Additive Manufacturing for Human Space Exploration

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Presented by:
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Additive Manufacturing

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- Daniel Cavender: Liquid Propulsion Systems Design
- Paul Gradl: Liquid Engine Component Development and Technology
- Derek O’Neal: Liquid Engine Component Development and Technology
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- Jim Richard: Liquid Engine Component Development and Technology
- Dave Eddlemen: Liquid Engine Component Development and Technology
- Travis Davis: Liquid Engine Component Development and Technology
- Dr. Doug Wells: MSFC Lead, AM Space Flight Hardware Standard and Specification
- Brian West: Additive Manufacturing Integration Lead

Agenda

NASA's In Space Manufacturing Initiative (ISM)

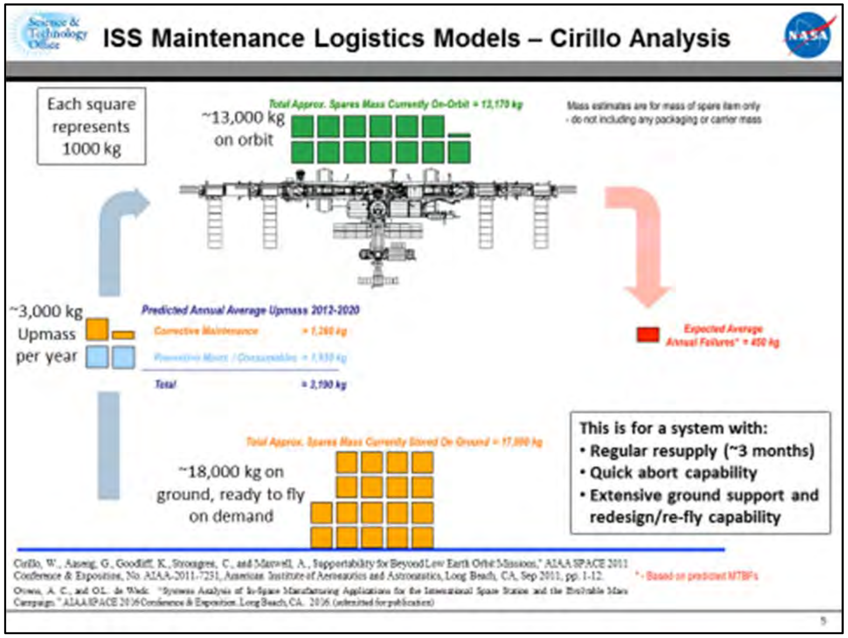
- The Case for ISM: WHY
- ISM Path to Exploration
- In Space Robotic Manufacturing and Assembly (IRMA)
- Additive Construction

Additively Manufacturing (AM) Development For Liquid Rocket Engine Space Flight Hardware

MSFC Standard and Specification For Additively Manufactured Space Flight Hardware

Summary

The Case for ISM: WHY



ISS Maintenance Logistics Models – Cirillo Analysis

Each square represents 1000 kg

~13,000 kg on orbit

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

Mass estimates are for mass of spare item only - do not including any packaging or carrier mass

~3,000 kg Upmass per year

Predicted Annual Average Upmass 2012-2020

Corrective Maintenance	= 1,260 kg
Preventive Maint. / Consumables	= 1,930 kg
Total	= 3,190 kg

Expected Average Annual Failures* = 450 kg

Total Approx. Spares Mass Currently Stored On Ground = 17,890 kg

~18,000 kg on ground, ready to fly on demand

This is for a system with:
- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Cirillo, W., Aaseng, G., Goodliff, K., Stromgren, C., and Maxwell, A., "Supportability for Beyond Low Earth Orbit Missions," AIAA SPACE 2011 Conference & Exposition, No. AIAA-2011-7231, American Institute of Aeronautics and Astronautics, Long Beach, CA, Sep 2011, pp. 1-12.

* - Based on predicted MTBFs

Owens, A. C., and O.L. de Weck. "Systems Analysis of In-Space Manufacturing Applications for the International Space Station and the Evolvable Mars Campaign." AIAA SPACE 2016 Conference & Exposition, Long Beach, CA. 2016 (submitted for publication)

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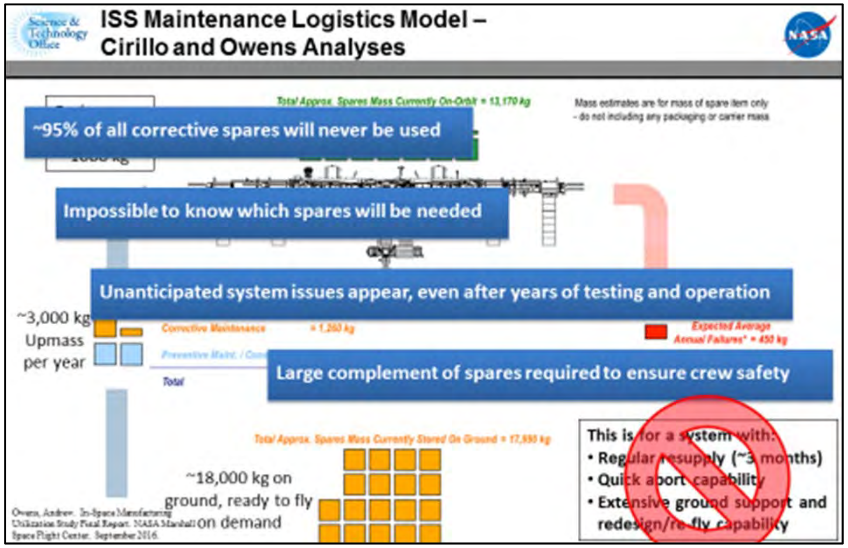

ISS Maintenance Logistics Model – Cirillo and Owens Analyses

~95% of all corrective spares will never be used

Impossible to know which spares will be needed

Unanticipated system issues appear, even after years of testing and operation

Large complement of spares required to ensure crew safety

Total Approx. Spares Mass Currently On-Orbit = 13,170 kg

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Owens, Andrew. In-Space Manufacturing Utilization Study Final Report. NASA Marshall Space Flight Center. September 2016.

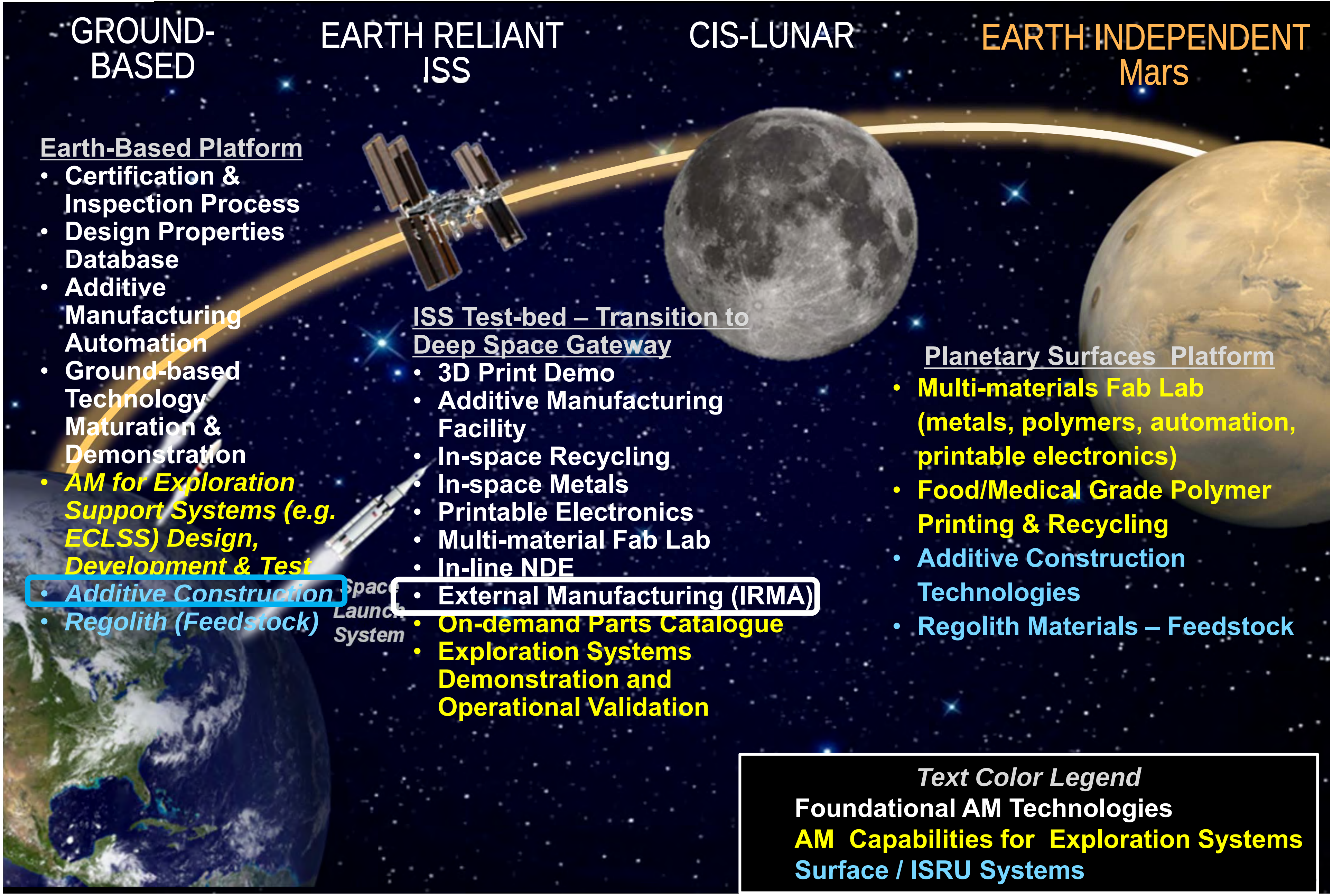
Current maintenance logistics strategy ***will not be effective*** for deep space exploration missions

Benefits from Incorporation of ISM

ISM offers the potential to:

- Significantly reduce maintenance logistics mass requirements
- Enable the use of recycled materials and in-situ resources for more dramatic reductions in mass requirements
- Enable flexibility, giving systems a broad capability to adapt to unanticipated circumstances
- Mitigate risks that are not covered by current approaches to maintainability

In-Space Manufacturing (ISM) Path to Exploration



GROUND-BASED

Earth-Based Platform

- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- Ground-based Technology Maturation & Demonstration
- *AM for Exploration Support Systems (e.g. ECLSS) Design, Development & Test*
- *Additive Construction*
- *Regolith (Feedstock)*

EARTH RELIANT ISS

ISS Test-bed – Transition to Deep Space Gateway

- 3D Print Demo
- Additive Manufacturing Facility
- In-space Recycling
- In-space Metals
- Printable Electronics
- Multi-material Fab Lab
- In-line NDE
- External Manufacturing (IRMA)
- On-demand Parts Catalogue
- Exploration Systems Demonstration and Operational Validation

CIS-LUNAR

EARTH INDEPENDENT Mars

Planetary Surfaces Platform

- Multi-materials Fab Lab (metals, polymers, automation, printable electronics)
- Food/Medical Grade Polymer Printing & Recycling
- Additive Construction Technologies
- Regolith Materials – Feedstock

Text Color Legend

Foundational AM Technologies

AM Capabilities for Exploration Systems

Surface / ISRU Systems

Key ISM Thrust Areas

FabLab
MSFC

First Plastics Printer
Made In Space

2nd Generation Plastics Printer
Made In Space

Health & Medical
Tethers Unlimited

Recycler/ Printer
Tethers Unlimited

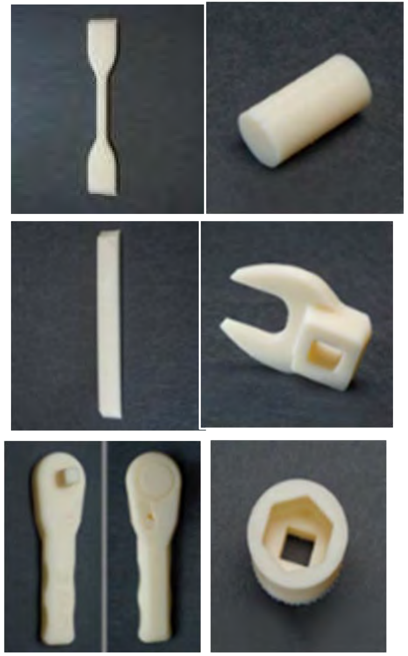
Printed Electronics
MSFC

In-Space Metallics
Made in Space
Ultra Tech
Tethers Unlimited
Techshot

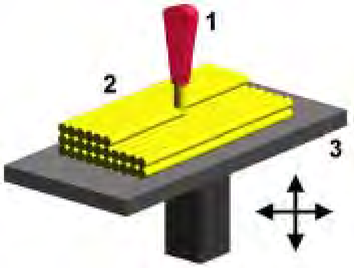
Common Use Recyclable Materials
Cornerstone Research Group
Tethers Unlimited

The First Step: The 3D Printing in Zero G Technology Demonstration Mission

The 3DP in Zero G Tech Demo delivered the first 3D printer on the ISS and investigated the effects of consistent microgravity on fused deposition modeling by printing 55 specimens to date in space.



- **Phase I prints (Nov-Dec 2014)** consisted of mostly mechanical test coupons as well as some functional tools
- **Phase II specimens (June-July 2016)** provided additional mechanical test coupons to improve statistical sampling



Fused 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)
Power	176 W
Feedstock	ABS Plastic

Printer inside Microgravity Science Glovebox (MSG)

3DP Phase 1 Key Observations

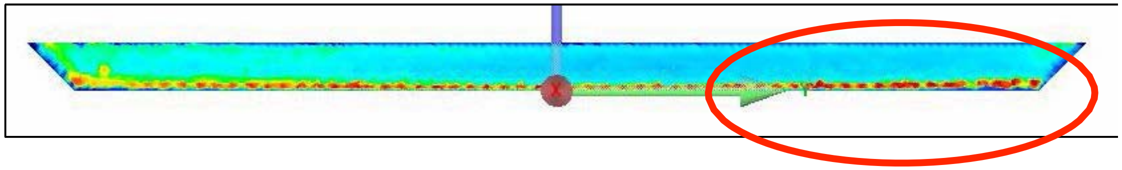
Material Properties

- Tensile and Flexure: Flight specimens stronger and stiffer than ground counterparts
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend

X-ray and CT Scans

- CT scans show more pronounced densification in lower half of flight specimens. [Not statistically significant]
- No significant difference in number or size of voids between the flight and ground sets

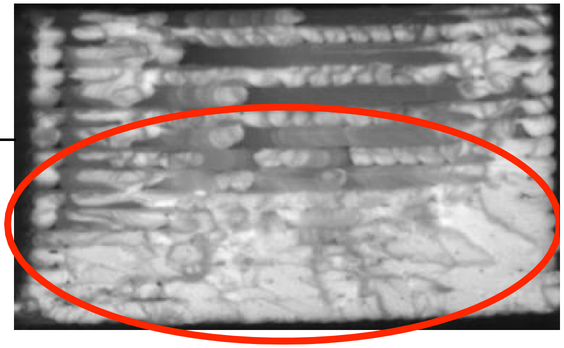
Structured Light Scanning



- Protrusions along bottom edges indicate that extruder tip may have been too close to the print tray (more pronounced for flight prints)

Microscopy

- Greater Densification of Bottom Layers (Flight tensile)

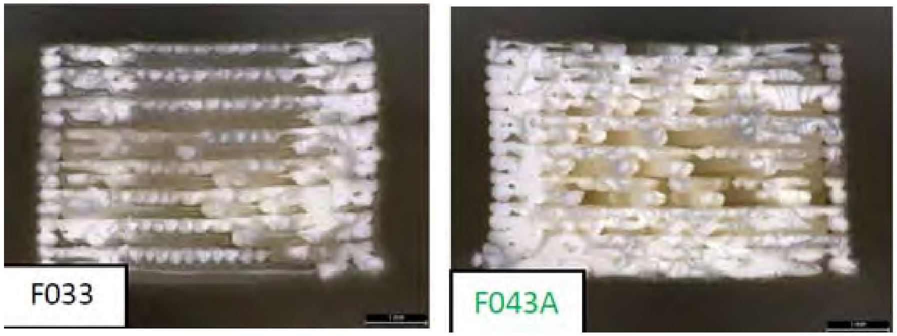


Process

- Z-calibration distance variation suspected to be primary factor driving differences between flight and ground sample
- Potential influence of feedstock aging are being evaluated further

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II)

- For Phase II operations, 25 specimens (tensile and compression) were built at an optimal extruder standoff distance.
- For the last 9 prints in the 34 specimen print matrix, extruder standoff distance was decreased intentionally to mimic the manufacturing process conditions for the Phase I flight prints (termed “suboptimal”).
- Complete Phase II data will be published on the NASA Technical Reports Server in December 2017.
- Key findings:
  - All prints to date with 3DP appear to be broadly part of the same family of data
  - No substantive chemical changes in feedstock noted through FTIR analysis
  - No evidence of microgravity effects noted in SEM analysis. Some variation in internal material structure between builds and with changes in process settings



Cross-section of PII tensile specimen manufactured at optimal extruder setting (left) compared with specimen manufactured at a reduced extruder standoff distance (right). Right image has a cross-section characteristic with PI flight prints.

Specimen set	Average ultimate tensile strength (KSI)	Coefficient of variation
Phase II	3.68	6.71
Phase II optimal	3.63	6.61
Phase II off-suboptimal	3.93	0.07
Phase I ground	3.46	1.71
Phase I flight	4.04	5.95

Key Results: The 3D Printing in Zero G Technology Demonstration Mission (Phase II): Additional Details

- ***Mass and density data for Phase I and Phase II (all subsets of data) appear to be part of the same data family***
- ***Mechanical Properties***
  - Tensile data and comparison with previous results suggest all data collected to date is part of a single large, albeit variable, data set.
  - Ground compression specimen performance is still somewhat distinct (higher) than other specimen sets. Specimens were manufactured at the farthest extruder distance.
- ***Structured light scanning***
  - Phase II flight specimens manufactured at the optimal extruder distance exhibit good agreement with the CAD model,
  - Some slight build to build variability in geometry.
  - Suboptimal compression specimens show fiber distortion and distortion in the center of the specimen.
  - Warpage and protrusions observed for Phase I tensile specimens are not present in Phase II flight tensile prints.
- ***Microscopy***
  - Suboptimal compression specimens:
    - Contain surface defects along the sides that appear to be printing defects where the fiber is distorted.
    - Cross-section showed voids in the center of the sample
    - Mechanically weaker than specimens manufactured at greater standoff distances.
  - Suboptimal tensile specimens show characteristic densification of first layers noted in Phase I flight specimens and subsequent ground-based study.
- ***FTIR***
  - Some small chemical changes between Phase I and Phase II flight feedstock (Phase II feedstock 2 years older).
  - Spectra still show a very high degree of similarity and are considered in family with one another.
- ***X-ray/CT analysis results still pending***
- ***Variations in Phase I data appear to be traceable to:***
  - Printer variability
  - Differences in manufacturing process settings (extruder standoff distance)
  - Data scatter characteristic of many additively manufactured materials and processes.

Overall, we cannot attribute any of the observations to microgravity effects.

ISM Utilization and the Additive Manufacturing Facility (AMF): Functional Parts

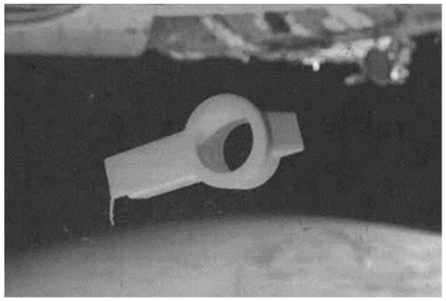
The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the second generation printer developed by Made in Space, Inc.
- AMF is a commercial, multi-user facility capable of printing ABS, ULTEM, and HDPE.
- To date, NASA has printed several functional parts for ISS using AMF

SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.

REM Shield Enclosure: Enclosure for radiation monitors inside Bigelow Expandable Activity Module (BEAM). Printed 3/20/17 (1 of 3).

Antenna Feed Horn: collaboration between NASA Chief Scientist & Chief Technologist for Space Communications and Navigation, ISM & Sciperio, Inc. Printed 3/9/17 and returned on SpaceX-10 3/20/17.



OGS Adapter: adapter attaches over the OGS air outlet and fixtures the velocicalc probe in the optimal location to obtain a consistent and accurate reading of airflow through the port. 7/19/2016.

Prater, Tracie, et al. “NASA’s In-space Manufacturing Project: Materials and Manufacturing Process Development Update.” Proceedings of the National Space and Missile Materials Symposium. June 2017.

In-space Robotic Manufacturing and Assembly (IRMA) Overview


Concept by Made In Space


Concept by Space Systems/Loral

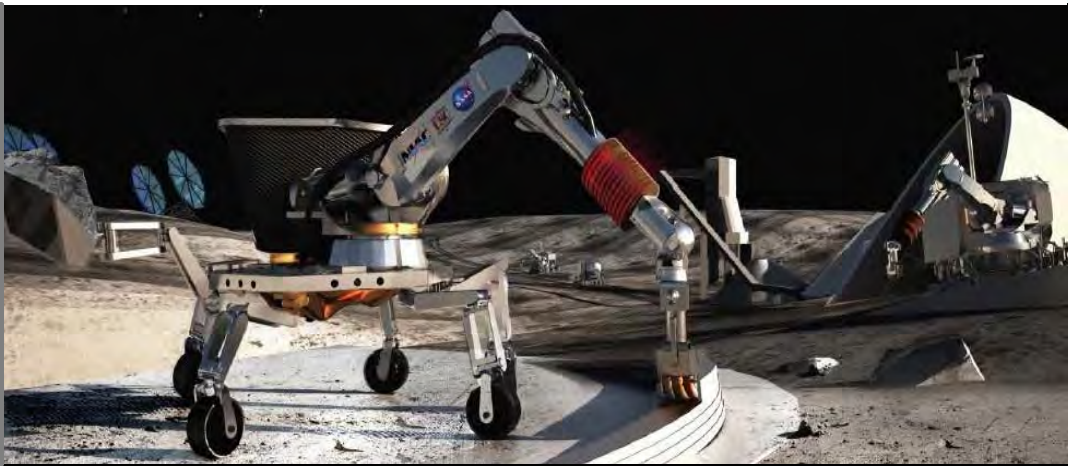

Concept by Orbital ATK

	Archinaut	Dragonfly	CIRAS
	A Versatile In-Space Precision Manufacturing and Assembly System	On-Orbit Robotic Installation and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors	A Commercial Infrastructure for Robotic Assembly and Services
Tipping Point Objective	A ground demonstration of additive manufacturing of extended structures and assembly of those structures in a relevant space environment.	A ground demonstration of robotic assembly interfaces and additive manufacture of antenna support structures meeting EHF performance requirements.	A ground demonstration of reversible and repeatable robotic joining methods for mechanical and electrical connections feasible for multiple space assembly geometries.
Team	Made In Space, Northrop Grumman Corp., Oceaneering Space Systems, Ames Research Center	Space Systems/Loral, Langley Research Center, Ames Research Center, Tethers Unlimited, MDA US & Brampton	Orbital ATK, Glenn Research Center, Langley Research Center, Naval Research Laboratory

Additive Construction Dual Use Technology Projects For Planetary and Terrestrial Applications

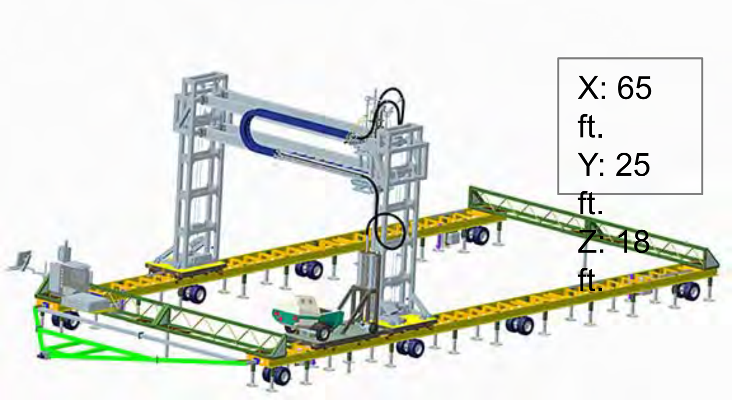
US Army Corps of Engineers®
Engineer Research and Development Center

Additive Construction with Mobile Emplacement (ACME) NASA



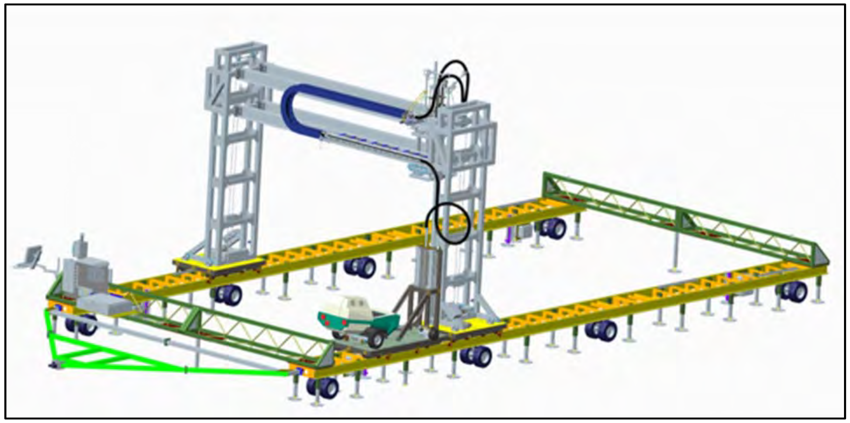
Shared Vision: Capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials.

Automated Construction of Expeditionary Structures (ACES) Construction Engineering Research Laboratory - Engineer Research and Development Center (CERL – ERDC)



B-hut
(guard shack)
16' x 32' x 10'

ACES-3: The World's Largest 3D Structural Printer

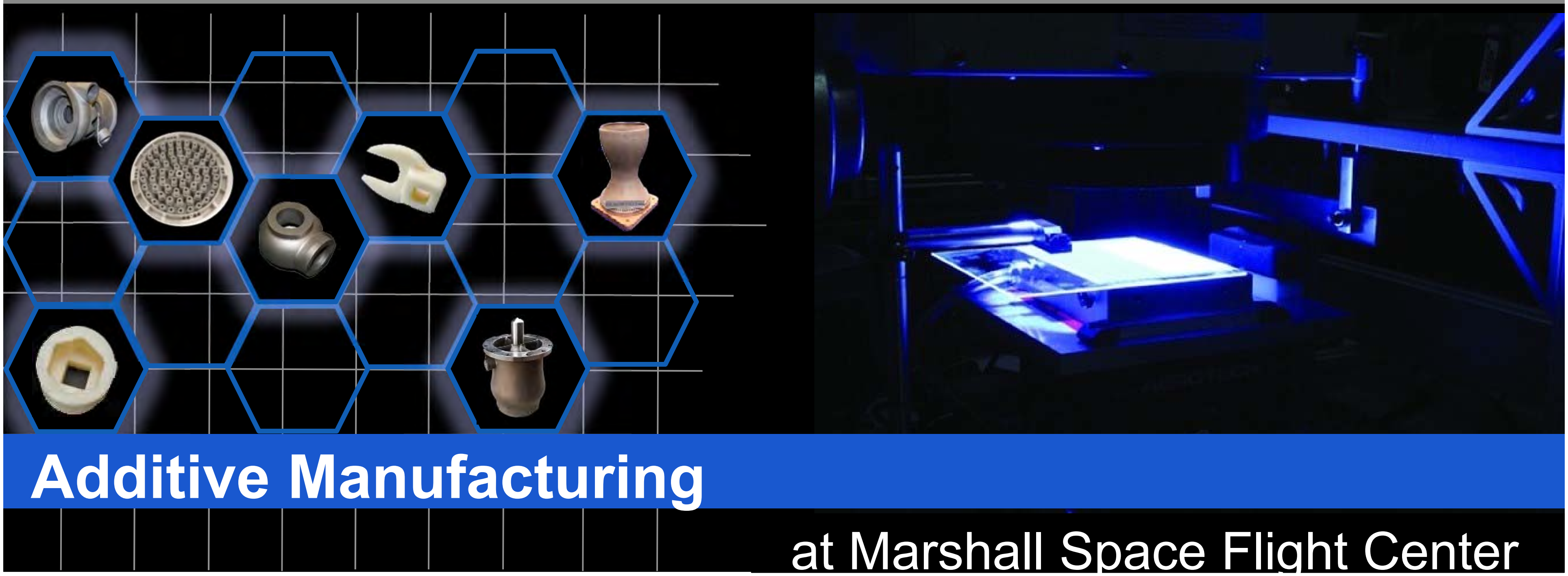


Model of ACES-3 Gantry System

ACES-3 System in Champaign, IL

ACES-3 in Champaign, IL, aerial view

KSC Material Delivery System

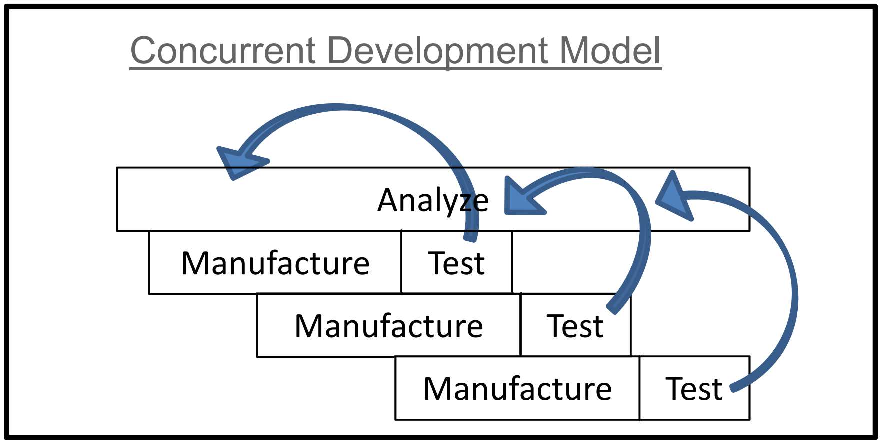


Additive Manufacturing Development for Liquid Rocket Engine Space Flight Hardware

Additive Manufacturing Design and Development for Space Propulsion System Applications

Strategic Vision:

- Defining the Development Philosophy of the Future
- Building Foundational Industrial Base
- Building Experience
- Developing "Smart Buyers" to enable Commercial Partners
- Enabling and Developing Revolutionary Technology
- SLM Material Property Data, Technology, and Testbed shared with US Industry


Concurrent Development Model

Analyze
Manufacture | Test
Manufacture | Test
Manufacture | Test

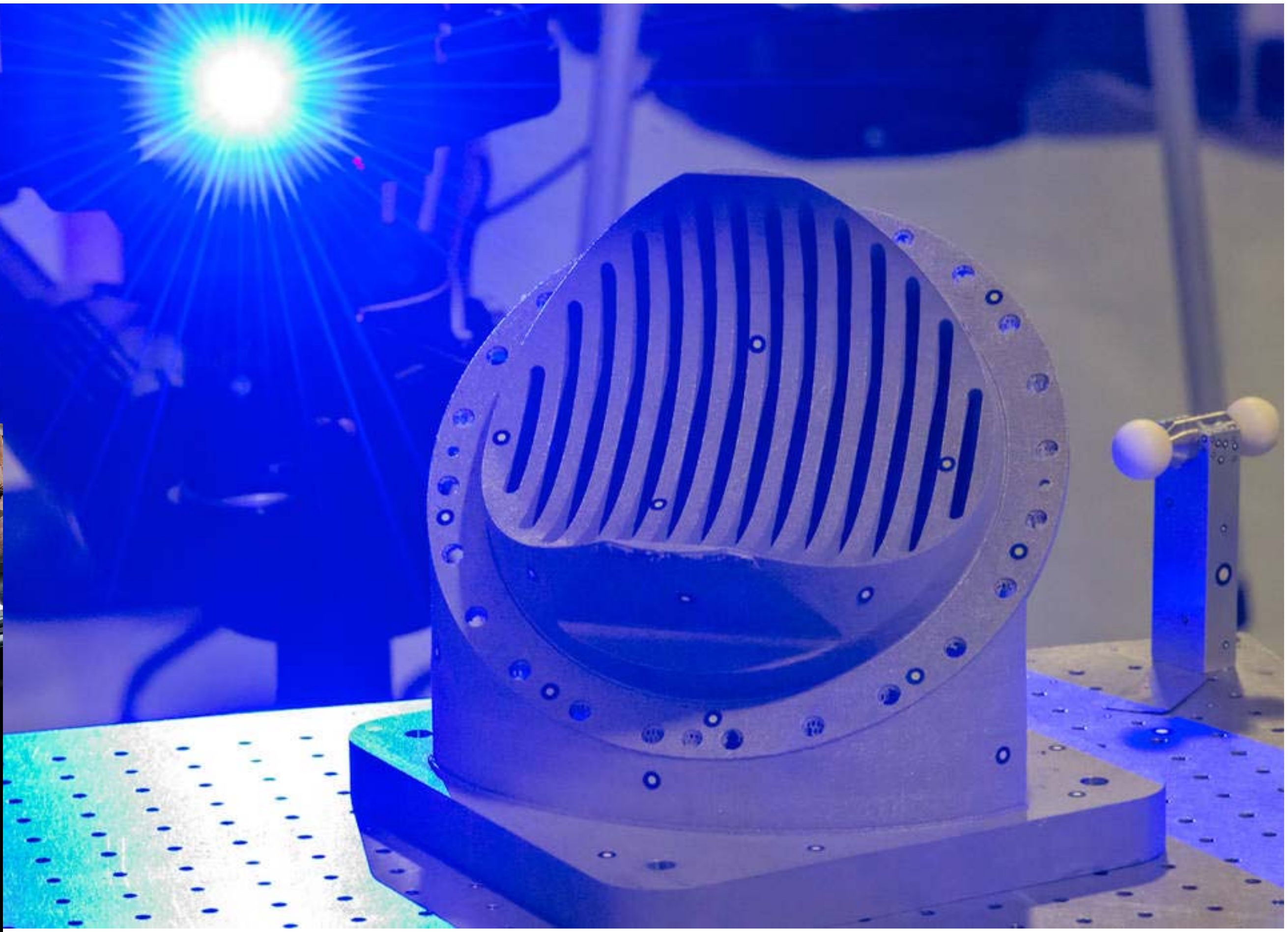
- Focus Areas:
  - SLS Core Stage Engine, RS-25
    - Process development and characterization
    - Material property characterization and database development (Inconel 718)
    - Pathfinder component fabrication
  - In Space Propulsion Class Additive Manufacturing Demonstrator Engine (AMDE)
    - Chambers
    - Injectors
    - Nozzles
    - Valves
    - Turbomachinery
  - Small Satellite Propulsion Components

SLS Program / RS-25 Engine Example Pogo Z-Baffle

Inconel 718

Used existing design with additive manufacturing to reduce complexity from <u>127 welds to 4 welds</u>

- 1 of 35 part opportunities being considered for RS25 engine

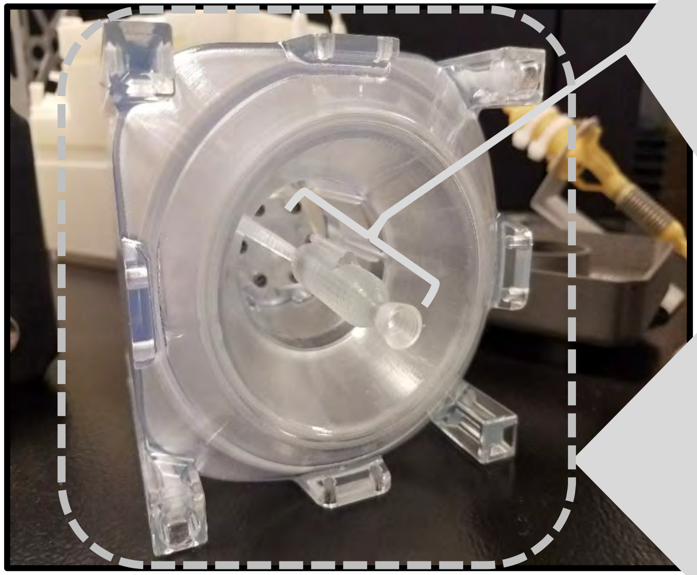


Ref: Andy Hardin / NASA MSFC

Small Satellite Propulsion Components Design and Development

CubeSat cuboidal tank design:

- Topology optimized
- Printed
- Successfully hydrostatic proof tested



- **Topology optimized monopropellant thruster thermal standoffs, injectors**
- **Reactors with integrated flow passages for small spacecraft**
- **CubeSat propulsion systems (1 Newton)**

Detailed design and fabrication of 3U and 6U CubeSat Propulsion Modules

Science & Technology Office

Additive Manufacturing Demonstrator Engine (AMDE) Major Hardware

Injector

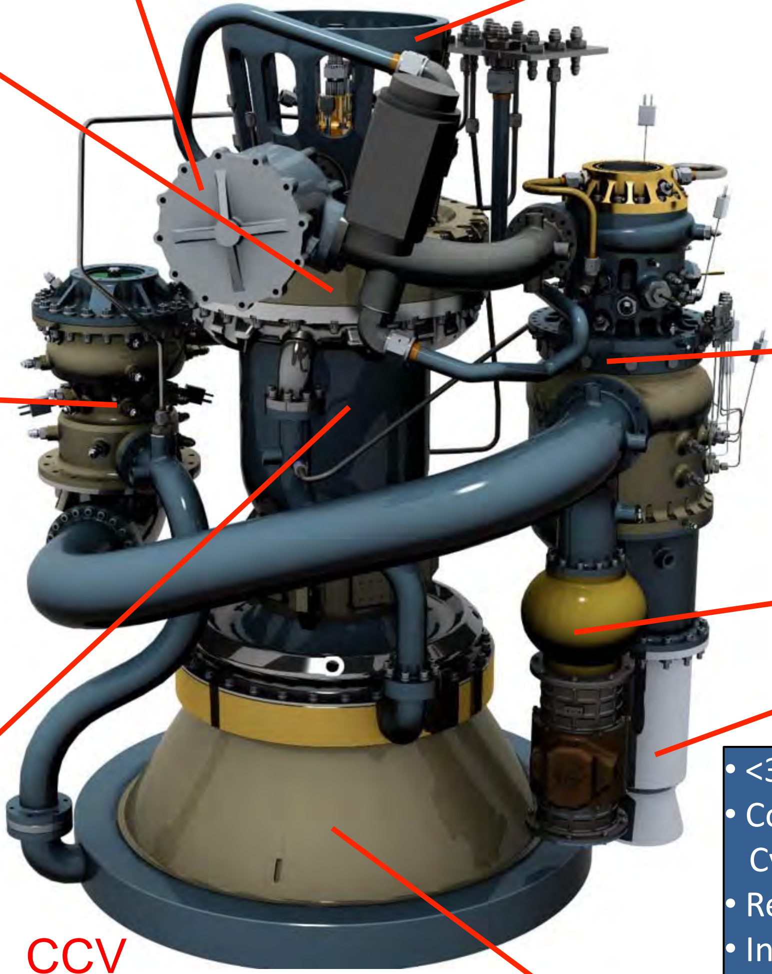
- Decreased cost by 30%
- Reduced part count: 252 to 6
- Eliminated critical braze joints
- Unique design features

FTP

- Schedule reduced by 45%
- Reduced part count: 40 to 22
- Successful tests in both Methane and Hydrogen
- Mass: 90% AM

MCC

- Schedule reduction > 50%
- SLM with GRCop-84
- Structural jacket and manifolds: Electron Beam Free Form Fabrication with Nickel Alloy
- Methane test successful



MOV
Part Count 1 vs. 6

Thrust Structure

MFV (Hidden)
Part Count 1 vs. 5

Mixer (Hidden)
Part Count 2 vs. 8

OTP
Part Count 41 vs. 80

OTBV
Part Count 1 vs. 5

Turbine Discharge Duct

CCV (Hidden)
Part Count 1 vs. 5

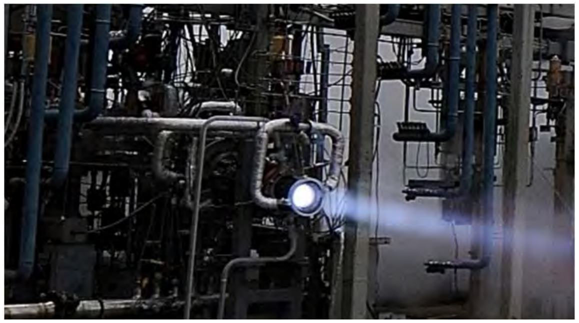
Regen Nozzle

- <30 welds vs 100+ traditionally
- Compressed Development Cycle 3 years vs. 7
- Reduced part counts
- Invested $10M, 25FTE over 3 years
- Estimated production & test cost for hardware shown $3M

Additive Combustion Chambers Assembly and Testing

GRCop-84 3D printing process developed at NASA and infused into industry

GRCop-84 AM Chamber Accumulated **6000 sec** hot-fire time at full power with no issues



LOX/Methane Testing of 3D-Printed Chamber Methane Cooled, tested full power

First successful hot fire test of a regen-cooled GRCop-84 3D printed MCC with an integral Electron Beam Free Form Fabrication (EBF3) deposited nickel superalloy jacket.

Morgan, K. L., Gradl, P., “Additive Manufacturing Overview: Recent Propulsion Applications,” Additive Manufacturing for Defense and Government Conference, July 2017

SLM GRCop-84 Chamber Testing

Additive Injector Development

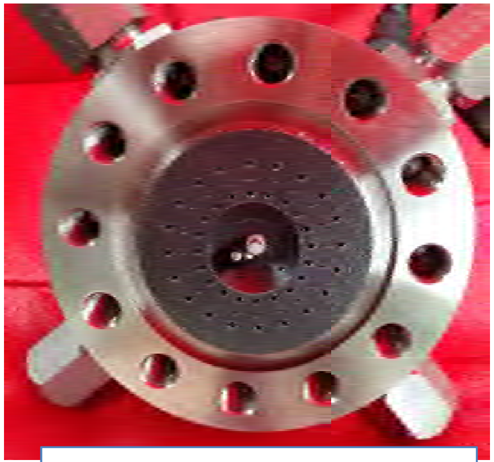
100# LOX Propane
Injector Built 2012
Tested Nov 2013

1.2K LOX Hydrogen
First Tested June 2013
>3900 sec hotfire

20K LPS Subscale Tested Aug 2013
(3) Subscale Injectors Tested

Methane 4K Injector
Printed manifolds and
parametric feature
Tested Sept 2015

LPS 35K Injector
Welded Manifolds
Tested Nov 2015



CH4 Gas Generator Injector
Testing Summer 2017

Ref: Brad Bullard Sandy Elam Greene

SLM Alloy 718 Injector Testing

Additively Manufactured Injectors Hot-fire Tested at NASA range from 1,200 lb_f to 35,000 lb_f thrust

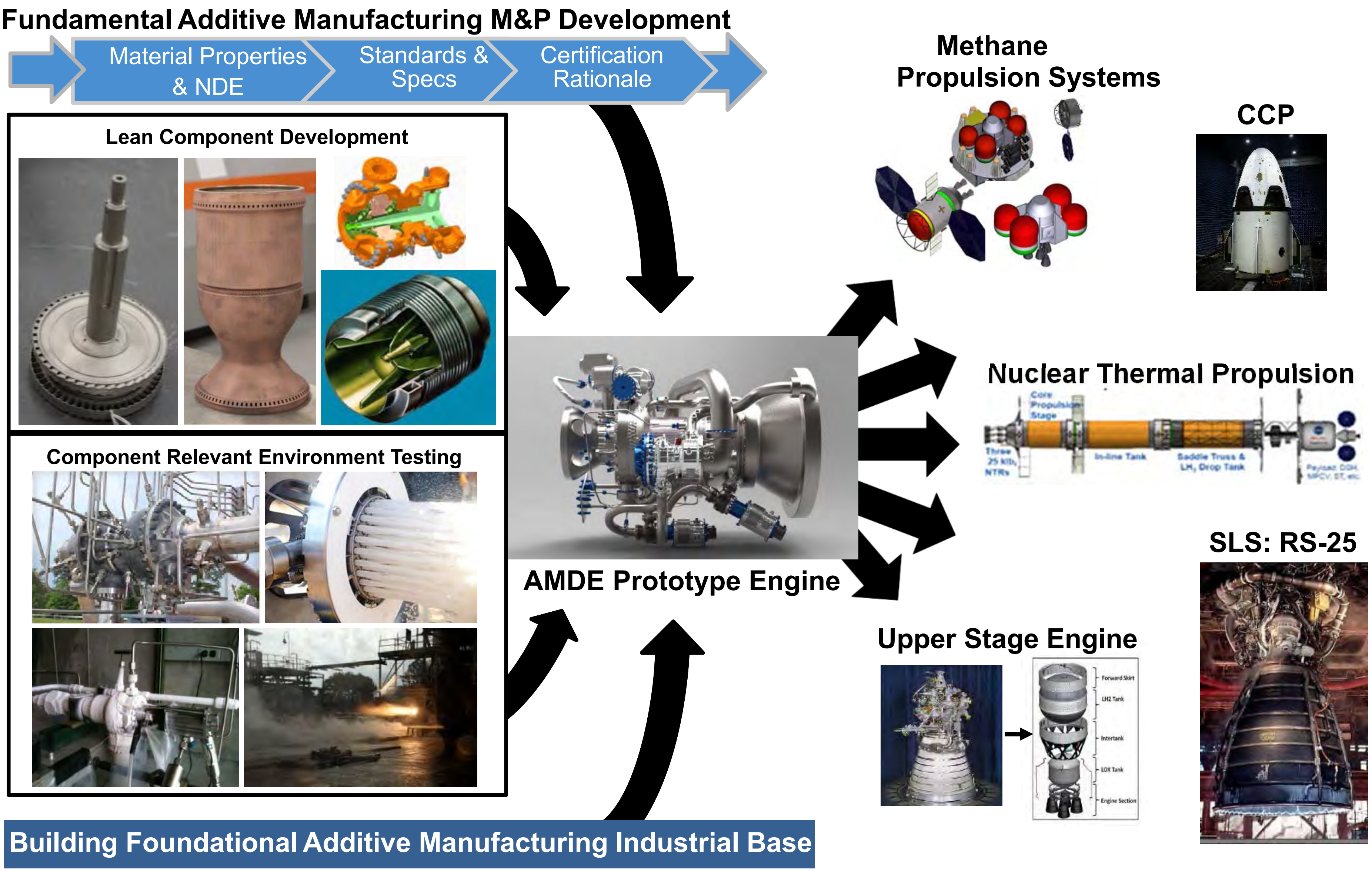
Large Scale Additive Deposition Nozzle Technology Development

[35] Morgan, K. L., Gradl, P., "Additive Manufacturing Overview: Recent Propulsion Applications," Additive Manufacturing for Defense and Government Conference, July 2017.

[36] 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.

[37] Gradl, P.R., Brandsmeier, W. Alberts, D., Walker, B., Schneider, J.A. Manufacturing Process Developments for Large Scale Regeneratively-cooled Channel Wall Rocket Nozzles. Paper presented at 63nd JANNAF Propulsion Meeting/9th Liquid Propulsion Subcommittee, December 5-9, 2016. Phoenix, AZ.

Future Outlook



Fundamental Additive Manufacturing M&P Development

Material Properties & NDE

Standards & Specs

Certification Rationale

Lean Component Development

Component Relevant Environment Testing

AMDE Prototype Engine

Methane Propulsion Systems

CCP

Nuclear Thermal Propulsion

SLS: RS-25

Upper Stage Engine

Building Foundational Additive Manufacturing Industrial Base

Additive Manufacturing

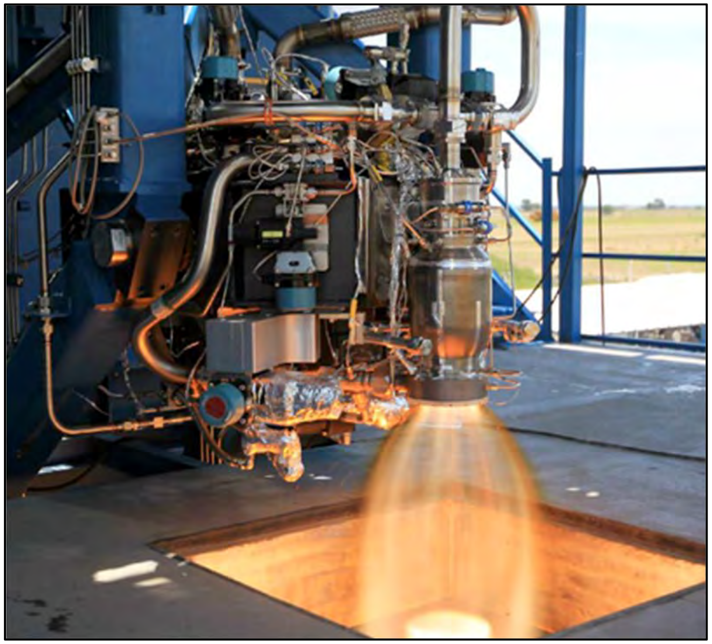
at Marshall Space Flight Center

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

AM in the Human Exploration and Operations Portfolio

Exploration Systems Development
ORION and SLS

Commercial Crew Program (CCP)
DRAGON V2



NASA Exploration Programs and Program Partners have embraced AM for its affordability, shorter manufacturing times, and flexible design solutions.

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

NASA cannot wait for national Standard Development Organizations to issue AM standards.

- Partners in crewed spaceflight programs (Commercial Crew, SLS and Orion) are actively developing AM parts
- In response to request by Commerical Crew Program (CCP), MSFC AM Standard drafted in summer 2015.
- Draft standard completed extensive peer review in Jan 2016.
- **Standard methodology adopted by CCP, SLS, and Orion**.
- Continuing to participate with standards organizations and other certifying Agencies.
- Goal is to incorporate AM requirements at an appropriate level in Agency standards and/or specifications.

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

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

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

MSFC Standard and Specification
Release Date: October 18, 2018

Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

Summary: In Space Manufacturing Applications

Conclusions from Systems Analysis of ISM Utilization for the Evolvable Mars Campaign: Why ISM

- Current maintenance logistics strategy will not be effective for deep space missions
- ISM has the potential to significantly reduce maintenance logistics mass requirements by enabling material commonality and the possibility of material recycling and ISRU for spares
- ISM should be considered and developed in parallel with the systems design

NASA is actively working to develop ISM capabilities:

- **Within Pressurized Volume:** Reduce the logistics challenges and keep astronauts safe and healthy in transit and on extraterrestrial surfaces
- **External/Free Space - IRMA:** Develop new commercial capabilities for robotic spacecraft construction, repair, refurbishment, and repurposing in LEO
- **Extraterrestrial Surfaces - Additive Construction:** Enable infrastructure to be robotically constructed pre- or post-arrival of astronauts on the extraterrestrial surface, whether that be the Moon or Mars.

MSFC is exploring ground-based development for ECLSS applications of AM starting with basic plastic replacement components.

To achieve functional capability supporting the Exploration timeline, ISM must work with Exploration systems designers now to identify high-value application areas and influence

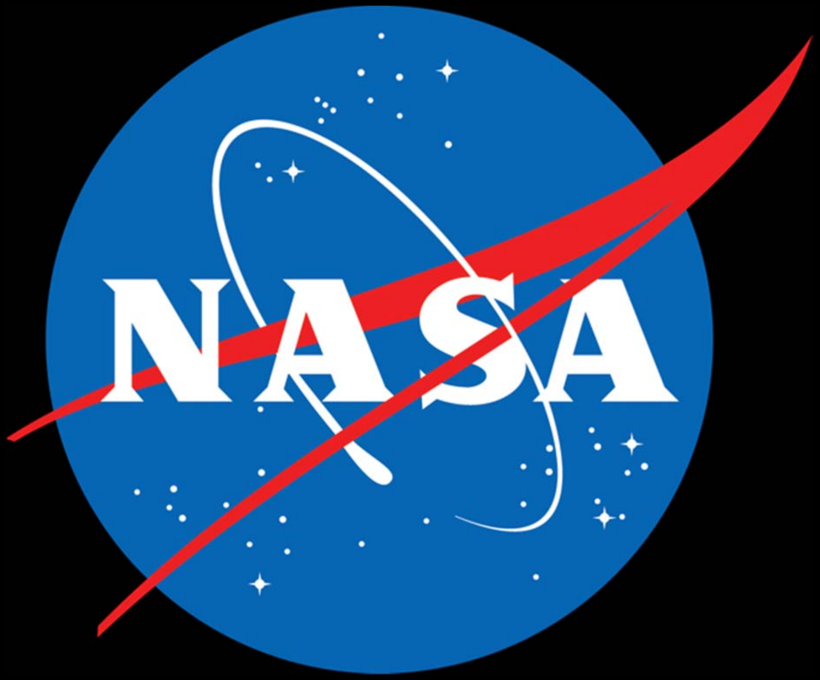
Summary: Space Propulsion System Applications

MSFC has made a major thrust in the application of AM for development of liquid rocket engines ranging from the Space Launch System Core Stage RS-25 engine, to In-Space Class prototype engines, to Cubesat propulsion systems.

- Process development, material property characterization, and component fabrication trials for RS-25 Inconel 718 material applications.
- New design and development philosophy successfully exercised to build AMDE, a prototype in-space class engine incorporating additive manufacturing to reduce costs, schedule and parts counts.
    - Designed and additively manufactured > 150 rocket engine parts in 2.5 years
    - Encompassed every major component and assembly of the engine
    - Developed and demonstrated capability to additively manufacture with copper.
    - Data, expertise, and testbed shared with industry for current/future developments
- Capabilities developed through AMDE experience have been applied to small satellite propulsion systems components design and development

NASA MSFC created a Standard and Specification for AM Spaceflight Hardware in response to near-term programmatic demand.

- Shaped the approach to additive parts for current human-rated space flight programs through early release of Draft Quality Standard approach.
- Standard and Specification provide a framework for consistent evaluation of AM Laser Powder Bed Fusion processes, properties, and components.


NASA

ReFabricator from Tethers Unlimited, Inc.: Closing the Manufacturing Loop

- Technology Demonstration Mission payload conducted under a Phase III SBIR with Tethers Unlimited, Inc.

- Refabricator demonstrates feasibility of plastic recycling in a microgravity environment for long duration missions
    - Closure of the manufacturing loop for FDM has implications for reclamation of waste material into useful feedstock both in-space an on-earth

- Refabricator is an integrated 3D printer (FDM) and recycler
    - Recycles 3D printed plastic (ULTEM 9085) into filament feedstock through the Positrusion process

- Environmental testing of engineering test unit completed at MSFC in April
    - Payload CDR completed in mid-June
    - Operational on ISS in 2018

Refabricator ETU

Prater, Tracie, et al. "NASA's In-space Manufacturing Project: Materials and Manufacturing Process Development Update." Proceedings of the National Space and Missile Materials Symposium. June 2017.

Common Use Materials Development: Recyclable Materials

- Logistics analyses show the dramatic impact of a recycling capability for reducing initial launch mass requirements for long duration missions
  - Current packaging materials for ISS represent a broad spectrum of polymers: LDPE, HDPE, PET, Nylon, PVC

- Tethers CRISSP (Customizable Recyclable ISS Packaging) seeks to develop common use materials (which are designed to be recycled and repurposed) for launch packaging
  - Work under Phase II SBIR
  - Recyclable foam packaging made from thermoplastic materials using FDM
  - Can create custom infill profiles for the foam to yield specific vibration characteristics or mechanical properties

- Cornerstone Research Group (CRG) is working under a Phase II SBIR on development of reversible copolymer materials
  - Designs have strength and modulus values comparable to or exceeding base thermoplastic materials while maintaining depressed viscosity that makes them compatible with FDM

CRISSP (image from Tethers Unlimited)

FDM prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from Cornerstone Research Group)

Toward an In-Space Metal Manufacturing Capability

- Made in Space Vulcan unit (Phase I SBIR)
  - Integrates FDM head derived from AMF, wire and arc metal deposition system, and a CNC end-mill for part finishing
- Ultra Tech Ultrasonic Additive Manufacturing (UAM) system (Phase I SBIR)
  - Prints parts using sound waves to consolidate layers of metal from foil feedstock
- Tethers Unlimited MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly) (Phase I SBIR)
  - Builds on ReFabricator recycling process
  - Bulk feedstock is CNC-milled
- Techshot, Inc. SIMPLE (Sintered Inductive Metal Printer with Laser Exposure) (Phase II SBIR)
  - AM process with metal wire feedstock, inductive heating, and a low-powered laser

Illustration of Vulcan Exterior Unit (image courtesy of Made in Space)

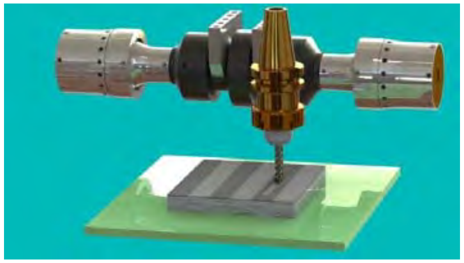
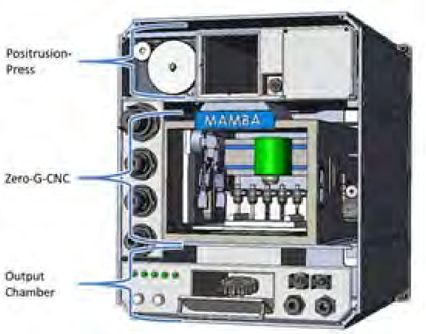
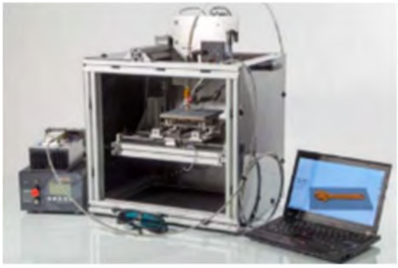


Illustration of UAM process (image courtesy of Ultra Tech)



Tethers Unlimited MAMBA concept. Image courtesy of Tethers Unlimited.

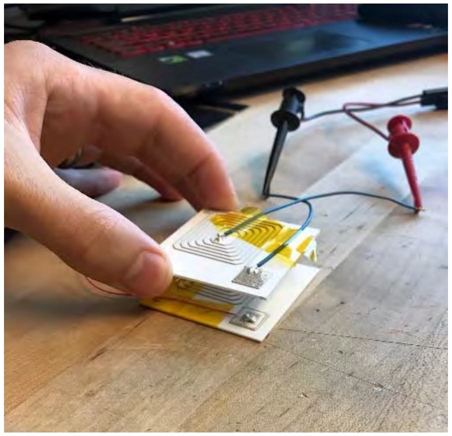


Techshot's SIMPLE, a small metal printer developed under a Phase I SBIR. Image courtesy of Techshot.

Ground-based Work on Printed Electronics

- Evaluating technologies to enable multi-material, digital manufacturing of components
- Development of additively manufactured wireless sensor archetype (MSFC)
  - Printed RLC circuit with coupled antenna
  - Capacitive sensing element is pressure, temperature, or otherwise environmentally sensitive material developed at MSFC
- Design of pressure switch for urine processor assembly (UPA)
  - Existing pressure switch has had several failures due to manufacturing flaw in metal diaphragm
  - In additive design, switching is accomplished via a pressure sensitive material
- Miniaturization and adaptation of printable electronics for microgravity environment will continue through two Phase 1 contracts awarded under SBIR subtopic In-Space Manufacturing of Electronics and Avionics
  - Techshot, Inc. (STEPS – Software and Tools for Electronics Printing in Space)
  - Optomec working on miniaturization of patented Aerosol Jet technology

MSFC nScrypt multimaterial printer
(4 heads and pick and place capability)



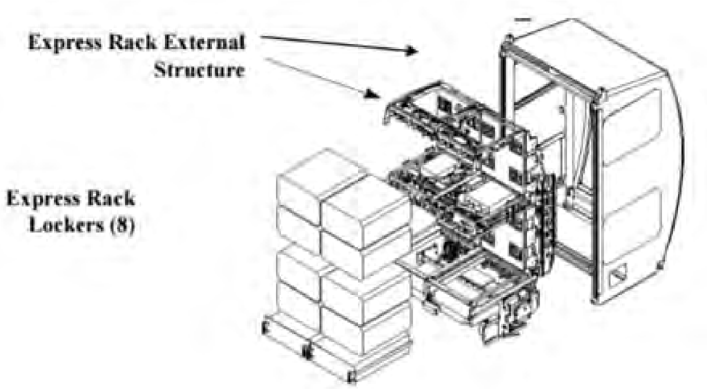
Printed wireless humidity sensor
(wires attached for characterization purposes)

The Multimaterial Fabrication Laboratory for ISS (“FabLab”)

Typical EXPRESS Rack structure

Power consumption for entire rack is limited to 2000 W

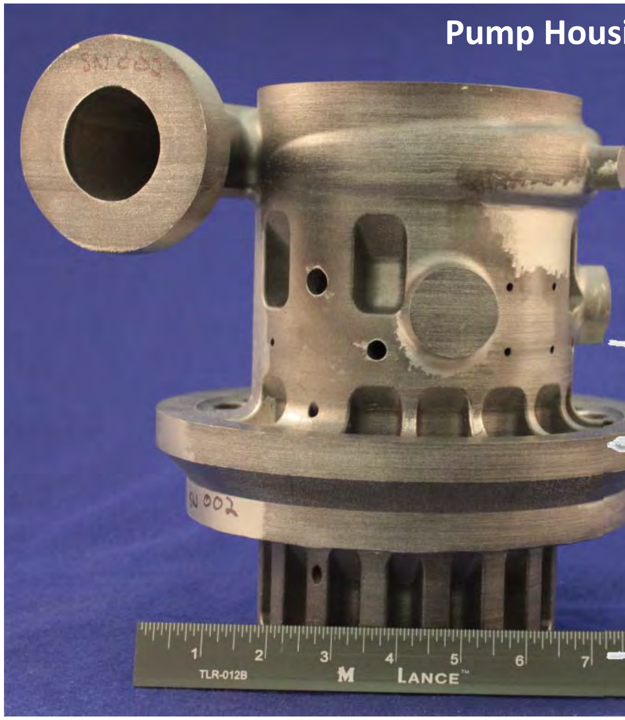
Payload mass limit for rack is less than 576 lbm



Threshold
The system should have the ability for on-demand manufacturing of multi-material components including metallics and polymers as a minimum.
The minimum build envelope shall be 6” x 6” x 6”.
The system should include the capability for earth-based remote commanding for all nominal tasks.
The system should incorporate remote, ground-based commanding for part handling and removal in order to greatly reduce dependence on astronaut time.*
The system should incorporate in-line monitoring of quality control and post-build dimensional verification.

- NASA is evaluating proposals to provide a feasible design and demonstration of a first-generation multimaterial, multiprocess In-space Manufacturing Fabrication Laboratory for demonstration on the ISS
- Minimum target capabilities include:
  - Manufacturing of metallic components
  - Meet ISS EXPRESS Rack constraints for power and volume
  - Limit crew time
  - Incorporate remote and autonomous verification and validation of parts
- Phased approach
  - Phase A – scaleable ground-based prototype
  - Phase B – mature technologies to pre-flight deliverable
  - Phase C – flight demonstration to ISS

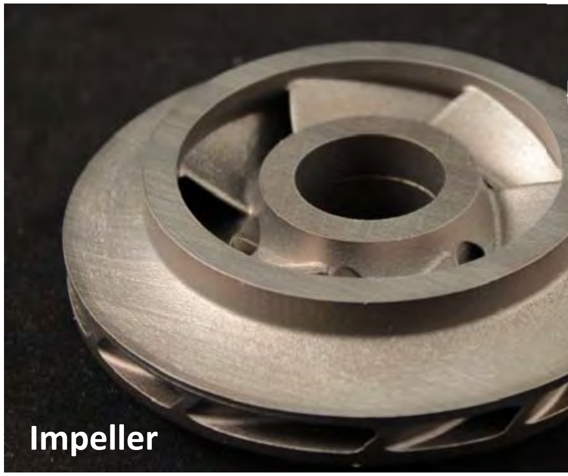
AM Turbomachinery – Liquid Oxygen Pump, 35k-lb$_f$ Test bed



Pump Housing

Turbine Housing

Shaft Baffle



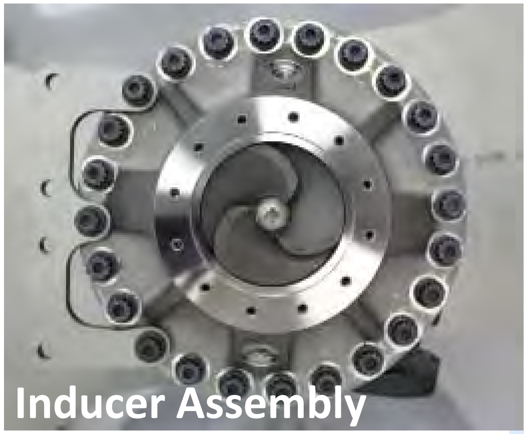
Impeller

Turbine Blades

Stator

Ref: Derek O’Neal / NASA MSFC

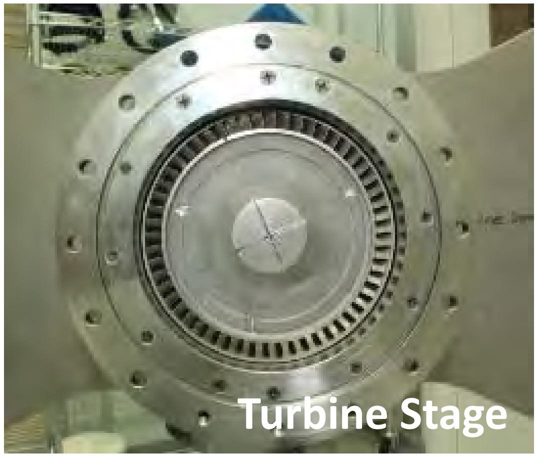
Turbomachinery – Fuel Turbopump



Inducer Assembly

Turbopump Assembly

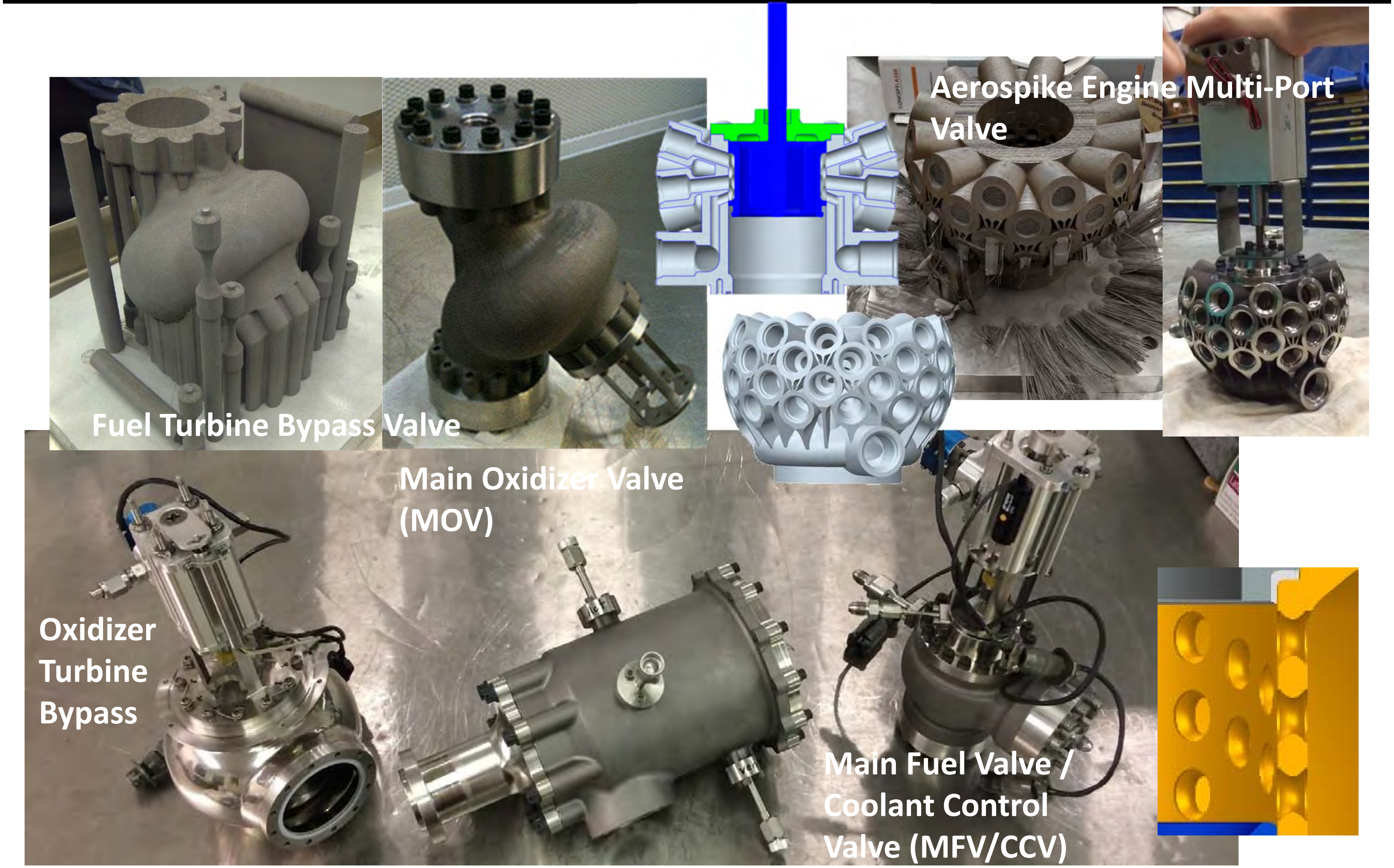
Rotating Assembly



Turbine Stage

Ref: Marty Calvert / NASA MSFC

Additively Manufactured Valves



Fuel Turbine Bypass Valve

Aerospike Engine Multi-Port Valve

Main Oxidizer Valve (MOV)

Oxidizer Turbine Bypass

Main Fuel Valve / Coolant Control Valve (MFV/CCV)

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