NASA Additive Manufacturing Initiatives: In Space Manufacturing and Rocket Engines

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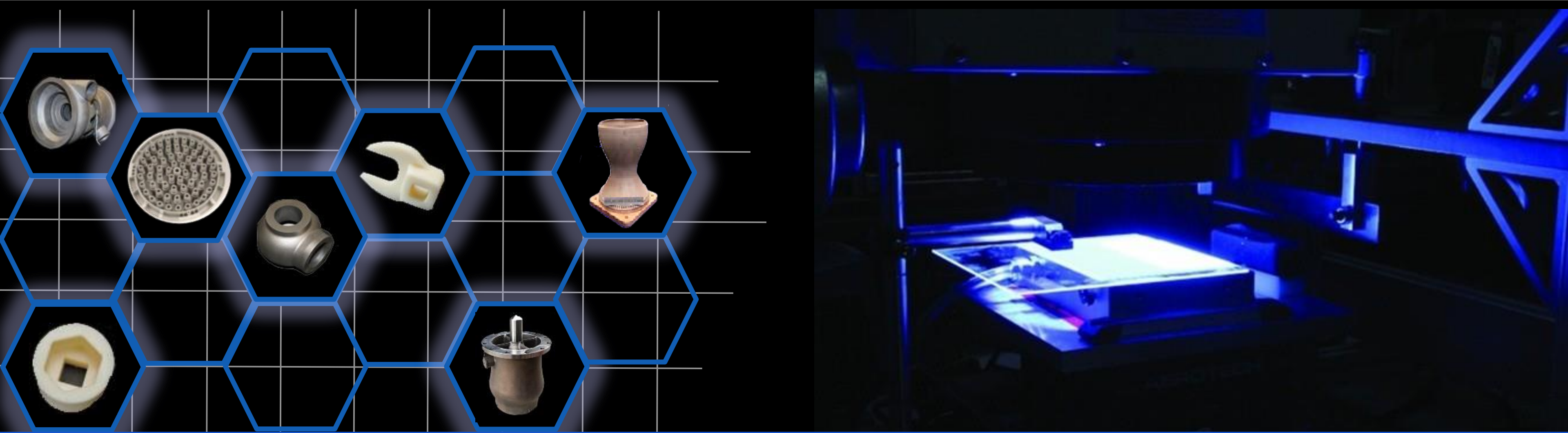
- Elizabeth Robertson: NASA MSFC Additive Manufactured Engine Technology Development
- Graham Nelson: NASA MSFC Additive Manufactured Engine Technology Development
- Nicolas Case: NASA MSFC Additive Manufactured Engine Technology Development
- Dr. Doug Wells: MSFC Lead, Additively Manufactured Spaceflight Hardware Standard and Specification

Agenda

1. NASA's In Space Manufacturing Initiative (ISM) For Exploration
2. Additive Manufacturing (AM) for Rocket Engines
3. Primary Challenges to Effective Use of Additive Manufacturing
4. Summary



In Space Manufacturing

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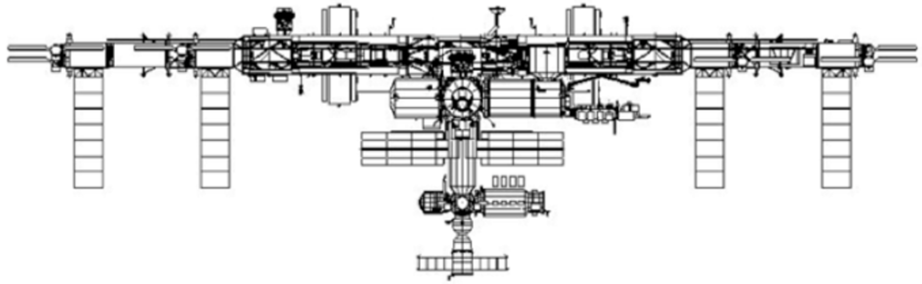
ISS Maintenance Logistics Model – Cirillo Analysis

Each square represents 1000 kg

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

~13,000 kg on orbit

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 = 17,990 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., Goodli_, 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.

Owens, A. C. and de Weck, O. L., \Increasing the Fidelity of Maintenance Logistics Representation in Breakeven Plots," 46th International Conference on Environmental Systems, No. ICES-2016-344, International Conference on Environmental Systems, Vienna, Austria, 2016.

* - Based on predicted MTBFs

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)*

Space Launch System

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
- On-demand Parts Catalogue
- Exploration Systems Demonstration and Operational Validation

CIS-LUNAR

Asteroids

EARTH INDEPENDENT Mars

Planetary Surfaces Platform

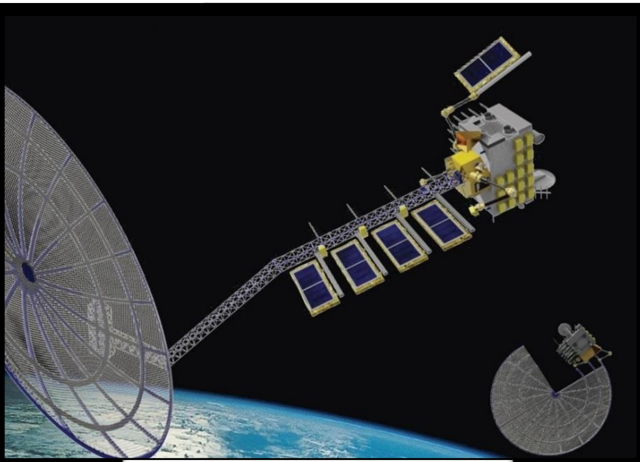
- Multi-materials Fab Lab (metals, polymers, automation, printable electronics)
- Food/Medical Grade Polymer Printing & Recycling
- Additive Construction Technologies
- Regolith Materials – Feedstock

Text Color Legend

Foundational AM Technologies
AM Capabilities for Exploration Systems
Surface / ISRU Systems

Key ISM Thrust Areas

In-space Robotic Manufacturing and Assembly Overview



Concept by Made In Space

Concept by Space Systems/Loral

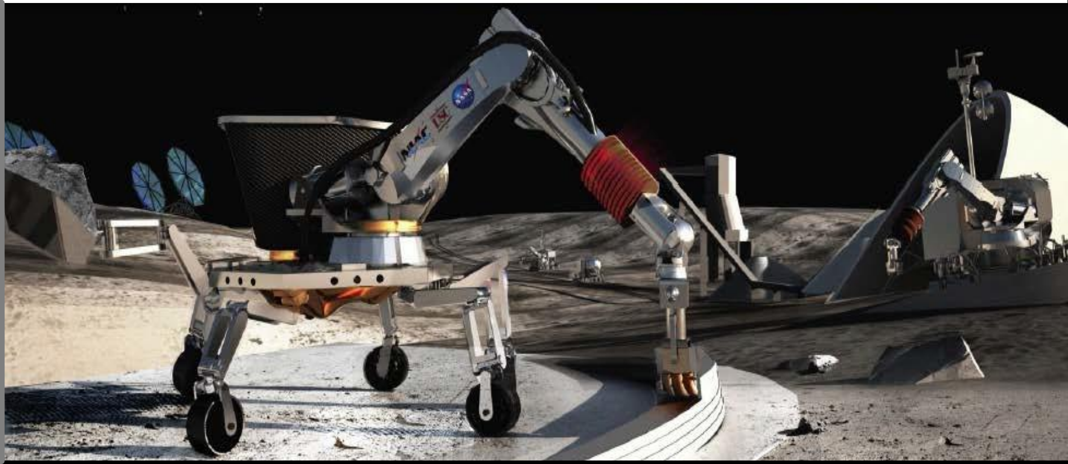
Concept by Orbital ATK

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

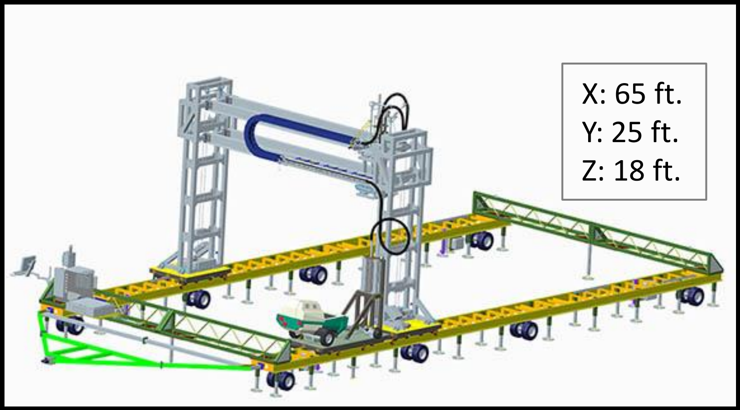
US Army Corps of Engineers
Engineer Research and Development Center

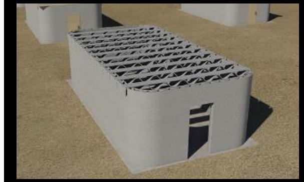
Additive Construction with Mobile Emplacement (ACME) NASA



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’

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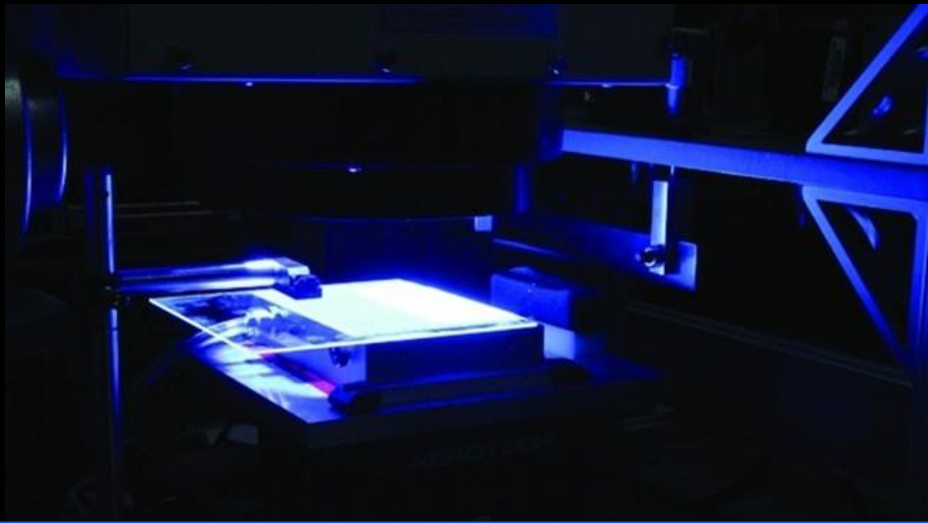


Additive Manufacturing

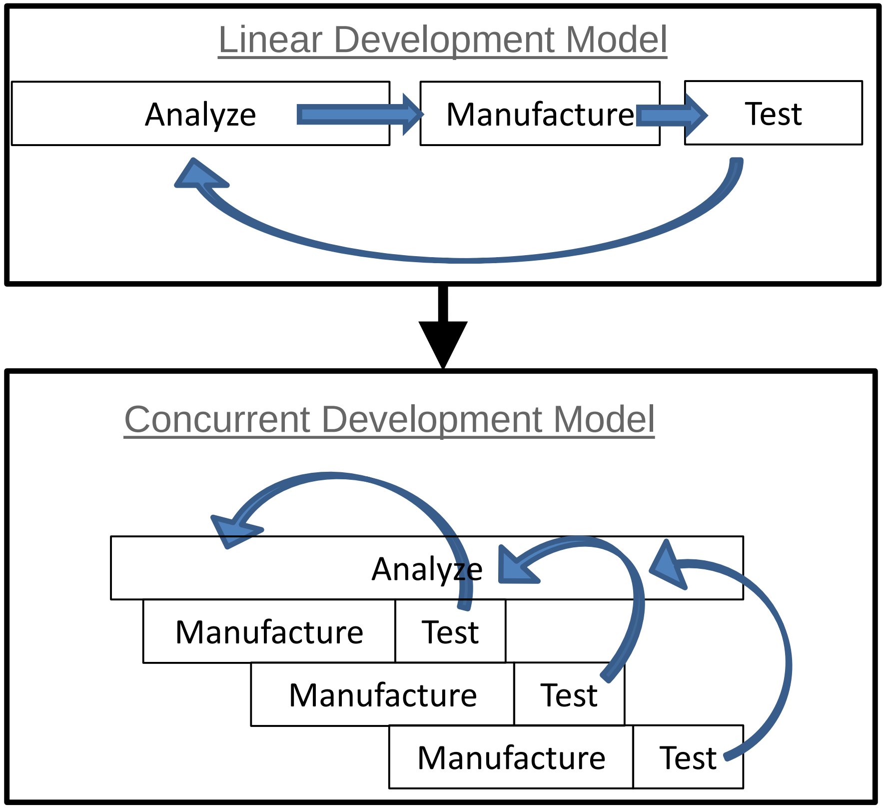
at Marshall Space Flight Center

Additive Manufacturing Development for Rocket Engine Space Flight Hardware

Additive Manufacturing Demonstrator Engine (AMDE) Project Objectives

Primary Objectives:

1. Demonstrate an approach that reduces the cost and schedule required for new rocket engine development
   - **Prototype engine in 2.5 years**
   - Operate lean
   - Shift to Concurrent Development Model
     – Use additive manufacturing (AM) to facilitate this approach
2. Advance the TRL of AM parts through component/system testing
3. Develop a cost-effective Upper-Stage or In-Space Class prototype engine

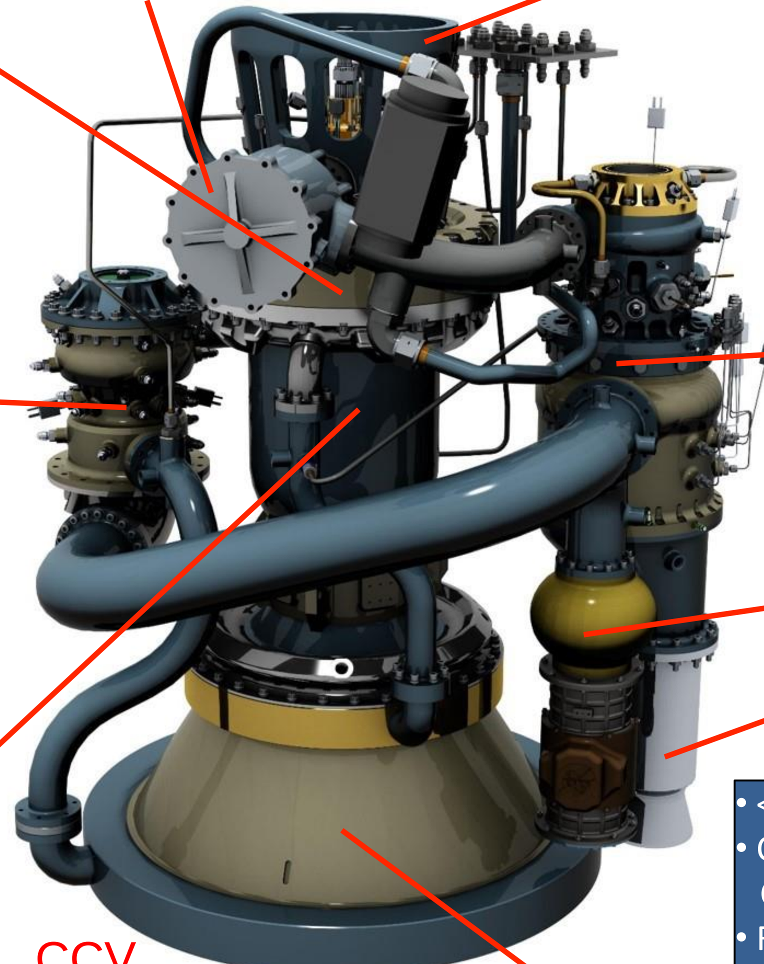


AMDE Reduced Part Count for Major Hardware

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
- Methane test successful
- Electron Beam Free Form
- Schedule reduction > 50%
- SLM with GRCop.
- Fabrication nickel alloy structural jacket and manifolds.



- <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

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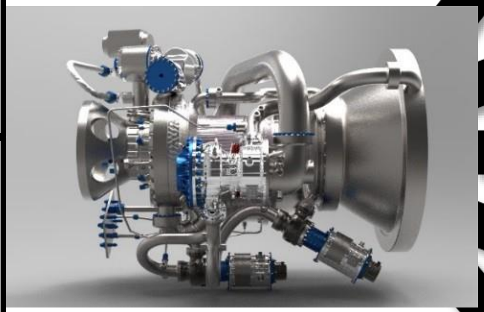
Future Outlook

Fundamental Additive Manufacturing M&P Development

Material Properties & NDE → Standards & Specs → Certification Rationale

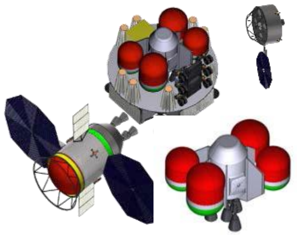
Lean Component Development

Component Relevant Environment Testing



AMDE Prototype Engine

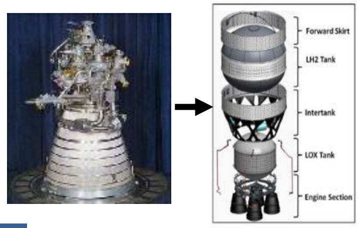
Methane Prop. Systems



CCP

Nuclear Propulsion

Upper Stage Engine



RS-25

Building Foundational Additive Manufacturing Industrial Base

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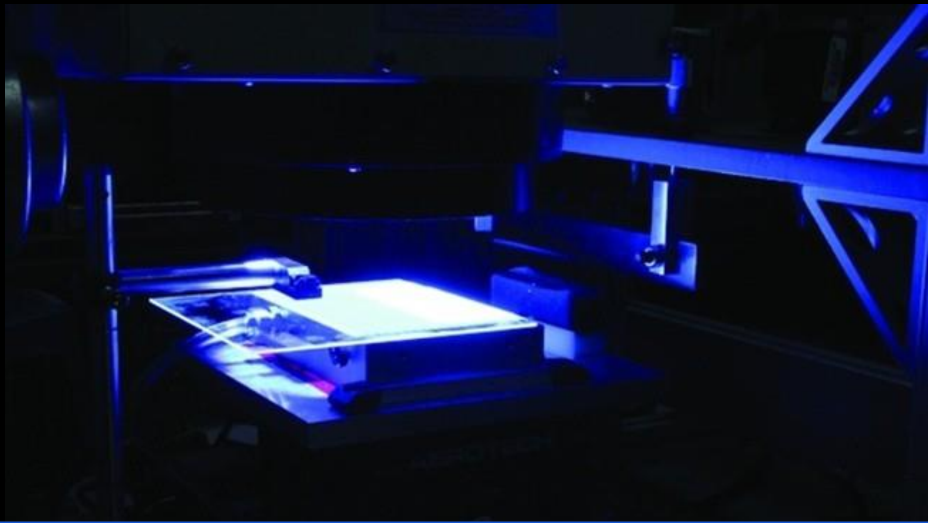

Additive Manufacturing

at Marshall Space Flight Center

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

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

- In response to request by CCP, MSFC AM Standard drafted in summer 2015.
- Draft standard completed extensive peer review in Jan 2016.
- Final revision currently in work; target release date of Spr 2017.
- **Standard methodology adopted by CCP, SLS, and Orion**.
- Partners in crewed space flight programs (Commercial Crew, SLS and Orion) are actively developing **AM parts**
- Continuing to watch progress of 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

THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
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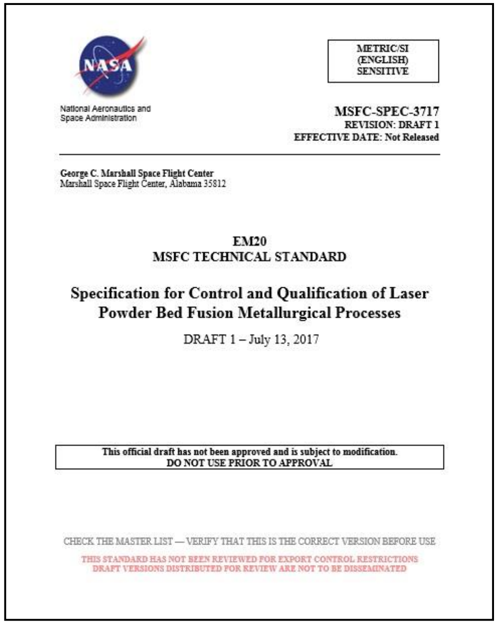

METRIC/SI (ENGLISH) SENSITIVE

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.
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Final revision currently in work; target release date of Fall 2017

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

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Summary

A Systems Analysis of ISM Utilization for the Evolvable Mars Campaign yielded the following conclusions:

- 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 to

- (1) Reduce the logistics challenges and keep astronauts safe and healthy in transit and on extraterrestrial surfaces
- (2) Add new commercial capabilities in spacecraft construction and repair in LEO
- (3) Enable infrastructure to be robotically constructed prior to the arrival of astronauts on the extraterrestrial surface, whether that be the Moon or Mars.

MSFC has made a major thrust in the application of additive manufacturing for development of liquid rocket engines.

- Successfully exercised a new design and development philosophy to build AMDE, a prototype in-space class engine incorporating additive manufacturing to reduce costs, schedule and parts counts.
- Designed and additively manufactured more than 150 rocket engine parts encompassing every major component and assembly of the engine in 2.5 years, including capability to additively manufacture with copper.
- Data, experience, and testbed shared with industry, exploration partners for current and future developments

NASA MSFC created a Standard and Specification for AM Spaceflight Hardware for near-term programmatic demand for a framework for consistent evaluation of AM processes and components. The draft served to shape the approach to additive parts for current human-rated space flight programs.

NASA

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

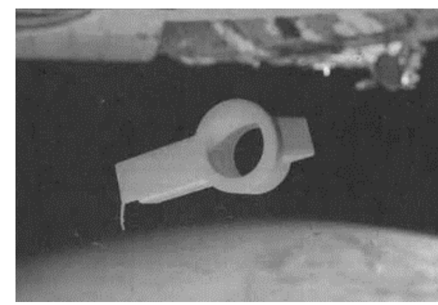
The Made in Space Additive Manufacturing Facility (AMF)

- Additive Manufacturing Facility (AMF) is the follow-on 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.

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.

Additive Construction Dual Use Technology Projects For Planetary and Terrestrial Applications

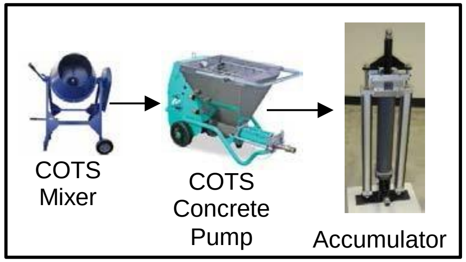
Additive Construction with Mobile Emplacement (ACME)

Planetary Regolith-based Concrete

Candidate Binder Materials

- Sorel-type cement (Mg0-based)
- Sulfur cement
- Polymers / trash
- Portland cement

Manual feed



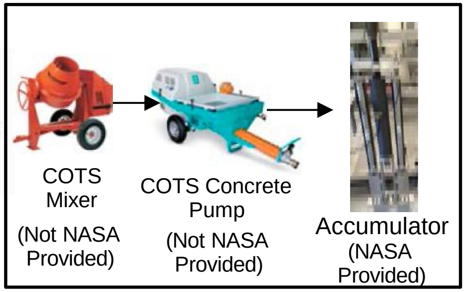
ACME 2 Nozzles

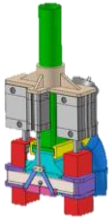
Subscale Optimized Planetary Structure

Gantry → *Materials* → *Dry Good Feed* → *Liquid Storage* → *Continuous Delivery and Mixing System* → *Nozzle* → *Print Trials*

Portland Cement

Storage Subsystems





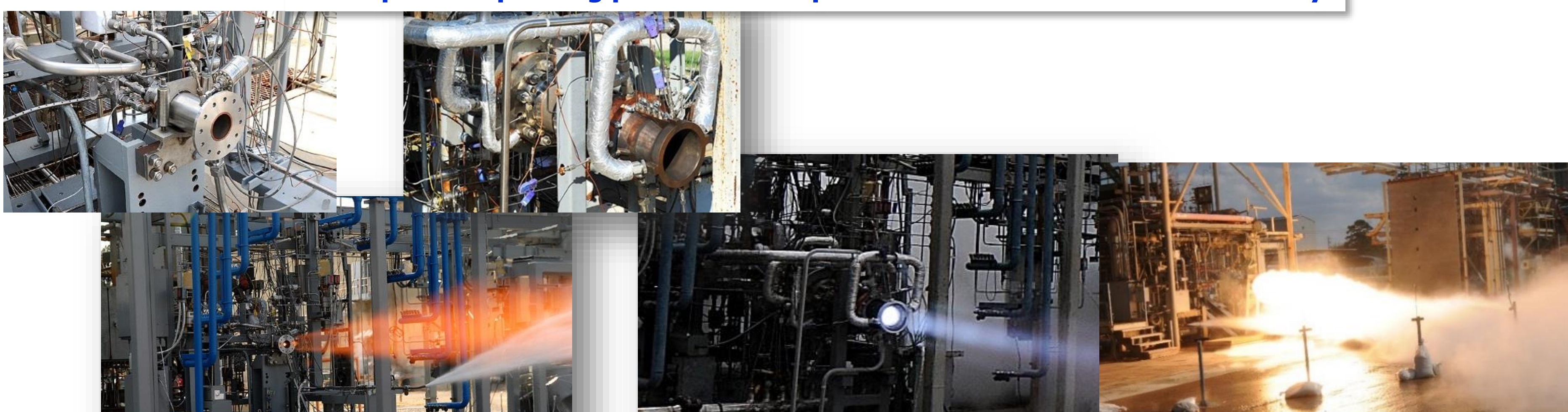
ACES 2 Nozzle

Guard Shack
(6' x 6' x 8')

Automated Construction of Expeditionary Structures (ACES)

Additive Combustion Chambers Assembly

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



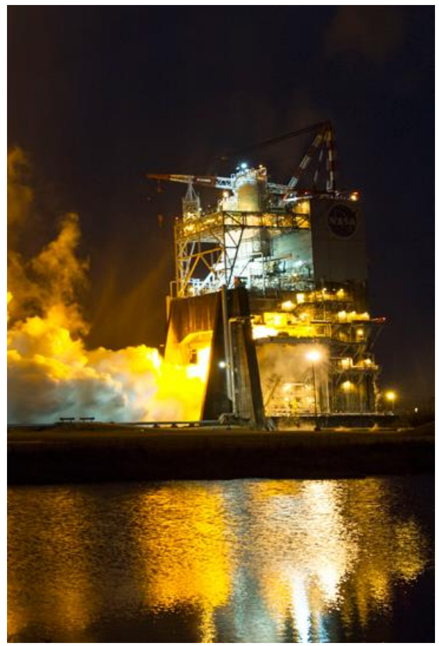
GRCop-84 AM Chamber Accumulated **2365 sec** hot-fire time at full power with no issues

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

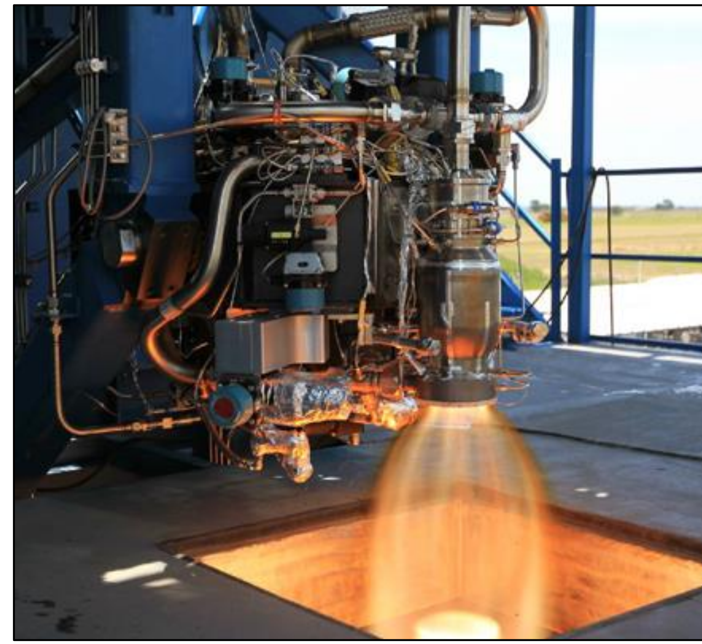
Ox-Rich Staged Combustion Subscale Main Injector Testing of 3D-Printed Faceplate

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.