National Aeronautics and Space Administration

marshall

NASA's In Space Manufacturing Initiative and Additive Manufacturing Development for Rocket Engine Space Flight Hardware

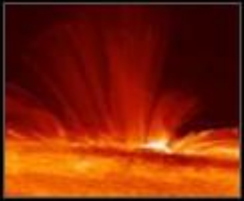
Presented to: Aeronautics and Space Engineering Board

National Academy of Sciences, Engineering and Medicine

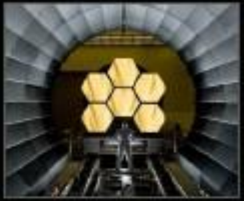
October 13, 2016

Beckman Center

Irvine, California








R.G. Clinton, Jr.

Acting Manager, Science and Technology Office

NASA, Marshall Space Flight Center

www.nasa.gov

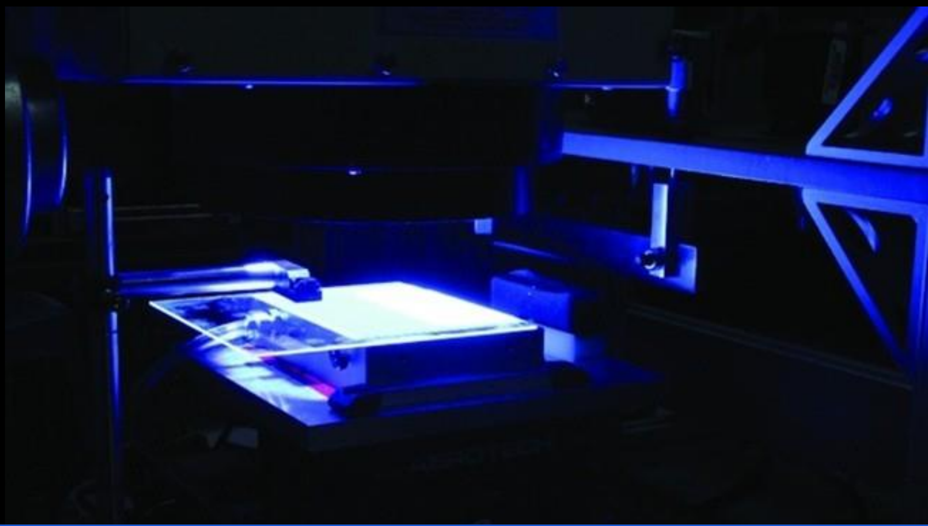
Science & Technology Office

Contributors

- Kristin Morgan: NASA MSFC Additive Manufacturing Lead
- Dr. Tracie Prater: NASA MSFC In Space Manufacturing Material Characterization Lead
- Elizabeth Robertson: NASA MSFC Additive Manufactured Engine Technology Development
- Mike Snyder: Made In Space Chief Designer
- Niki Werkheiser: NASA MSFC In Space Manufacturing Project Manager
- Andrew Owens: NASA Tech Fellow, MIT PhD Canidate

Agenda

- **Discussion Topics**
  - How is Additive Manufacturing Used in Your Field/Application Area Today?
  - How Do You Expect Additive Manufacturing to be Used in ISM Portfolio 5 Years?
  - Why Have You Chosen to Move into Additive Manufacturing, and What Technical Capabilities Are You Focused On?
  - What Do You Believe the Major Challenges Are to More Effective Use of Additive Manufacturing?
  - What Corollary or Overlapping Technologies have been Important to the Effective Utility of Additive Manufacturing in your Application Space?
- **In Space Manufacturing Initiative (ISM)**
  - In Space Manufacturing Path to Exploration
  - Evolvable Mars Campaign Assessment
  - ISM Portfolio
  - ISM Program Timeline
- **Additive Manufacturing Development for Rocket Engine Space Flight Hardware**
  - Additive Manufactured Engine Technology Development (AMETD)
  - Proposed Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware
  - Challenges to Effective Use of Additive Manufacturing
- **Summary**



Additive Manufacturing

at Marshall Space Flight Center

In Space Manufacturing Initiative

In-space Manufacturing Path to Exploration

Science & Technology Office

GROUND-BASED	EARTH RELIANT ISS	PROVING GROUND Cis-lunar	EARTH INDEPENDENT Mars

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

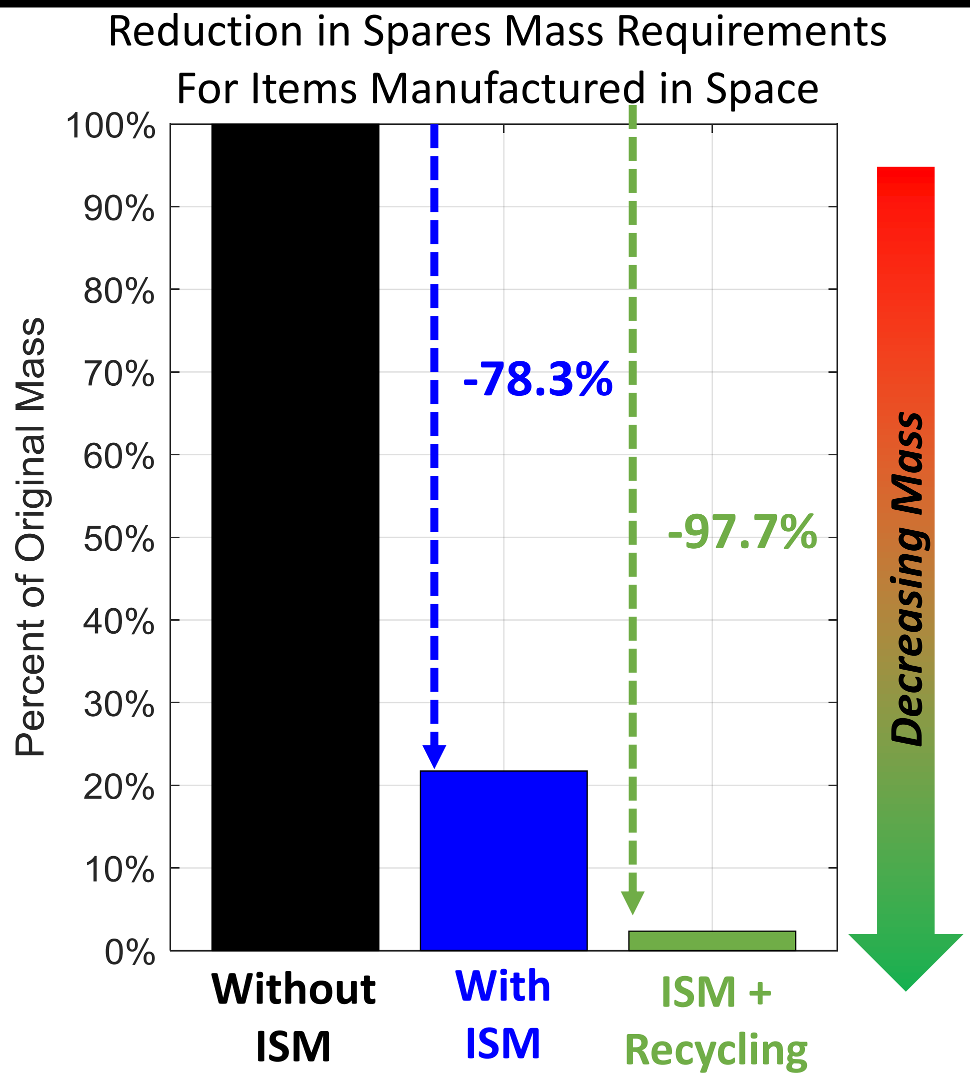
ISS Test-bed Platform
- 3D Print Demo
- Additive Manufacturing Facility
- In-space Recycling
- In-space Metals
- Printable Electronics
- Multi-material Fab Lab
- In-line NDE
- External Manufacturing
- On-demand Parts Catalogue
- Exploration Systems Demonstration and Operational Validation

Asteroids

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

Text Color Legend
Foundational AM Capabilities
AM for Exploration Systems
Surface / ISRU Systems

ISM Provides Solutions for Exploration Logistics



This case examined parts associated with fluid flow (i.e. fans, valves, ducts, piping, etc.). Approx. 1/3 of total components were assumed to be manufactured in-space.

ISM significantly reduces the mass that needs to be carried to cover maintenance demands by enabling on-demand manufacturing from common raw materials

ISM enables the use of recycled materials and in-situ resources, allowing even more dramatic reductions in mass requirements

ISM enables flexibility, giving systems a broad capability to adapt to unanticipated circumstances. This mitigates risks that are not covered by current approaches to maintainability.

In-Space Manufacturing is a strong solution to maintenance logistics challenges that can

- **Reduce mass**
- **Mitigate risk**
- **Enable adaptable systems**

Owens and de Weck 2016

Evolvable Mars Campaign Conclusions and Recommendations

EMC Conclusions

- **ISM is a necessary paradigm shift in space operations, not a 'bonus'**
- **Applications should look at recreating *function*, not form**
- **ISM is a capability, not a subsystem, and has broad applications**

EMC Key Recommendations

- **ISM team needs to be working with exploration system designers now to identify high-value application areas and influence design**
  - Define driving functional and interface requirements
  - Provide expertise to designers to translate traditional design to ISM design
  - Perform testing and demonstration
- **Monitor and leverage rapidly advancing commercial advanced manufacturing technologies**
  - Adapt commercial technology for spaceflight applications to take advantage of cost/schedule savings
  - Collaborate with industry, academia, other government
- **ISS is a critical testbed for driving out these capabilities**
  - Develop technology and process experience via on-orbit testing
  - Identify demo/test opportunities for existing ISM infrastructure (3DP, AMF)
  - Develop and test FabLab in preparation for springboard to Cis-lunar 'Proving Ground'

In-space Manufacturing Portfolio

IN-SPACE POLYMERS

- ISS On-demand Mfctr. w/polymers.
- 3D Print Tech Demo
- Additive Manufacturing Facility with Made in Space, Inc.
- Material Characterization & Testing

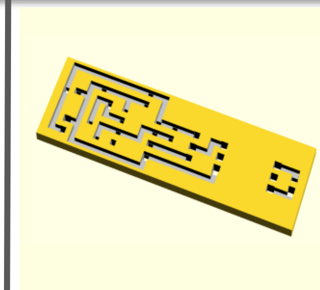
IN-SPACE RECYCLING

- Refabricator ISS Demo with Tethers Unlimited, Inc. (TUI) for on-orbit 3D Printing & Recycling.
- Multiple SBIRs underway on common-use materials & medical/food grade recycler

MULTI-MATERIAL 'FAB LAB' RACK

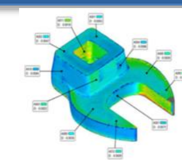
- Develop Multi-material Fabrication Laboratory Rack as 'springboard' for Exploration missions
- In-space Metals ISS Demo
- nScrypt Multi-material machine at MSFC for R&D

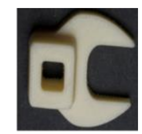
PRINTED ELECTRONICS



- MSFC Conductive & Dielectric Inks patented
- Designed & Tested RFID Antenna, Tags and ultra-capacitors
- 2017 ISM SBIR subtopic
- Collaboration w/Ames on plasma jet technology.

IN-SPACE V&V PROCESS





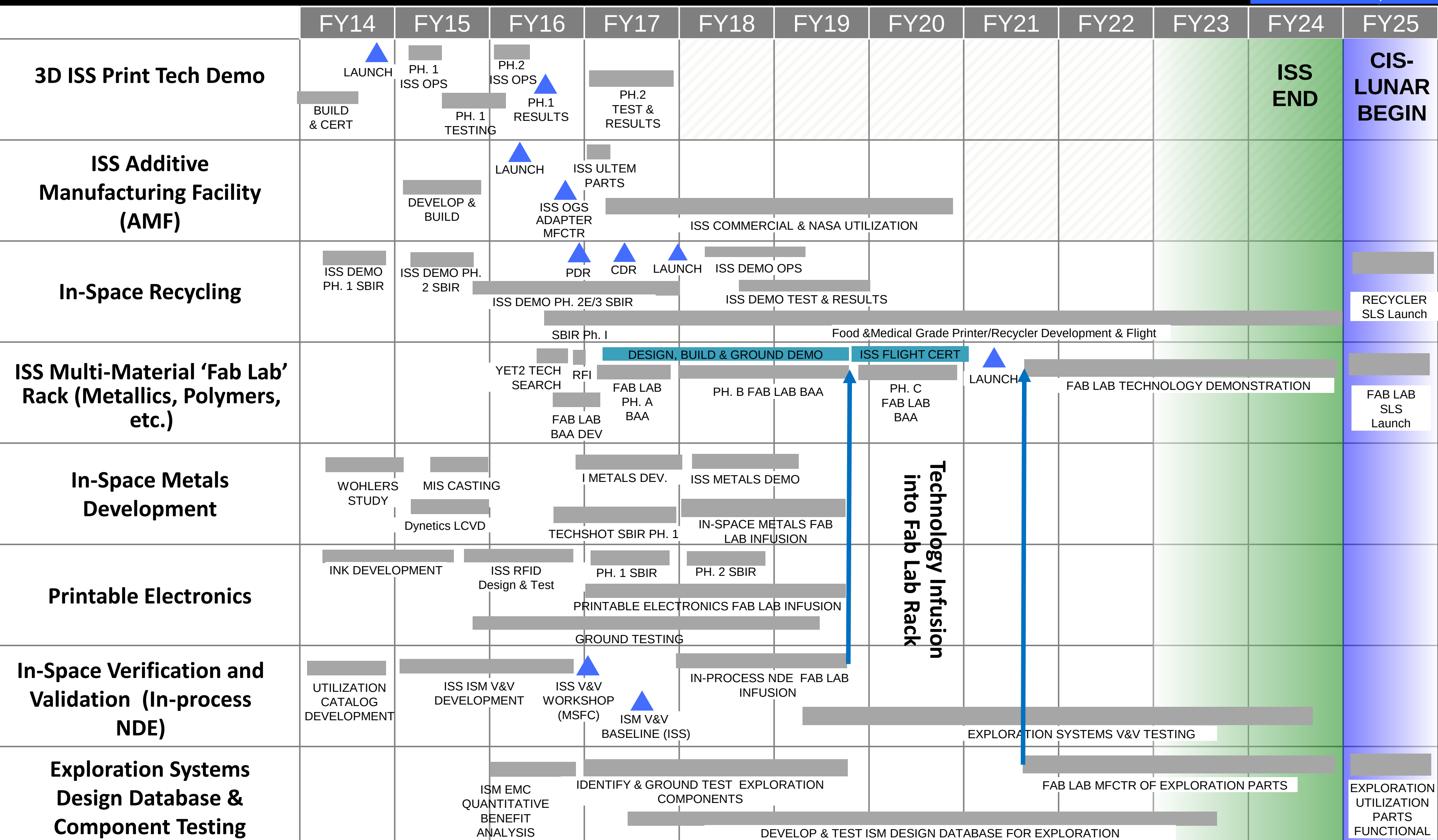
- Develop & Baseline on-orbit, in-process certification process based upon the DRAFT Engineering and Quality Standards for Additively Manufactured Space Flight Hardware

EXPLORATION DESIGN DATABASE & TESTING (In-transit & Surface Systems

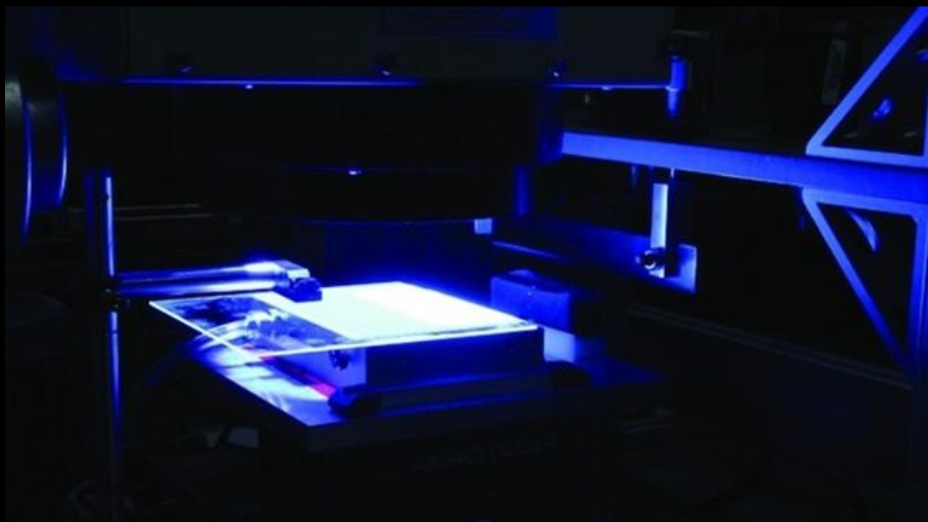
- Develop design-level database for applications
- Materials dev. & characterize for feedstocks (in-transit & surface) in MAPTIS DB.
- Design & test high-value components for ISS & Exploration (ground & ISS)

In-space Manufacturing Program Timeline

Transition to 'Proving Ground'



ISM must influence Exploration design now & develop the corresponding technologies. At the current resource levels, ISM will not achieve needed capability within the required mission timeframe.



Additive Manufacturing

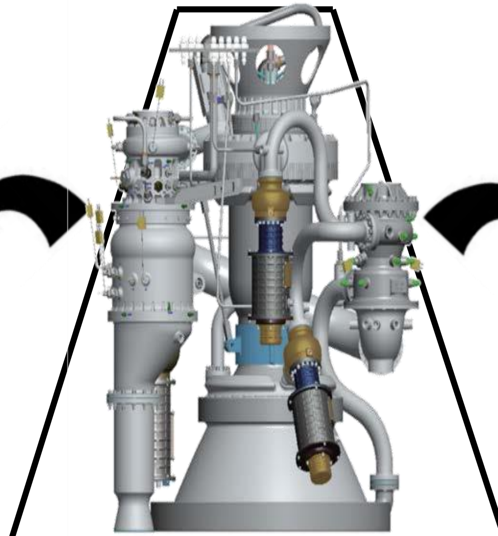
at Marshall Space Flight Center

Additive Manufacturing Development for Rocket Engine Space Flight Hardware

Strategic Vision for Future AM Engine Systems

Defining the Development Philosophy of the Future

- Dramatic Reduction in Design Development, Test and Evaluation (DDT&E) Cycles
- Transforming Manual to Automated Manufacturing
- Integrating Design with Manufacturing



Bridging the gap between the present and future projects that are coming

Building Experience "Smart Buyer" to enable Commercial Partners

Building Foundational Industrial Base

RTI | Directed Manufacturing, Inc.

Additive Manufacturing LLC

Stratasys

LINEAR MOLD & ENGINEERING

INCODEMA SHAPING THE FUTURE

RPM INNOVATIONS, INC.

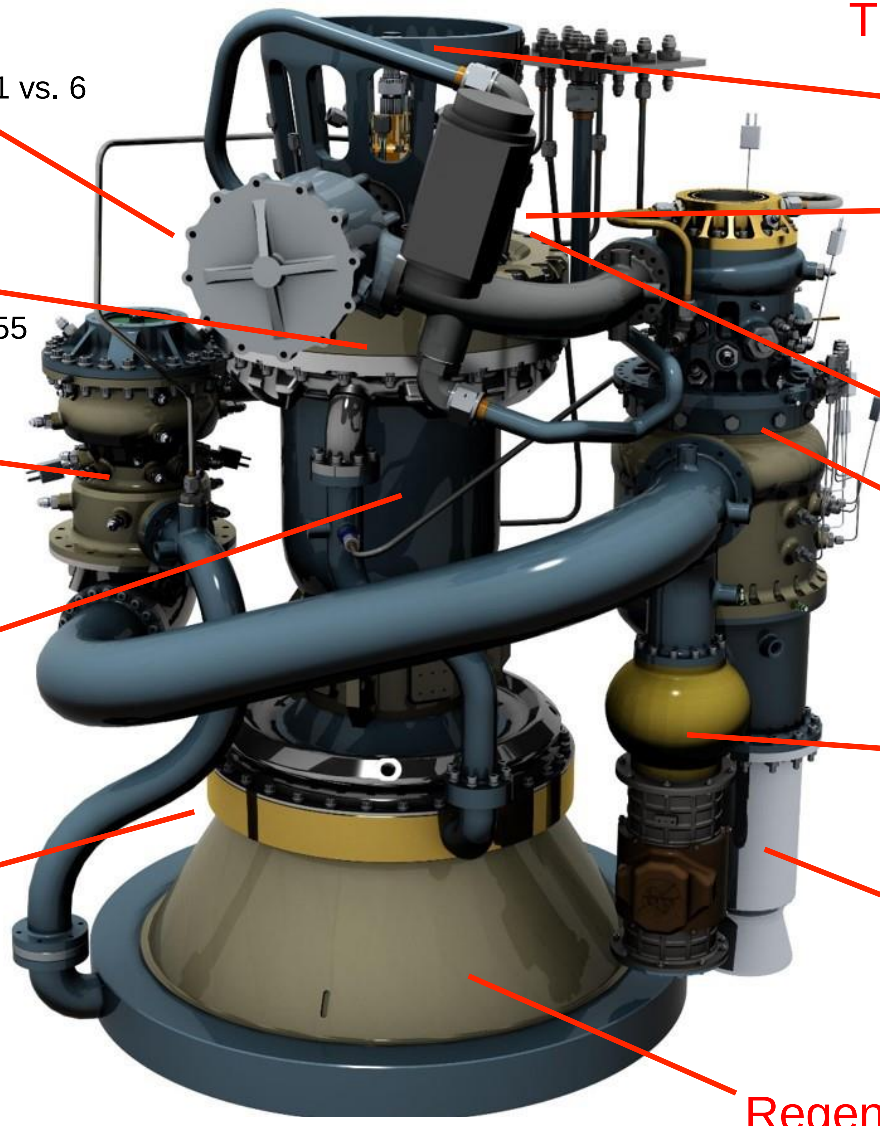
Transferring "Open Rights" SLM Material Property Data & Technology to U.S. Industry

Enabling & Developing Revolutionary Technology

Game-Changing Aspects

State of the Art		Additive Manufactured Engine Technology Development
• **DDT&E Cost** – $1-4 Billion – 500 FTE	*1/10th Dev Cost & Resources*	• **AMETD Cost** – $50 Million (projected) – 50 FTE
• **DDT&E Time** – 7-10 years	*1/2 Dev Lead Time*	• **AMETD DDT&E Time** – 2-4 years
• **Hardware Lead Times** – 3-6 Years	*1/6th Production Time*	• **Hardware Lead Times** – 6-12 Months
• **Engine Cost** – $20 - $50 Million	*1/10th Reoccurring Cost*	• **AMETD Engine Cost** – $1-5 Million
• **Applicability** – Often proprietary – Design for particular mission by a particular contractor		• **Applicability** – Provide relevant data to multiple customers (SLS, Commercial partners, other government agencies) – Flexible testbed configuration can accommodate other's hardware / design concepts

Reduction in Parts Count for Major Hardware



Note: Part counts examples are for major piece parts and do not include bolts, nuts, washers, etc

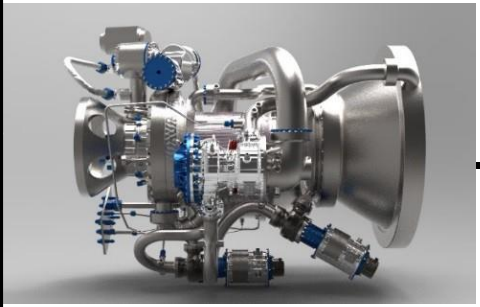
Future Outlook

Fundamental Additive Manufacturing M&P Development

Material Properties & NDE → Standards & Specs → Certification Rationale

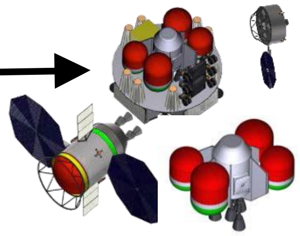
Lean Component Development

Component Relevant Environment Testing



AMETD Prototype Engine

Methane Prop. Systems



Nuclear Propulsion

CCP

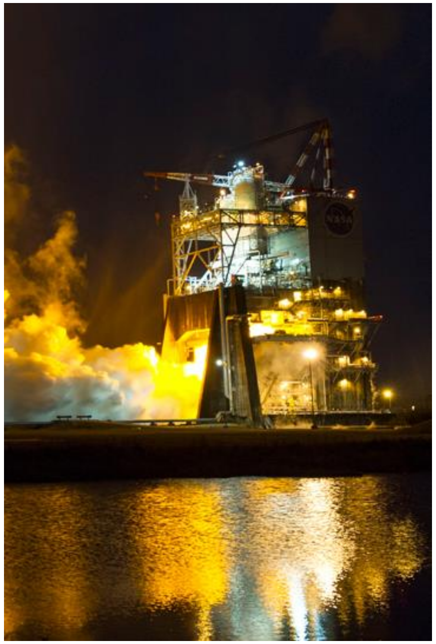
Upper Stage Engine

RS-25

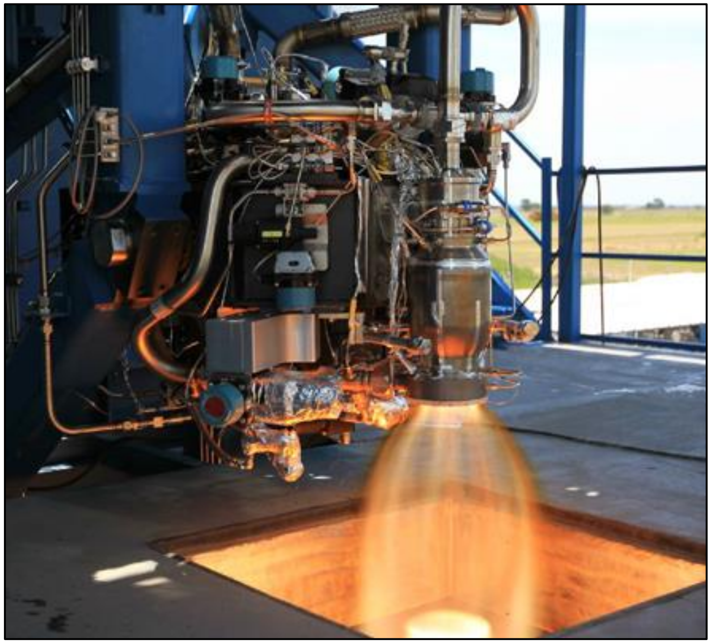
Building Foundational Additive Manufacturing Industrial Base

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.

13 AM parts are baselined for spaceflight hardware. 40 AM parts are in tradespace.

Science & Technology Office

AM Qualification and Certification at NASA


SpaceX's AM SuperDraco Engine

Program partners in crewed space flight programs (Commercial Crew, SLS and Orion) are actively developing **AM parts scheduled to fly as early as 2018.**

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.

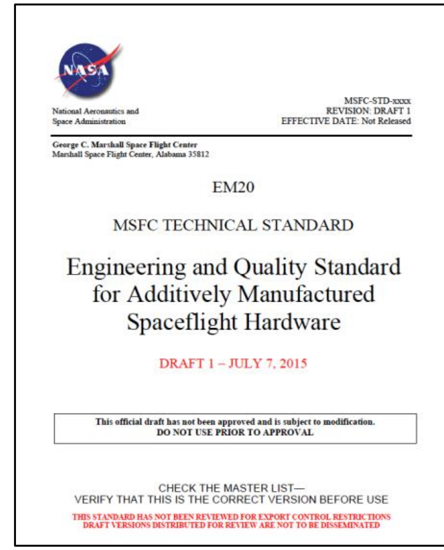
Draft standard completed extensive peer review in Jan 2016.

Final revision currently in work; target release date of Dec 2016.

Standard methodology adopted by CCP, SLS, and Orion.

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.


National Aeronautics and Space Administration

MSFC-STD-xxxx
REVISION: DRAFT 1
EFFECTIVE DATE: Not Released

George C. Marshall Space Flight Center
Marshall Space Flight Center, Alabama 35812

EM20

MSFC TECHNICAL STANDARD

Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware

DRAFT 1 – JULY 7, 2015

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

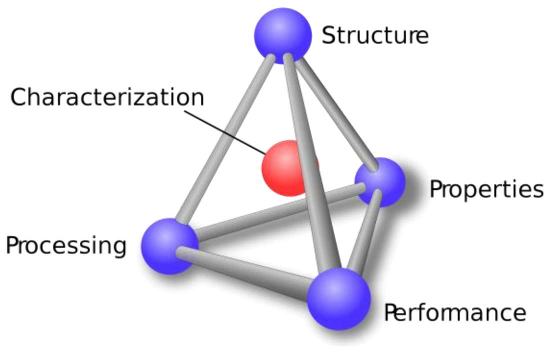
THIS STANDARD HAS NOT BEEN REVIEWED FOR EXPORT CONTROL RESTRICTIONS
DRAFT VERSIONS DISTRIBUTED FOR REVIEW ARE NOT TO BE DISSEMINATED

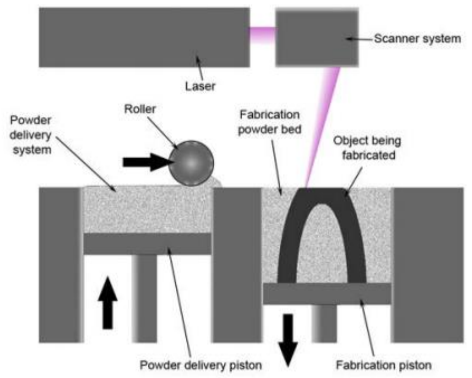
Target release date: December 2016

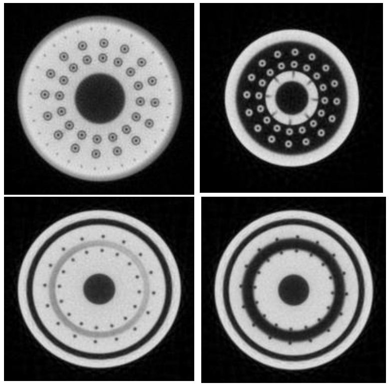
Standardization is needed for consistent evaluation of AM processes and parts in critical applications.

Major Challenges to Effective Use of AM

Material Relationships (Understanding the basics)	In-Process Controls (Controlling what you do)	Post-Process Controls (Evaluating what you get)







Challenge: Understanding of the AM process-structure-properties-performance relationships (in operational environments) is necessary for critical applications, yet also costly and time-consuming. Few data are available in open literature. Commercial AM adopters tend to hold their relationship data as IP.

Challenge: AM is an emerging and evolving technology with virtually no process history apart from extrapolation to weld and/or casting methods. Understanding AM process failure modes and effects, identifying observable metrics, and establishing process witnessing methods is essential to part reliability.

Challenge: AM parts with as-built surface roughness, non-uniform grain structure, and/or internal surfaces challenge the capability of standard NDE methods. Quantified NDE methods for AM material and feature must be established in support of NASA's damage tolerance qualification methods.

Part reliability rationale comes from sum of materials relationships, in-process, and post-process controls. Weakness in one must be compensated by the others.

Beyond these challenges, In-Space Manufacturing faces the additional obstacles of: (1) remote operations; (2) microgravity environment; (3) no NDE capability currently on ISS.

Summary: In-Space Manufacturing

- **In-space manufacturing is a critical capability needed to support NASA's deep space exploration missions**
  - Increase in reliability
  - Reduction in logistics burden (make it or take it)
  - Recycling capabilities
  - Flexibility in design
- **NASA has taken the first step towards in-space manufacturing capability by successfully demonstrating 3D print technology on ISS**
- **The journey through development and proving ground trials is a long one**
  - Foundational technologies are yet to be demonstrated
  - Design for repair culture needs to be embraced
  - Applications need to be validated in operational environment
  - ISS is a critical testbed

In order to have functional capability that supports the Exploration timeline, ISM must work with Exploration systems designers now to identify high-value application areas and influence design process.

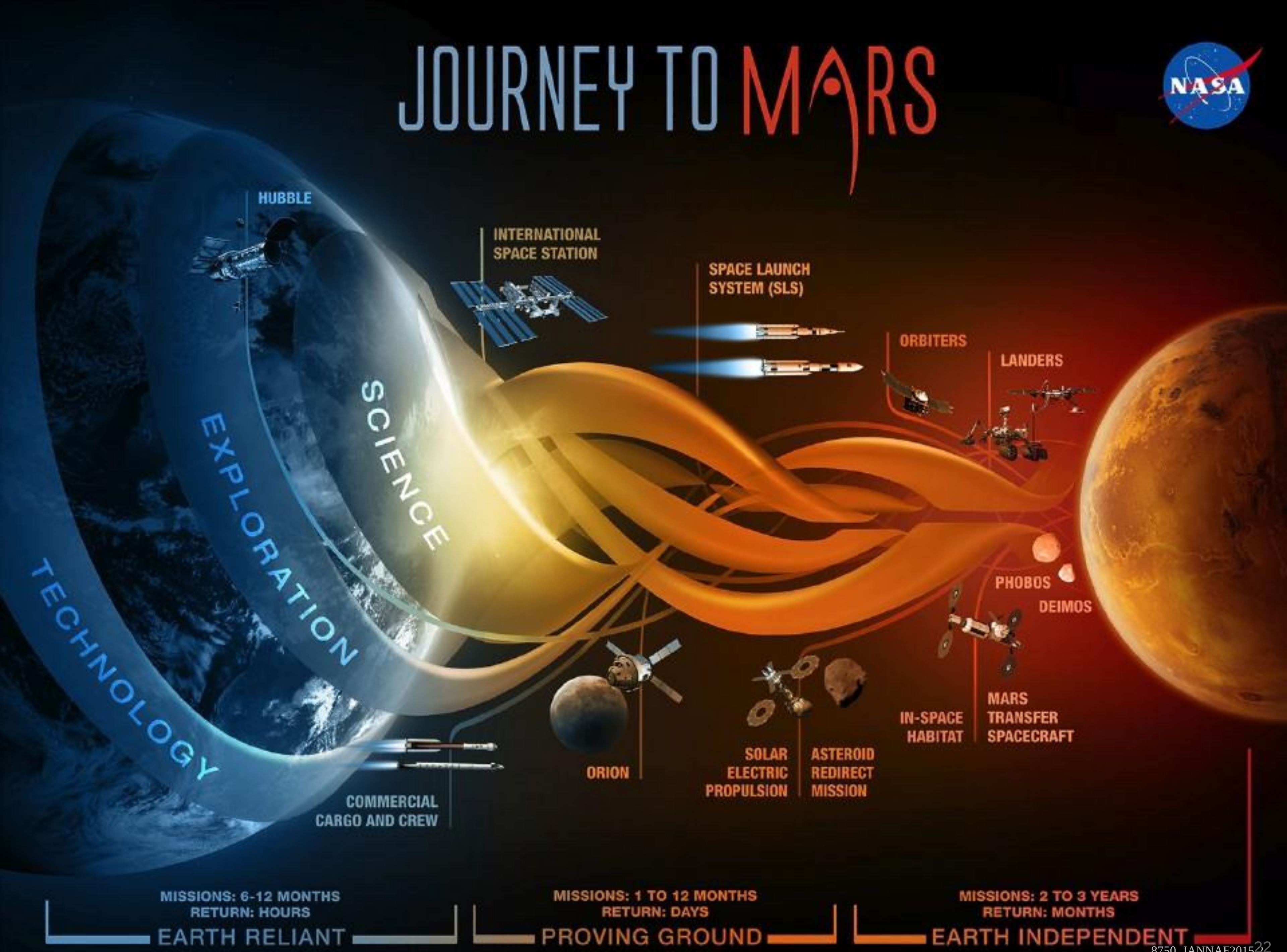
Summary: Additive Manufacturing of Rocket Engines for Human Space Exploration

- **Additive Manufactured Engine Technology Development (AMETD) is catalyst for culture change**
  - Demonstrated game changing aspects of cost and schedule reduction
  - Dramatic impacts on Design, Development, Test and Evaluation (DDT&E) cycle time reduction and philosophy
  - Established technology testbed for future developments
- **Certification approach for additively manufactured rocket engine components developed by MSFC defines the expectations for engineering and quality control in developing critical AM parts**
  - Standard allows innovation while managing risk
  - Final revision target release date is December 2016
  - Standard methodology adopted by CCP, SLS, and Orion
  - Standard methodology framework being adapted for ISM

Standardization is needed for Additive Manufacturing process qualification, part certification, and risk assessments

The Future Is Closer Than You Think

BACKUP CHARTS



JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
ORION
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
IN-SPACE HABITAT
MARS TRANSFER SPACECRAFT
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS
EARTH RELIANT
MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS
PROVING GROUND
MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS
EARTH INDEPENDENT

Science & Technology Office

Key Knowledge Gaps and Risks

- **Available standards will not mitigate AM part risk to a level equivalent to other processes for some time to come!**
- **Known Unknowns needing investment:**
  - Unknown failure modes :: limited process history
  - Open loop process, needs closure or meaningful feedback
  - Feedstock specifications and controls
  - Thermal processing
  - Process parameter sensitivity
  - Mechanical properties
  - Part Cleaning
  - Welding of AM materials
  - AM Surface improvement strategies
  - NDE of complex AM parts
  - Electronic model data controls
  - Equipment faults, modes of failure
  - Machine calibration / maintenance
  - Vendor quality approvals
  - Dynamic technology development in AM industry and applications

Knowledge gaps exist in the basic understanding of AM Materials and Processes, creating potential for risk to certification of critical AM Hardware.

3D Printer International Space Station (ISS) Technology Demonstration - Results

- Ground Control specimens were printed in May 2014 on the flight unit in the Microgravity Science Glovebox (MSG) mock-up facility at MSFC
- The 3D Print Tech Demo launched to ISS on SpaceX-4 in September 2014
- Installed in the Microgravity Science Glovebox on ISS in November 2014
- A total of 21 specimens were printed on ISS in the MSG in November-December 2014, including the uplinked ratchet handle.
- Specimens underwent inspection and testing at MSFC from May to September 2015:
  - Structured light scanning
  - X-ray and CT scan
  - Microscopy
  - Density
  - Mechanical testing
- Small population sizes make comparisons between ground and flight specimens non-definitive

Results were published as a NASA technical publication in Summer 2016

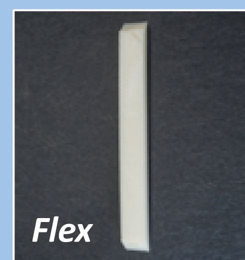
Phase I Prints

Completed Phase 1 Technology Demonstration Goals

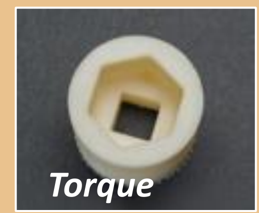
- ➢ Demonstrated critical operational function of the printer
- ➢ Completed test plan for 42 ground control and flight specimens
- ➢ Identified influence factors that may explain differences between data sets

Phase II – Objectives
- Statistical sampling
- Demonstrate critical maintenance functions of printer
- Definitive determination of potential microgravity influences on properties and parts

Mechanical Property Test Articles



Functional Tools



Printer Performance Capability

3DP Phase 1 Key Observations

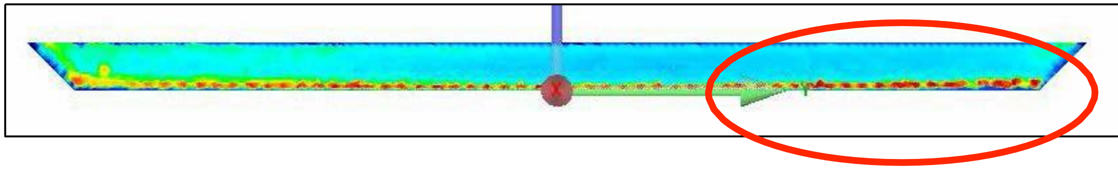
Material Properties

- 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

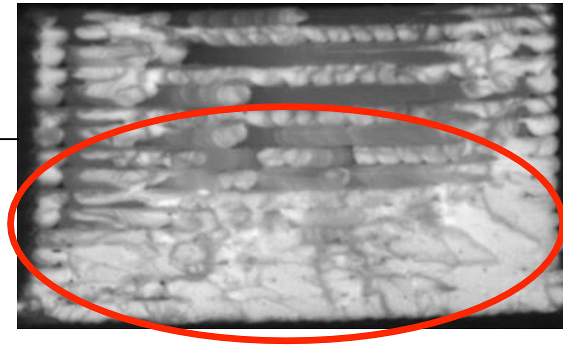
Structured Light Scanning



- 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

In-Space Manufacturing Elements

Material Characterization Database Development

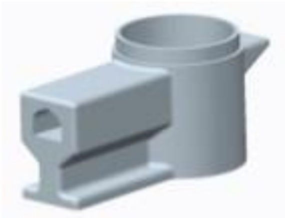
- Objectives:
  - Characterize and document any microgravity effects on printed parts and resulting mechanical properties
  - Develop design-level database for microgravity applications
- Additional on-orbit prints of engineering test articles are planned with ISS (3D Printer and AMF)
- All datasets will be available through the MSFC Materials and Processes Technical Information System (MAPTIS)

On-demand ISM Utilization Catalogue Development

- Objective:
  - Develop a catalogue of approved parts for in-space manufacturing and utilization
- Joint effort between MSFC AM M&P experts, space system designers, and JSC ISS Crew Tools Office and Vehicle Systems Office
- Documenting on-orbit printing process with users and ISS Program (safety, human factors, etc.)
- Developing V&V/Quality Control/Certification process for Candidate Part inclusion in catalogue based upon the DRAFT Engineering and Quality Standards for Additively Manufactured Space Flight Hardware

Compression Testing of Mechanical Flight Sample 7/21/15

OGS AAA Inlet Adaptor



Freedom 360 Virtual Reality Rig

In-Space Manufacturing Elements

AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space (MIS)

- First commercial in-space manufacturing platform
- Incorporates lessons learned from 3D Printer ISS Tech Demo
- Maintenance procedures/capability modified to reduce crew time
- Leveling and calibration done with on-board systems
- Build surface modified for appropriate balance between print adherence and ease of removal
- Integral cameras and sensors supply all data and imagery for automated monitoring
- Expanded materials capabilities:
  - ABS
  - HDPE
  - PEI/PC
- AMF launched to ISS on March 22, 2016. Part production initiated in June 2016.

In-space Recycler ISS Tech Demonstration Development (SBIR 2014)

- Objective: Recycle 3D printed parts into feedstock to help close logistics loop
- Phase I recycler developments completed by Made In Space and Tethers Unlimited
- Phase II SBIR awarded to Tethers Unlimited for the In-space Recycler for proposed ISS Technology Demonstration in FY2018

Additive Manufacturing Facility

Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo

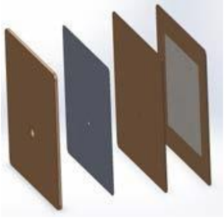
In-Space Manufacturing Elements

Launch Packaging Recycling (Common Use Materials) SBIR 2015

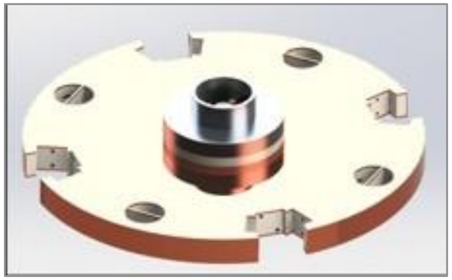
- Objective: Develop common use ISS packaging material(s) that can be recycled to product Feedstock for Future Fabrication needs
- Two Phase II SBIRS award in Spring 2016
  - Cornerstone, Inc.
  - Tethers Unlimited

In-space Printable Electronics Technology Development

- Objective: Develop capability to print electronics in microgravity environment for space exploration applications.
- Collaborating with Xerox Palo Alto Research Center (PARC), NASA Ames Research Center, and AMRDEC
- Roadmap developed targeting ISS technology demonstration
- Printed a Radio Frequency Identification (RFID) antenna for testing as part of the RFID Enabled Autonomous Logistics Management Tech Demo
- Additive ultracapacitors have been developed, tested, & patented
- MSFC ultracapacitor being used on Pulsed Plasma Thruster for Cubesats



3D Printed RFID Antenna, layers



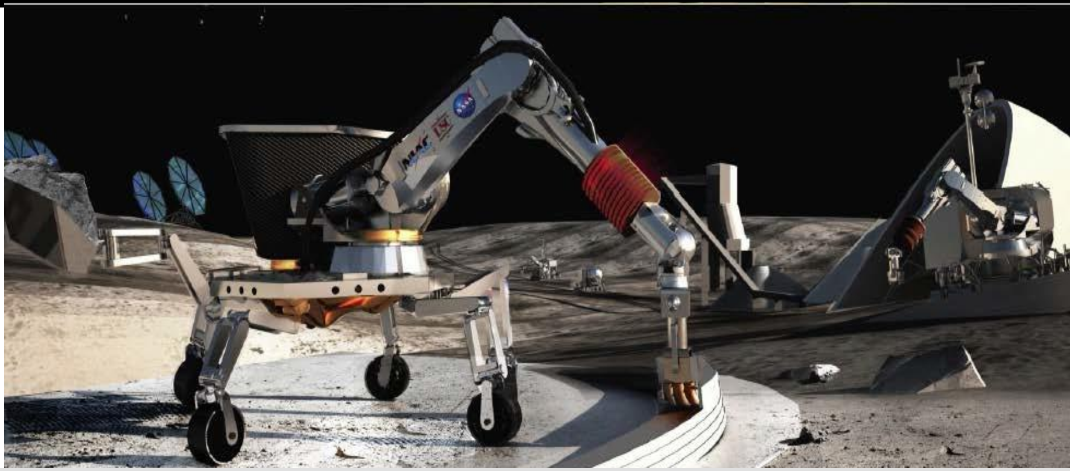
Cubesat Pulsed Thruster ultracapacitor structure (top view – ultracap is white material)

Cubesat Pulsed Thruster ultracapacitor structure (bottom view)

Science & Technology Office

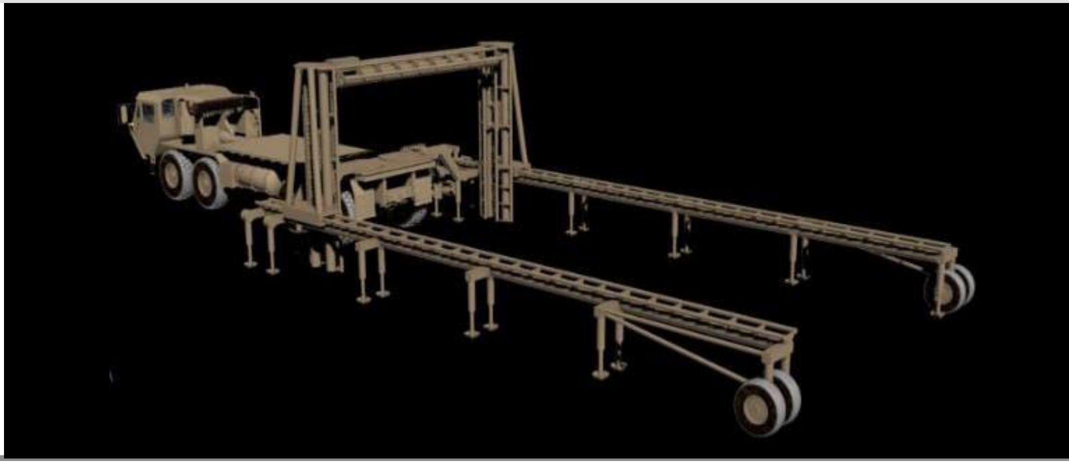
Collaborative Additive Construction Projects

Additive Construction with Mobile Emplacement (ACME)



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

Automated Construction of Expeditionary Structures (ACES)



Collaborative Additive Construction Projects Status

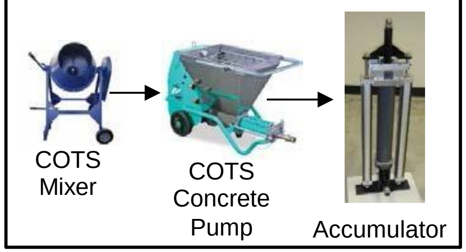
Additive Construction with Mobile Emplacement (ACME)

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

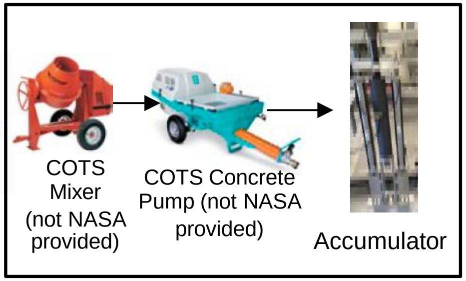
Gantry → *Materials* → *Dry Good Feed* → *Liquid Storage* → *Continuous Delivery and Mixing System* → *Nozzle* → *Print Trials*

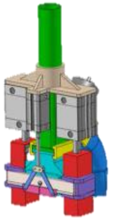
ACME 3

S.B. ACES 3

Portland Cement

Storage Subsystems





ACES 2 Nozzle

Full Guard Shack
(6'x8')

Automated Construction of Expeditionary Structures (ACES)

Technology Development for External In Space Manufacturing and Assembly

Space Technology Mission Directorate's Tipping Point Projects – Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures

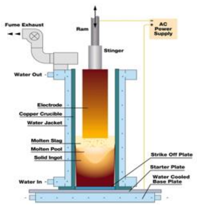
- **Dragonfly: On-Orbit Robotic Installation and Reconfiguration of Large Solid RF Reflectors**
  Space Systems Loral of Palo Alto, California
  - Project provides the next generation of performance advancements in GEO ComSats: more apertures for greater geographic coverage variation, reconfigurable apertures for mission/fleet versatility, larger apertures for greater throughput, and mission enabling unique optics.
- **Public-Private Partnership for Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures**
  Orbital ATK of Dulles, Virginia
  - Project will perform an integrated ground demonstration including robotically deployed rigid backbone and welding using precision alignment.
- **Versatile In-Space Robotic Precision Manufacturing and Assembly System - *Made in Space, Inc. of Moffett Field, California***

AM Qualification Challenges

There is more to AM than manufacturing…

AM machines create a unique material product form – typically the purview of the foundry or mill

Subtractive Forging Process



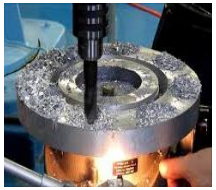
1. Ingot Making

2. Cutting

3. Heating

4. Forging

5. Heat Treating

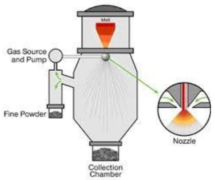


6. Machining

7. Inspection

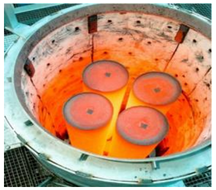
8. Delivery with CoC

Additive SLM Process



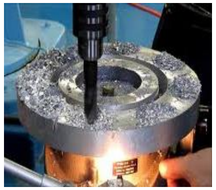
1. Powder Making

2. Printing



3. HIPing

4. Heat Treating



5. Machining

6. Inspection

7. Final Part

NASA Discussions with OGAs

FAA – Immediate need for AM certification path. Applicants are beginning to seek approval for AM parts (the GE fuel nozzle was addressed as a point solution). FAA typically relies on AMS standards to assess flightworthiness criteria. Those standards are in work, yet currently unavailable. Advocating development of a National Roadmap for Additive Manufacturing with emphasis on durability and damage tolerance qualification methodologies.

AFRL/Wright-Patterson – Concerns primarily centered on reliability and repeatability of AM parts in high-volume production settings. Extensive work with ORNL to characterize the variability of Ti-6Al-4V built with electron-beam powder bed process. Executing 3-year Title III agreement with Aerojet Rocketdyne to demonstrate selective laser melting of engine components.

NAVAIR – Advocate of applying Integrated Computational Materials Engineering (ICME) to quantify the interdependence of processing-structure-property-performance for AM materials. Recently qualified (as a point solution) a flight-critical AM Ti-6Al-4V link and fitting for test flights on the V-22 Osprey.