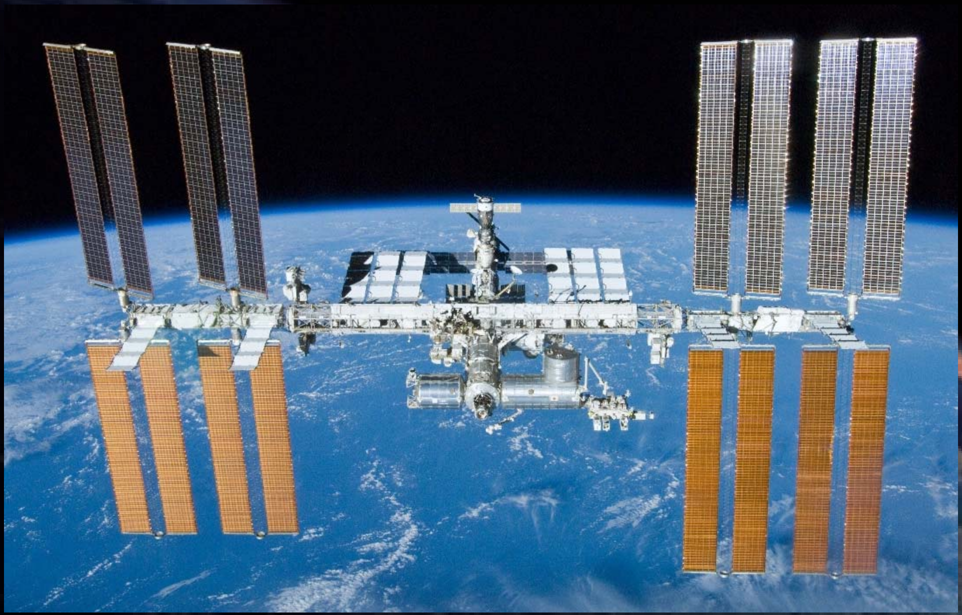


Melt deposition modeling:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

3D Print Specifications	
Dimensions	33 cm x 30 cm x 36 cm
Print Volume	6 cm x 12 cm x 6 cm
Mass	20 kg (w/out packing material or spares)
Est. Accuracy	95 %
Resolution	.35 mm
Maximum Power	176W (draw from MSG)
Software	MIS SliceR
Traverse	Linear Guide Rail
Feedstock	ABS Plastic



A Vision of In-Space Manufacturing



-In-space fabrication and repair of plastics using 3D printing
-Qualification/inspection of on-orbit parts using structured light scanning
-Printable small satellite technologies
-On-orbit plastic feedstock recycling
-In-space metals manufacturing process demonstration
-Welding in space
-Additive construction using regolith

Additive Manufacturing at MSFC

For space

Short term

Long term

In space

Additive Manufacturing at MSFC

-Primary focus on for-space AM is powder bed fusion processes

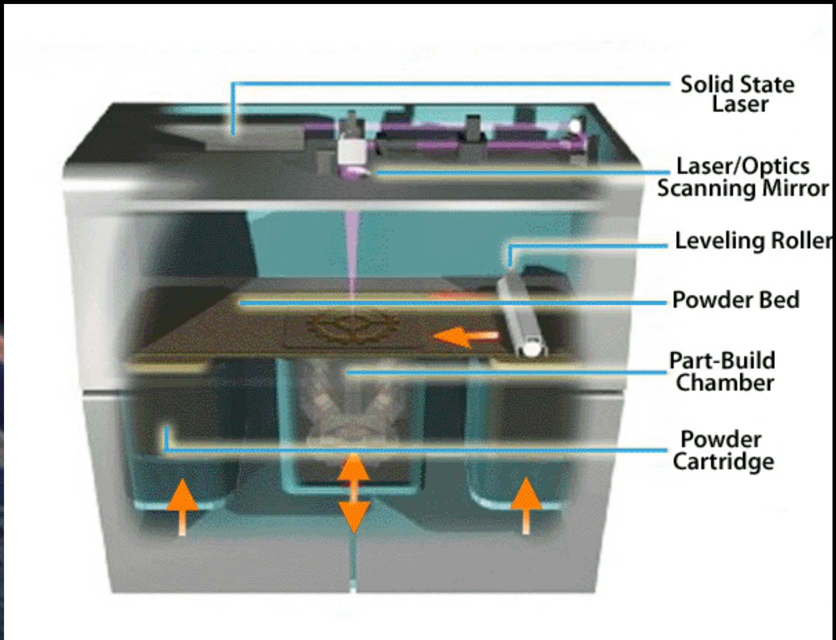
-Electron beam melting (EBM) machine for Titanium

-Concept Laser M1 and M2 for Selective Laser Melting (SLM) of Inconel 718 and Inconel 625 in addition to Copper alloys

-addition of Xline expands build volume by a factor of 6

Selective Laser Melting (SLM) Process Flow

1. 3D CAD model of part sliced into layers
2. Laser scan path is calculated which defines the boundary contour and the fill sequence
3. Powder is fed uniformly onto build plate by a wiper
4. Laser melts the deposited powder layer
5. Melted particles fuse and solidify to form a layer of the component
6. Build table is lowered and additional powder is fed onto plate
7. After part is complete, it undergoes stress relief and EDM is used to separate it from the build plate
8. Part may be subject to additional post-processing (Hot Isostatic Press and/or heat treatment)



Selective Laser Melting (SLM)

Controlled Process Variables

Base material
Powder characteristics
Deposition pattern
Layer thickness
Hatch spacing
Laser power
Laser scan speed
Post-build material conditioning

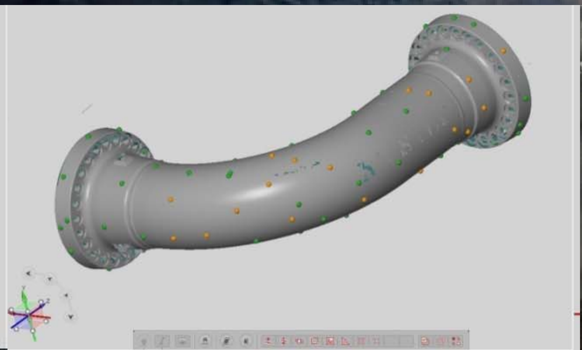
Material properties

Yield strength
Ultimate strength
Elongation
Reduction in area
Plastic strain
Modulus
Density
Fracture toughness
Material consolidation
Hardness
Surface roughness
Environmental effects
Fluid compatibility

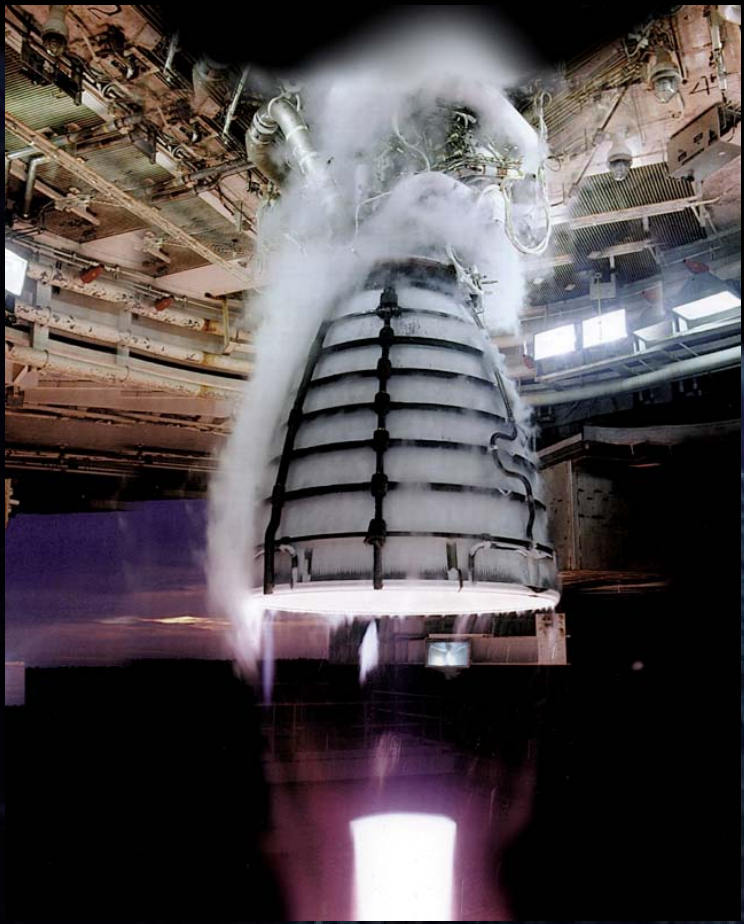
SLM process development for AM propulsion hardware is a manufacturing optimization problem. Build parameters must be optimized to ensure production of a material that will be able to perform in its intended use environment.

Recent AM Builds at MSFC

- -F1 engine reconstruction
- -In718 1200 lb thrust injector
- -two In718 main combustion chambers
- -In625 nozzle for Morpheus project
- -100 lb injector and fin set for NanoLaunch
- -multiple turbomachinery parts



Additive Manufacturing at NASA MSFC



NASA MSFC's role in the broader aerospace additive manufacturing community is three-fold:

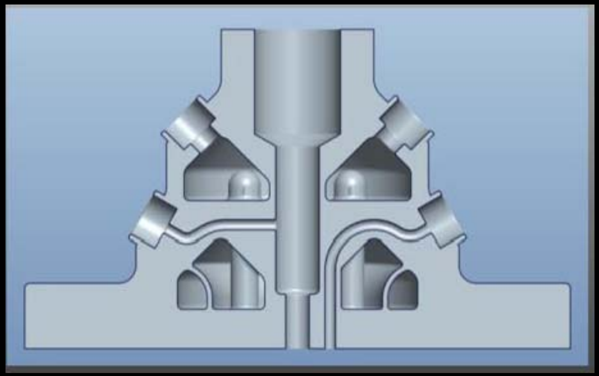
1) Smart buyer

2) Tech transfer

3) Anomaly resolution

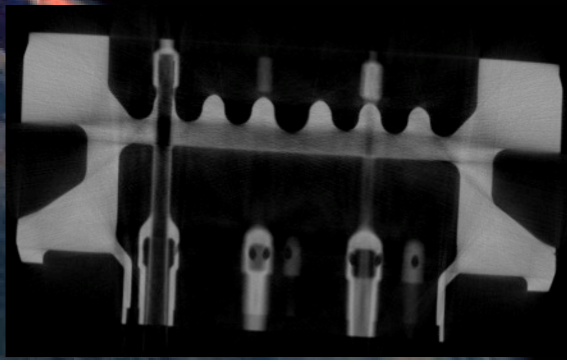
Challenges in Additive Manufacturing

Materials Characterization



Standard Design Practices

Process Modeling, Monitoring, and Control



Flight Certification

Materials Informatics for Additive Manufacturing at MSFC

Development of an AM database will provide a single source data repository that can be used to:

- Characterize materials
- Explore relationships between process variables and material properties
- Disseminate validated materials property data to the modeling, simulation, and design community
- Aid in the development of materials standards and protocols

Additive Manufacturing: The Path to Flight

Certification: the affirmation by the program, project, or other reviewing authority that the verification and validation process is complete and has adequately assured the design and as-built hardware meet the established requirements to safely and reliably complete the intended mission.

Additive Manufacturing: The Path to Flight

-**Develop** part classification approach based on consequences of failure

-**Understand** process failure modes

-**Characterize** process variability

-**Verify** individual build lot quality (lot acceptance testing)

-**Develop** guidelines and specifications for AM materials, processes, and design

  -**Provide** recommendations to vendors on allowable practices and certification limits

  -**Incorporate** AM materials and processes into existing NASA standards

Summary

- Additive manufacturing (AM) offers tremendous promise for the rocket propulsion community.
- Foundational work must be performed to ensure the safe performance of AM parts.
- Government, industry, and academia must collaborate in the characterization, design, modeling, and process control to accelerate the certification of AM parts for human-rated flight.

Questions

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