NASA Additive Manufacturing Initiatives: In Space Manufacturing and Rocket Engines

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- Dr. Doug Wells: MSFC Lead, Additively Manufactured Spaceflight Hardware Standard and Specification
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
Additive Manufacturing

at Marshall Space Flight Center

In Space Manufacturing
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

Predicted Annual Average Upmass 2012-2020

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

~3,000 kg Upmass per year

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

* - 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)

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

**EARTH INDEPENDENT Mars**
- 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

- **Printed Electronics**
  - MSFC

- **In-Space Metallics**
  - Made In Space
  - Ultra Tech

- **Recycler/Printer**
  - Tethers Unlimited

- **Common Use Recyclable Materials**
  - Cornerstone Research Group
  - Tethers Unlimited

- **Techshot**
  - Tethers Unlimited
In-space Robotic Manufacturing and Assembly Overview

**Archinaut**
A Versatile In-Space Precision Manufacturing and Assembly System

**Dragonfly**
On-Orbit Robotic Installation and Reconfiguration of Large Solid Radio Frequency (RF) Reflectors

**CIRAS**
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

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’

X: 65 ft.
Y: 25 ft.
Z: 18 ft.
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.

**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**
- <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

**CCV (Hidden)**
Part Count 1 vs. 5

**Regen Nozzle**
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

Building Foundational Additive Manufacturing Industrial Base

Methane Prop. Systems

CCP

Nuclear Propulsion

RS-25

Upper Stage Engine

Future Outlook
Additive Manufacturing

at Marshall Space Flight Center

MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware
Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

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


**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.

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

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 and 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

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 (MgO-based)
- Sulfur cement
- Polymers / trash
- Portland cement

**Manual feed**

**Continuous Delivery and Mixing System**
- COTS Mixer
- COTS Concrete Pump
- Accumulator

**Materials**

**Dry Good Feed**
- Portland Cement

**Liquid Storage**
- Storage Subsystems

**Gantry**

**Nozzle**
- ACME 2 Nozzles
- ACES 2 Nozzle

**Print Trials**
- Subscale Optimized Planetary Structure
- 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
NASA Exploration Programs and Program Partners have embraced AM for its affordability, shorter manufacturing times, and flexible design solutions.