

Additive Manufacturing for Human Space Exploration



Additive Manufacturing for Aerospace And Space
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- Andy Hardin: NASA MSFC SLS Liquid Engines Office
- Dr. Doug Wells: NASA MSFC Lead, Additively Manufactured Space Flight Hardware Standard and Specification

Agenda

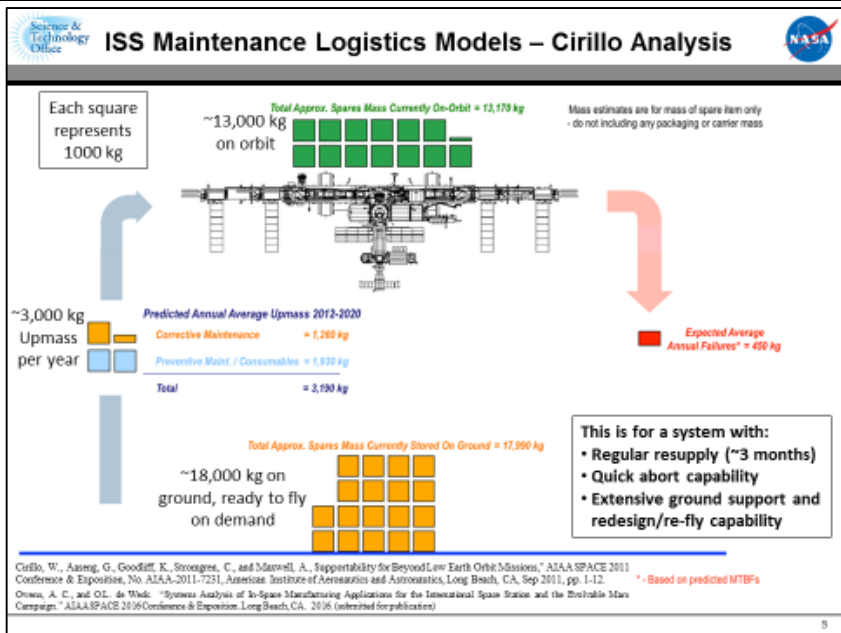
NASA's In Space Manufacturing Initiative (ISM)

- The Case for ISM: WHY
- ISM Path to Exploration
 - Results from 3D Printing in ZeroG Technology Demonstration Mission
 - ISM Challenges
- 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

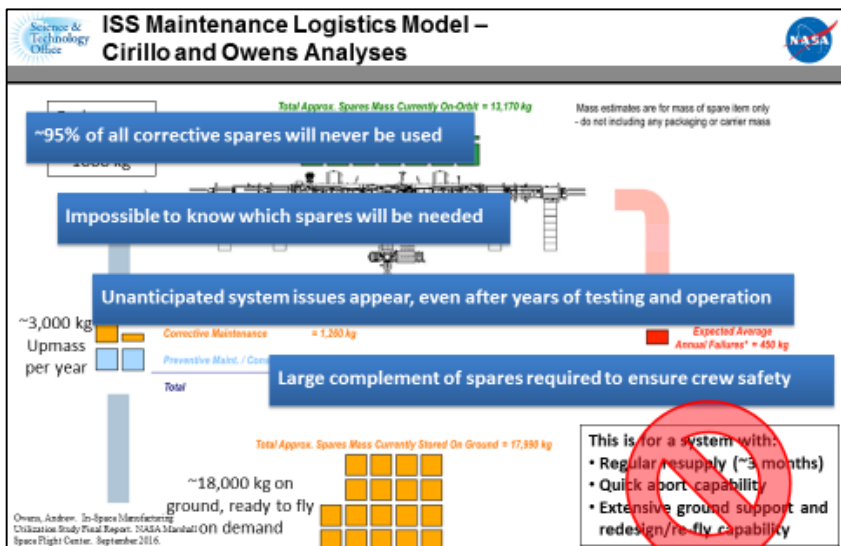


Current maintenance logistics strategy **will not be effective** for deep space exploration missions

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

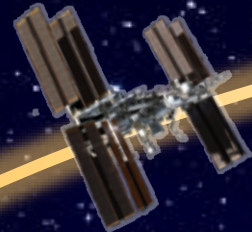


GROUND-BASED

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



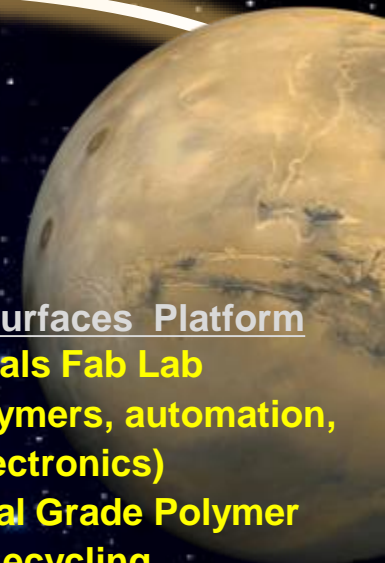
ISS Test-bed – Transition to Deep Space Gateway

- 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**

Space Launch System

Text Color Legend

Foundational AM Technologies

AM Capabilities for Exploration Systems

Surface / ISRU Systems

Key ISM Thrust Areas



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



The 3DP in Zero G Tech Demo delivered the first 3D printer to ISS and investigated the effects of consistent microgravity on fused deposition modeling

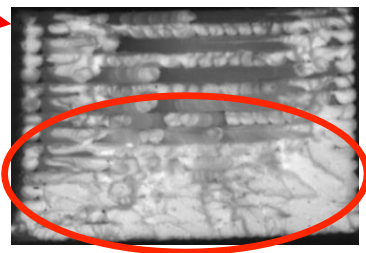
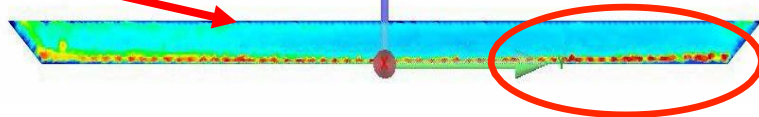
Phase I Prints (Nov-Dec 2014): mechanical property test articles; range coupons; and functional tools



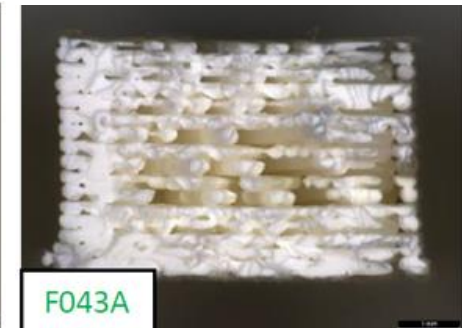
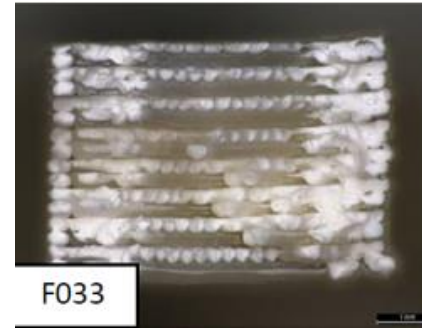
Printer inside Microgravity Science Glovebox (MSG)

Key Observations:

- Tensile and Flexure: Flight specimens stronger and stiffer than ground specimens
- Compression: Flight specimens are weaker than ground specimens
- Density: Flight specimens slightly more dense than ground specimens; compression specimens show opposite trend
- Structured Light Scanning: Protrusions along bottom edges (more pronounced for flight prints)
- Microscopy: Greater Densification of Bottom Layers (flight tensile and flexure)
- Z-Calibration distance variation suspected to be primary factor driving differences between flight and ground samples
- Potential influence of feedstock aging are being evaluated further



- Phase II Prints:
 - 25 specimens (tensile + compression) built at an optimal extruder standoff distance.
 - 9 specimens printed with intentionally decreased extruder standoff distance to mimic Phase I flight process conditions
- Key findings:
 - No substantive chemical changes in feedstock
 - No evidence of microgravity effects noted in SEM, SLS, CT analysis. Some internal structure variation between builds and with changes in process settings (primarily compression)
 - All prints to date with 3DP appear to be broadly part of the same family of data
 - Phase I data variations appear traceable to:
 - Differences in manufacturing process settings (extruder standoff distance)
 - Data scatter characteristic of many additively manufactured materials and processes.
 - Printer variability



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

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

- Lack of demonstrated metallic AM capability in microgravity.
 - MSFC has 4 SBIR projects working on metallic AM systems targeted for use in microgravity
 - MSFC is currently evaluating proposals submitted in response to our FabLab solicitation, which is expected to include a metallic AM printing capability.
- Operating in the space environment.
 - Space operations face constraints that terrestrial operation do not such as power, volume, and environmental limitations
 - Operations of these capabilities and resulting printed parts must be safe for the astronauts.
 - Certification of parts fabricated on orbit or in transit
 - Overall, the technologies developed must be much smaller, safer, and much more autonomous than earth-based counterparts.
- Culture change.
 - Systems that plan to use on-demand manufactured parts must institute a ‘design for maintainability’ approach.
 - ISM team needs to be working with exploration system designers now to identify high-value application areas and influence design
 - ISM is a necessary paradigm shift in space operations, not a ‘bonus’



In-space Robotic Manufacturing and Assembly (IRMA) Overview



Concept by Made In Space



Concept by Space Systems/Loral



Concept by Orbital ATK

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



US Army Corps of Engineers.
Engineer Research and Development Center

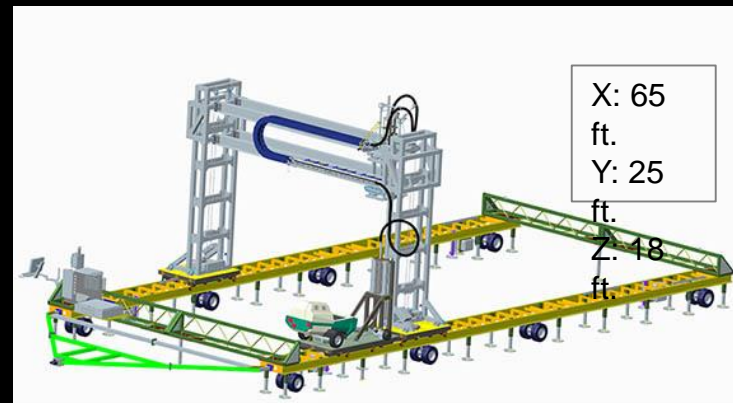
Additive Construction with Mobile Emplacement (ACME) NASA



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

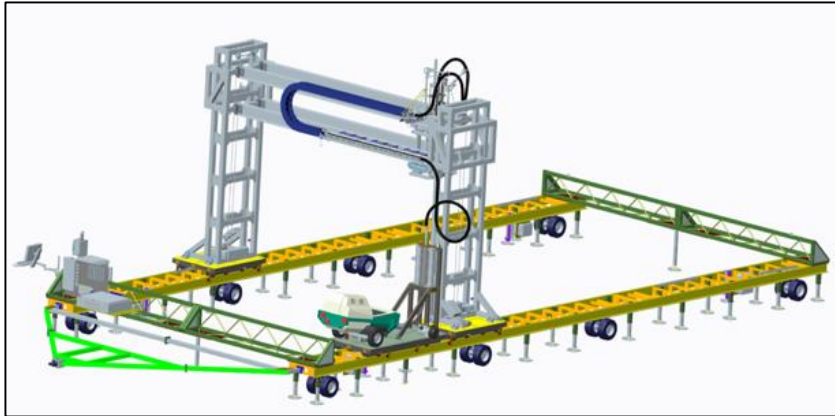
Automated Construction of Expeditionary Structures (ACES)

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



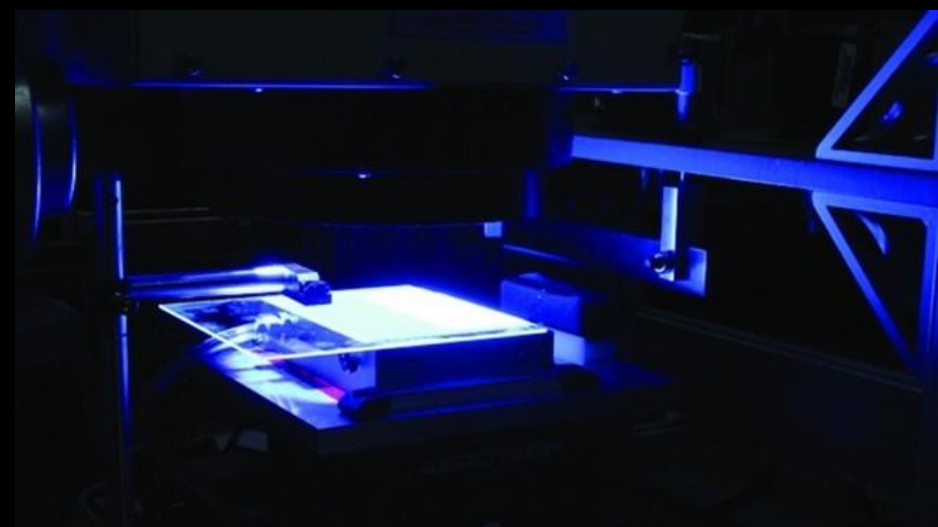
ACES-3 System in Champaign, IL



ACES-3 in Champaign, IL, aerial view



KSC Material Delivery System



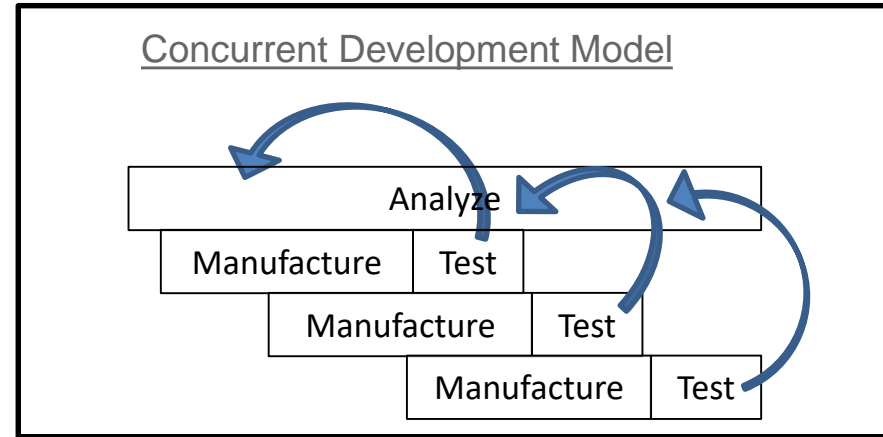
Additive Manufacturing

at Marshall Space Flight Center

Additive Manufacturing Development for Liquid Rocket Engine Space Flight Hardware

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



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
 - Valves
 - Injectors
 - Turbomachinery
 - Nozzles
- Small Satellite Propulsion Components

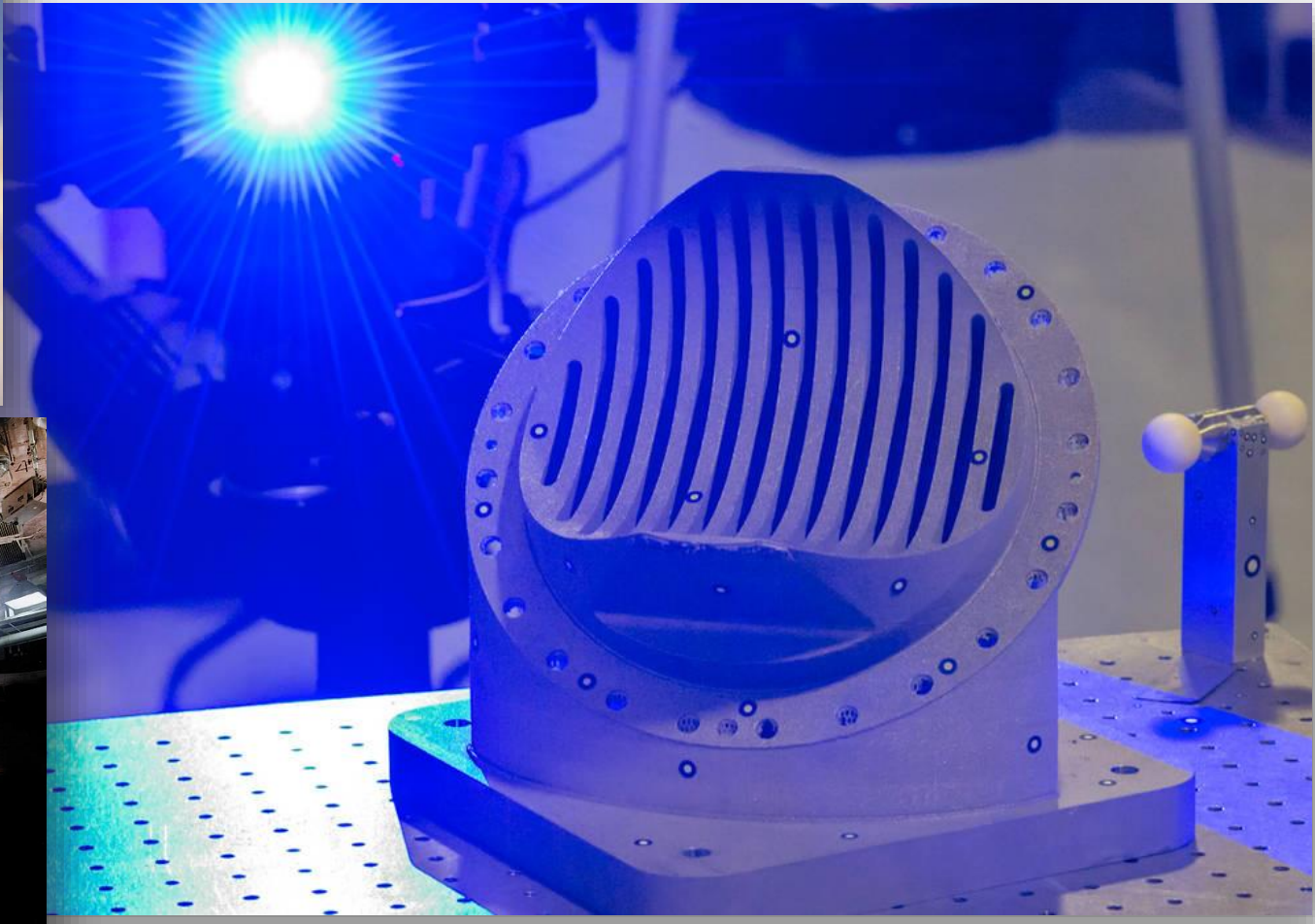
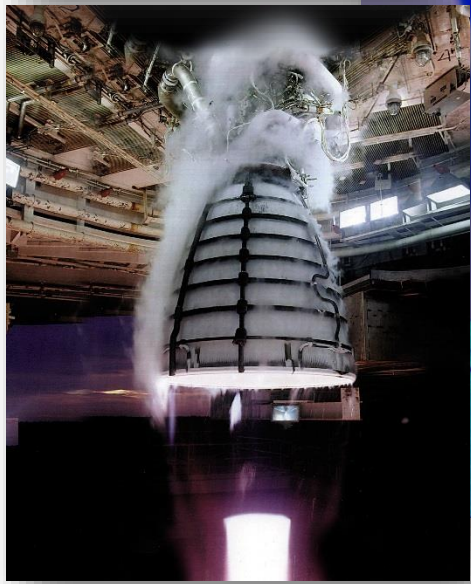
SLS Program / RS-25 Engine Example Pogo Z-Baffle



Inconel 718

Used existing design with additive manufacturing to reduce complexity from 127 welds to 4 welds

- 1 of 35 part opportunities being considered for RS25 engine



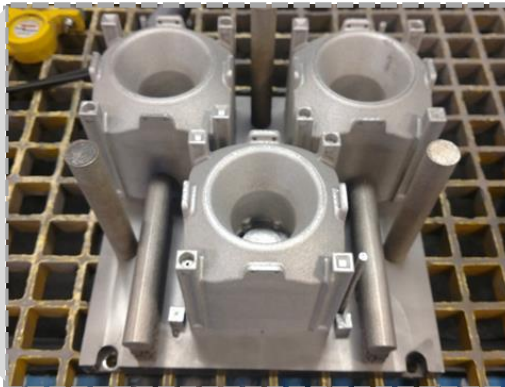


CubeSat cuboidal tank design:

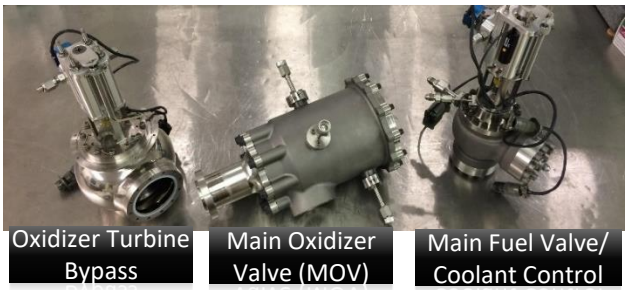
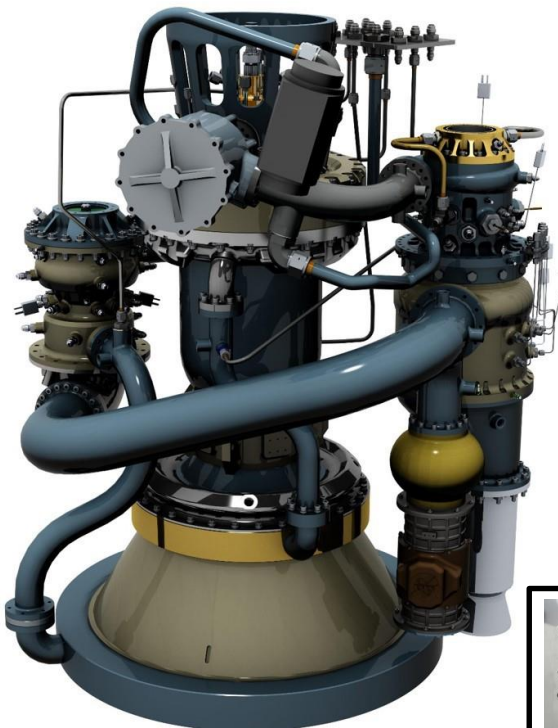
- Topology optimized
- Printed
- Successfully hydrostatic proof tested



- 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



Oxidizer Turbine Bypass Main Oxidizer Valve (MOV) Main Fuel Valve/Coolant Control

Valve Development



100 lb LOX Propane 1.2K LOX Hydrogen 20K AMDE Lox Hydrogen

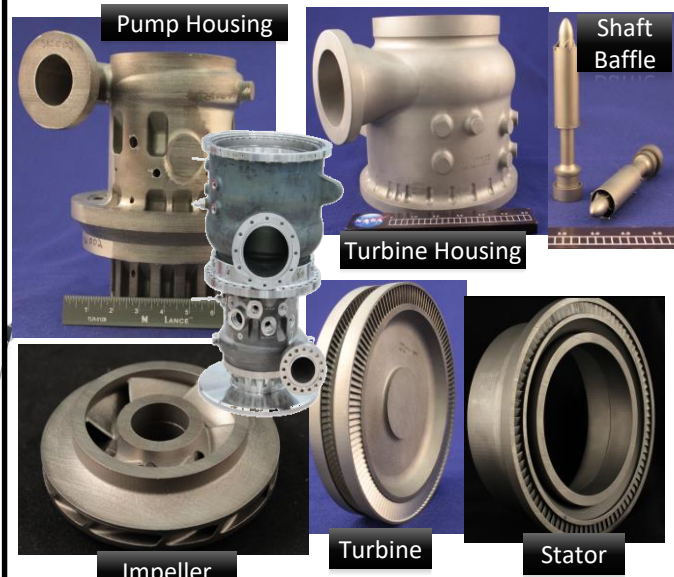


4K Methane 20K AMDE Lox Hydrogen 35k Methane GG

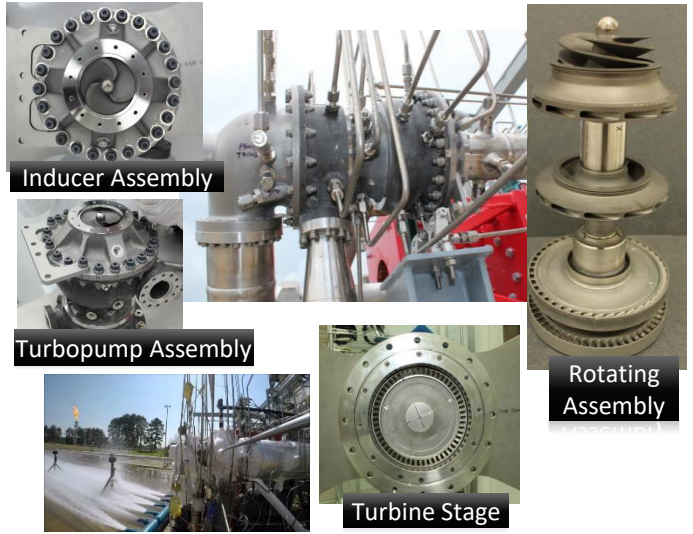
Injector Development



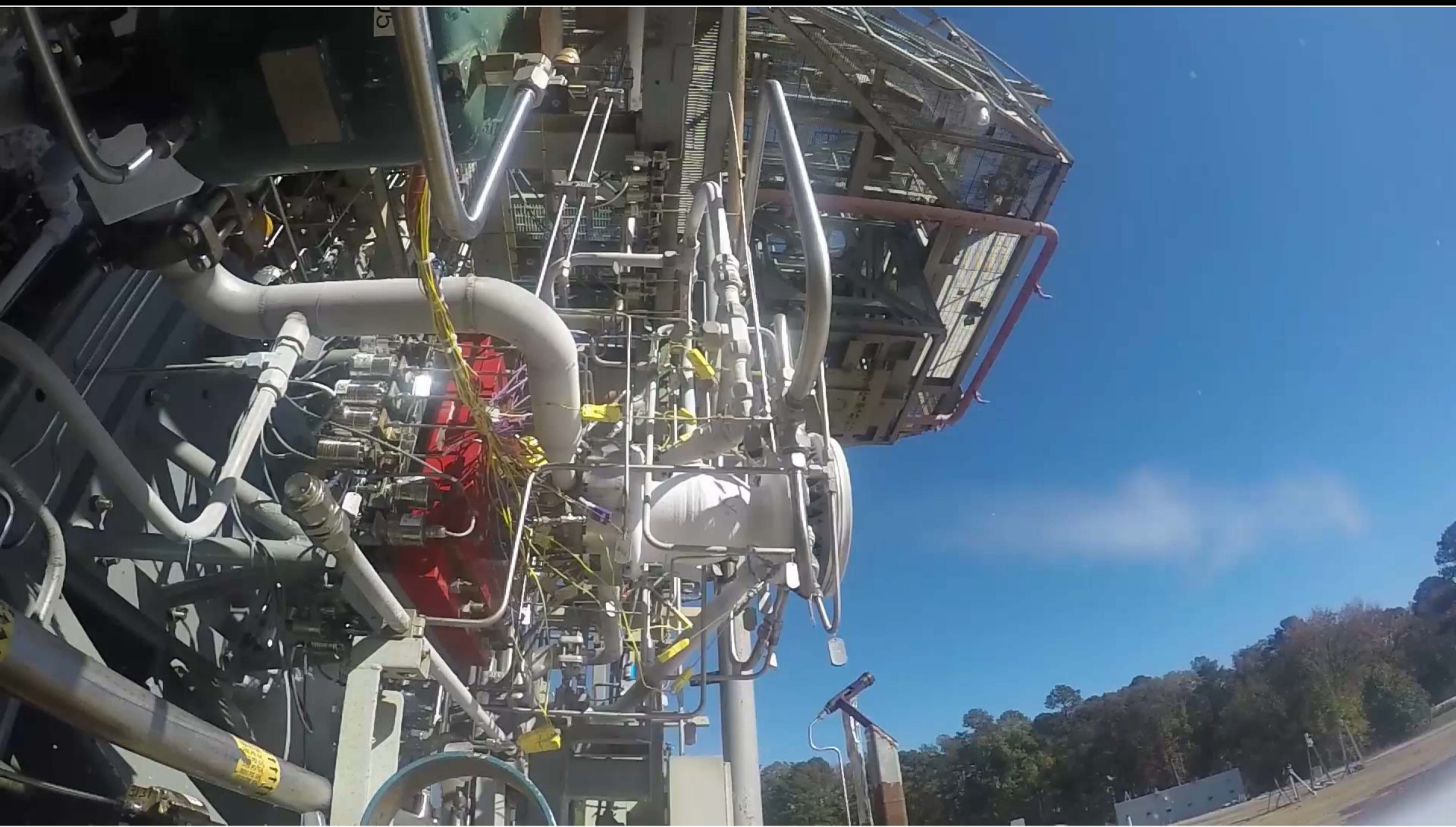
Copper Main Combustion Chamber Development

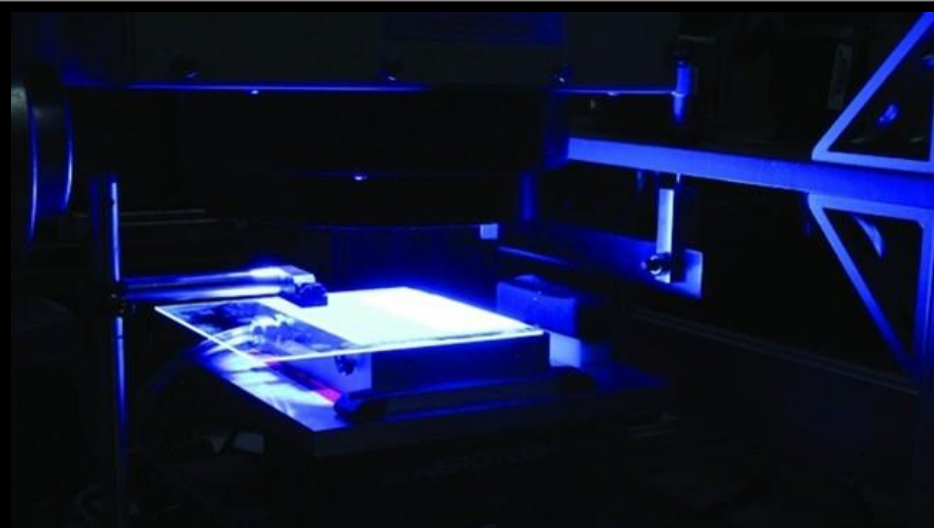


Liquid Oxygen Turbopump Development



Fuel Turbopump Development



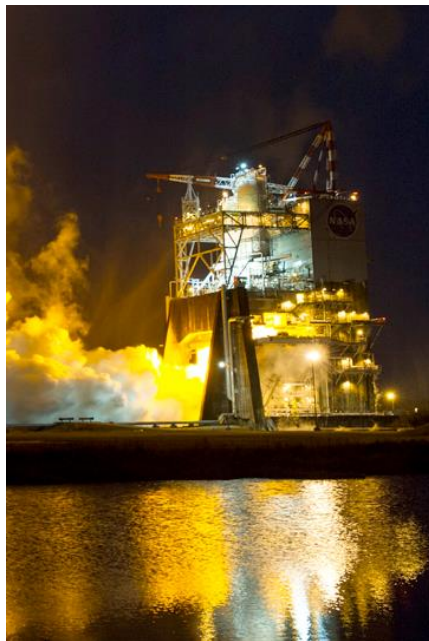


Additive Manufacturing

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MSFC Standard and Specification for Additively Manufactured Spaceflight Hardware

Exploration Systems Development ORION and SLS



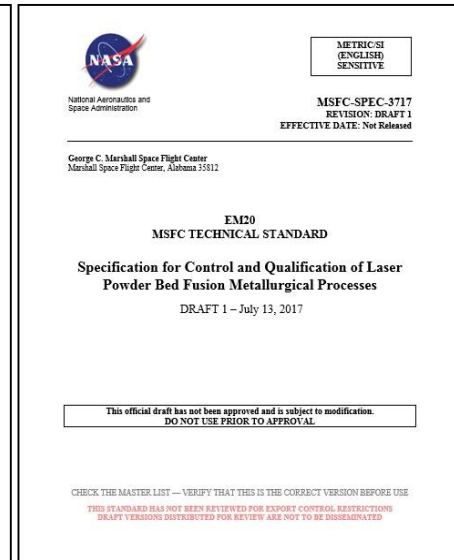
Commercial Crew Program (CCP) DRAGON V2



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

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 Commercial 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.



MSFC Standard and Specification
Release Date: October 18, 2018

Standardization is needed for consistent evaluation of AM processes and parts in critical 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. ISS is a critical testbed.
- **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.

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

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.

