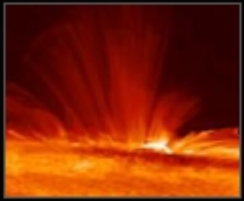
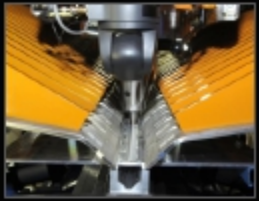
National Aeronautics and Space Administration

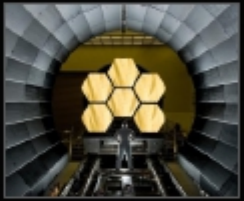
Additive Manufacturing at NASA Marshall Space Flight Center: In-space and For-space Initiatives

Additive Manufacturing for Defense and Government Symposium
December 8-9, 2015
Arlington, VA

marshall







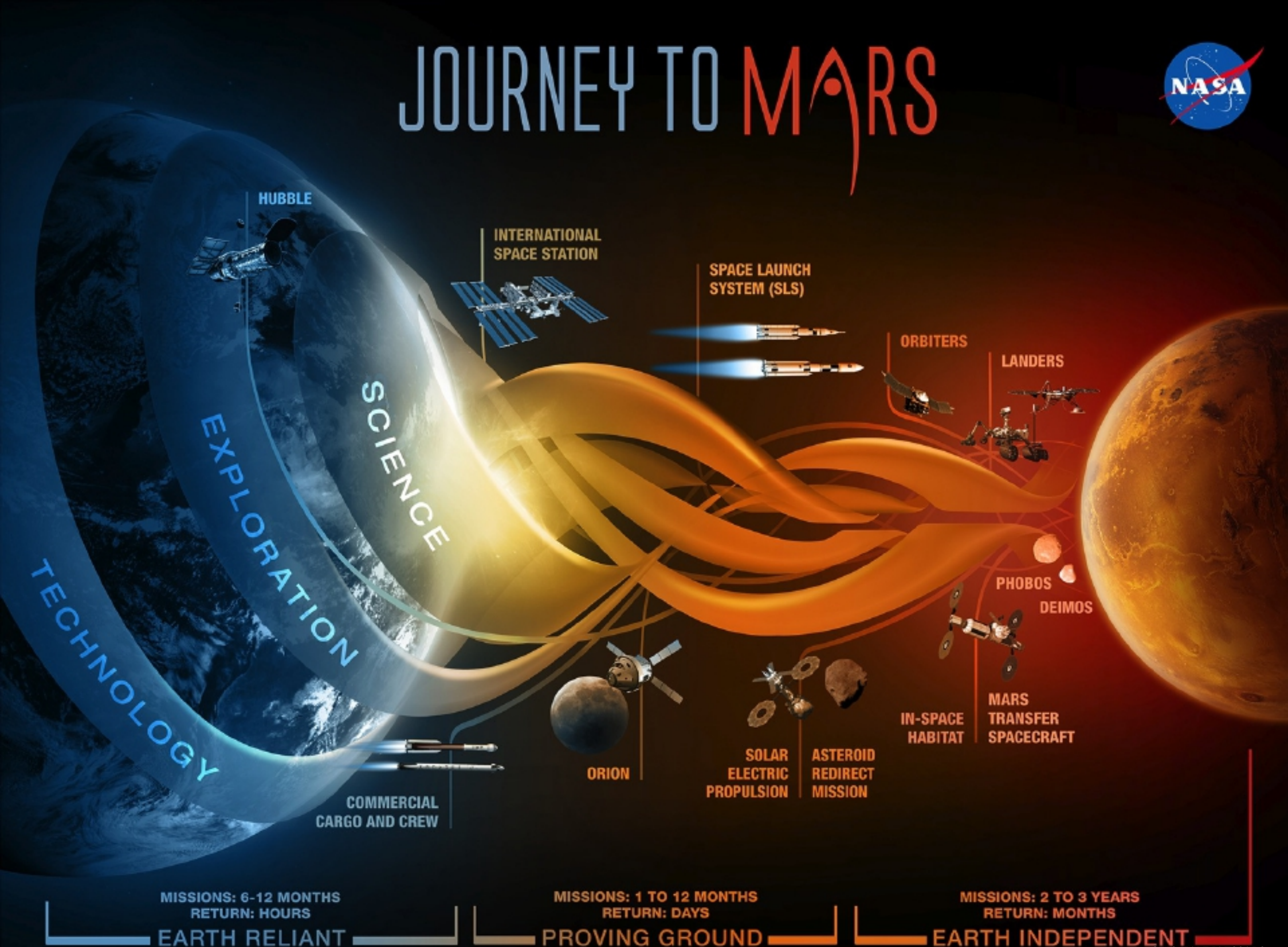

R.G. Clinton, Jr. *Deputy Manager, Science and Technology Office*

Kristin Morgan *Project Manager, AMSII*

www.nasa.gov

Agenda

- **NASA's Journey to Mars – Where will Additive Manufacturing Contribute?**
- **In Space Manufacturing Initiative (ISM)**
  - 3D Printer International Space Station Technology Demonstration Initial Results
  - ISM Elements
  - ISM Roadmap
- **Additive Manufacturing of Liquid Rocket Engine Components**
  - Additive Manufacturing Demonstrator: Liquid Propulsion System
  - Proposed Certification Approach for Additively Manufactured Spaceflight Hardware
  - Additive Manufacturing Structural Integrity Initiative (AMSII)
- **Summary**

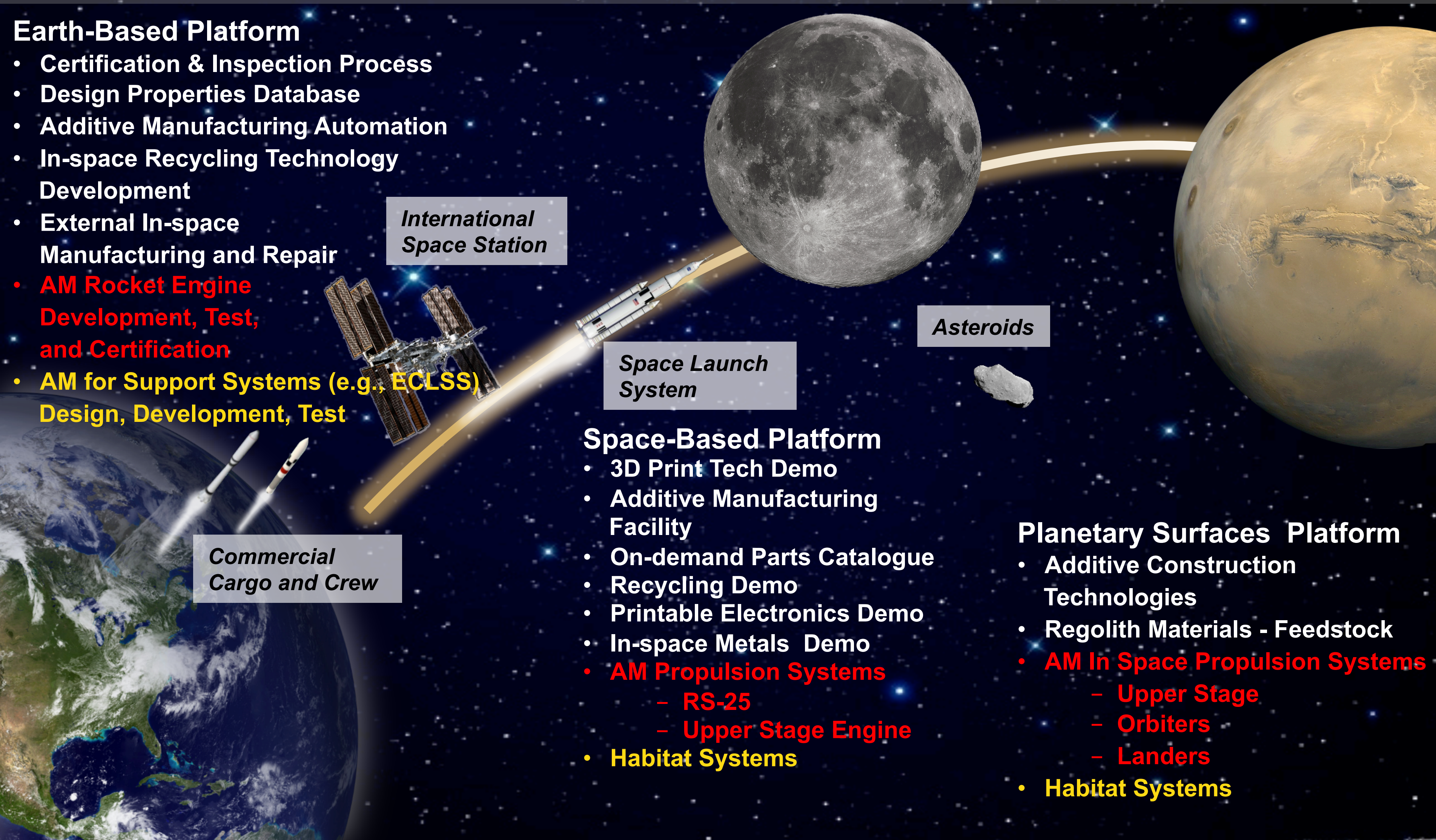


JOURNEY TO MARS
NASA
HUBBLE
INTERNATIONAL SPACE STATION
SPACE LAUNCH SYSTEM (SLS)
ORBITERS
LANDERS
SCIENCE
EXPLORATION
TECHNOLOGY
PHOBOS
DEIMOS
MARS TRANSFER SPACECRAFT
IN-SPACE HABITAT
SOLAR ELECTRIC PROPULSION
ASTEROID REDIRECT MISSION
ORION
COMMERCIAL CARGO AND CREW
MISSIONS: 6-12 MONTHS
RETURN: HOURS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

Science & Technology Office

Additive Manufacturing Path to Exploration

NASA



EARTH RELIANT | PROVING GROUND | EARTH INDEPENDENT

Earth-Based Platform

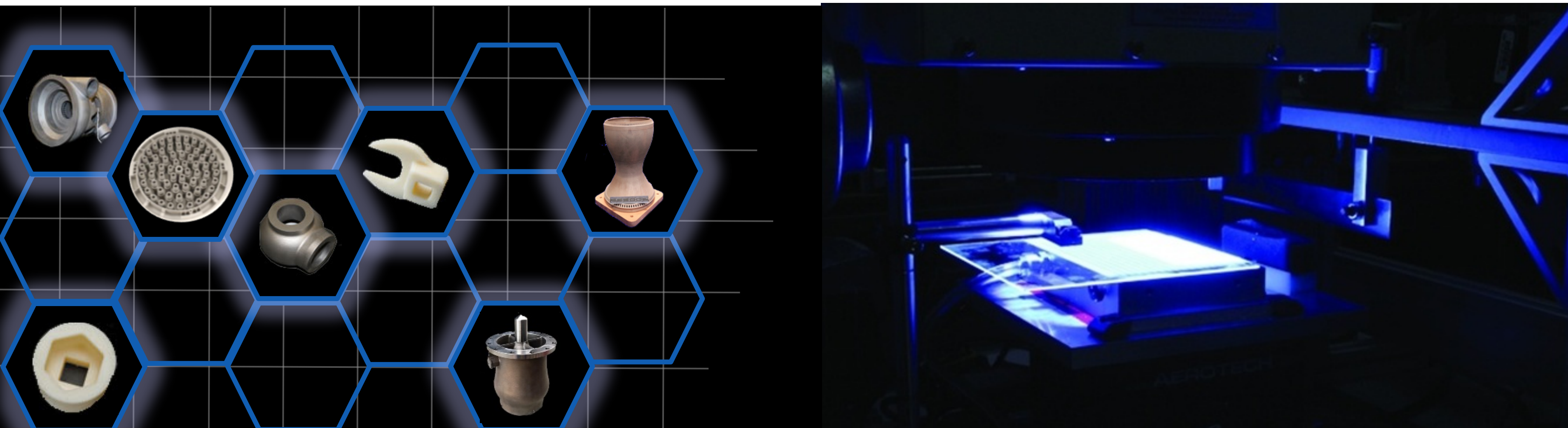
- Certification & Inspection Process
- Design Properties Database
- Additive Manufacturing Automation
- In-space Recycling Technology Development
- External In-space Manufacturing and Repair
- AM Rocket Engine Development, Test, and Certification
- AM for Support Systems (e.g., ECLSS) Design, Development, Test

Space-Based Platform

- 3D Print Tech Demo
- Additive Manufacturing Facility
- On-demand Parts Catalogue
- Recycling Demo
- Printable Electronics Demo
- In-space Metals Demo
- AM Propulsion Systems
  - RS-25
  - Upper Stage Engine
- Habitat Systems

Planetary Surfaces Platform

- Additive Construction Technologies
- Regolith Materials - Feedstock
- AM In Space Propulsion Systems
  - Upper Stage
  - Orbiters
  - Landers
- Habitat Systems



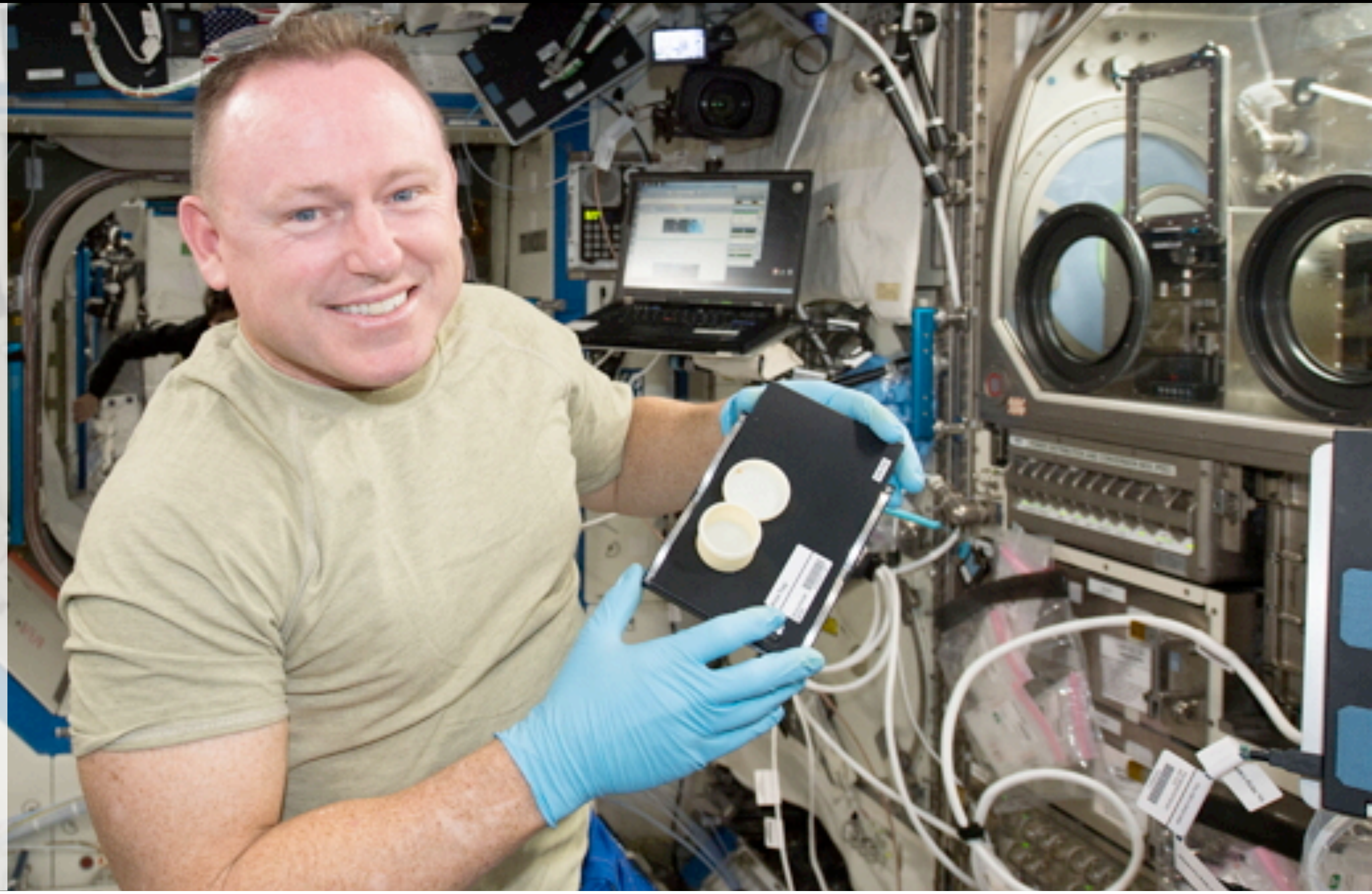
Additive Manufacturing

at Marshall Space Flight Center

In Space Manufacturing Initiative

Top 10 Ways ISS Is Helping NASA Get to Mars

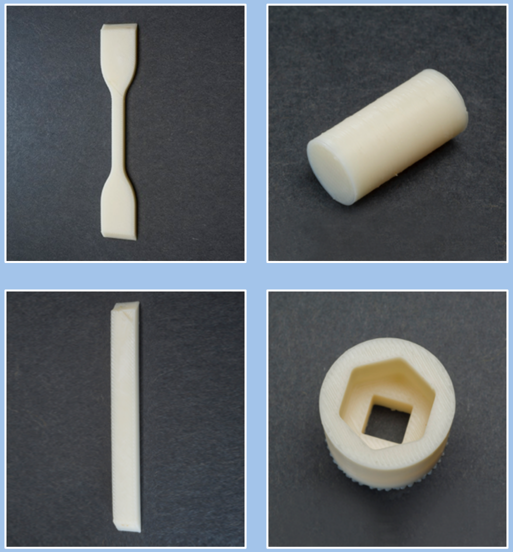
1. Understanding how to manufacture items in space (3-D Printing)

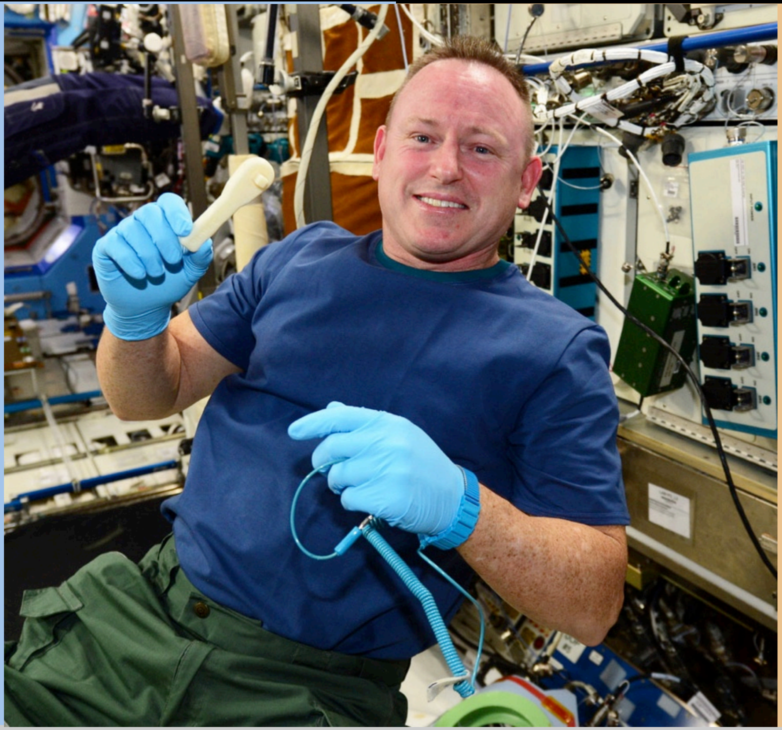


As crews head to Mars, there may be items that are unanticipated or that break during the mission. Having the ability to manufacture new objects on demand while in space will greatly benefit missions. The 3-D Printing in Zero-G Technology Demonstration validates that a 3-D printer works normally in space. This is the first step towards establishing an on-demand machine shop in space, which is a critical enabling component for crewed missions to deep space.

3D Printer International Space Station Technology Demonstration

Mechanical Property Test Articles





Functional Tools

Printer Performance Capability

3D Print ISS Technology Demonstration - Preliminary Results

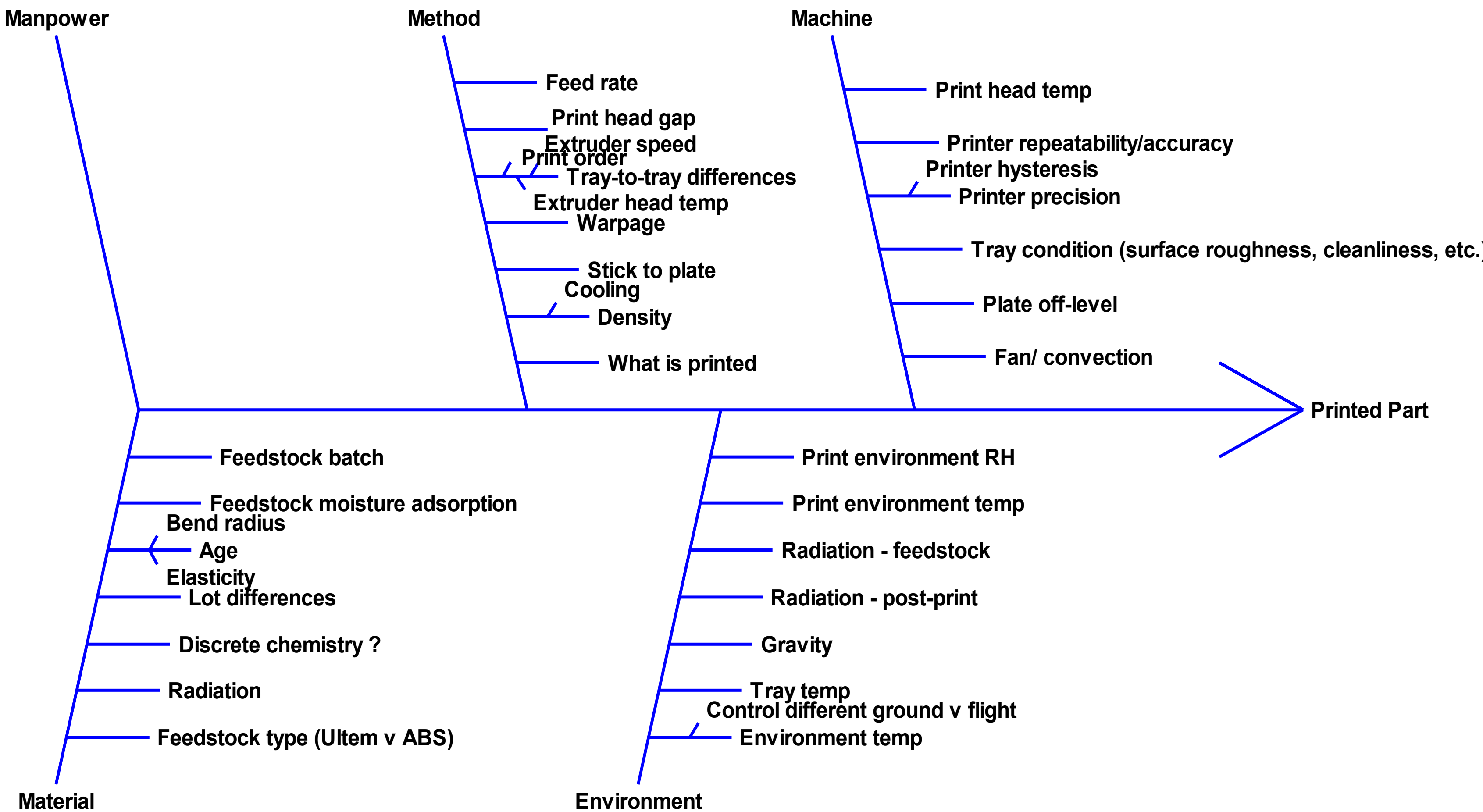
Threshold Requirement: The In-Space Manufacturing (Former 3D Print) project shall produce 3D multi layer object(s) that generate data (operational parameters, dimensional control, mechanical properties) to enhance understanding of 3D printing process in space

- A total of 21 parts were printed on ISS, including the uplinked ratchet handle.
- Corresponding Ground Control Samples were printed using the flight printer prior to launch.
- Inspection and testing of all articles included:
  - Structured light scanning
  - X-ray and CT scan
  - Microscopy
  - Density
  - Mechanical testing
- Mechanical Properties
  - Differences were observed in mechanical properties (strength and modulus) between flight and ground samples
- Density
  - Small, but statistically significant differences in classical (gravimetric) density were measured between flight and ground samples
  - Density correlates positively with mechanical properties

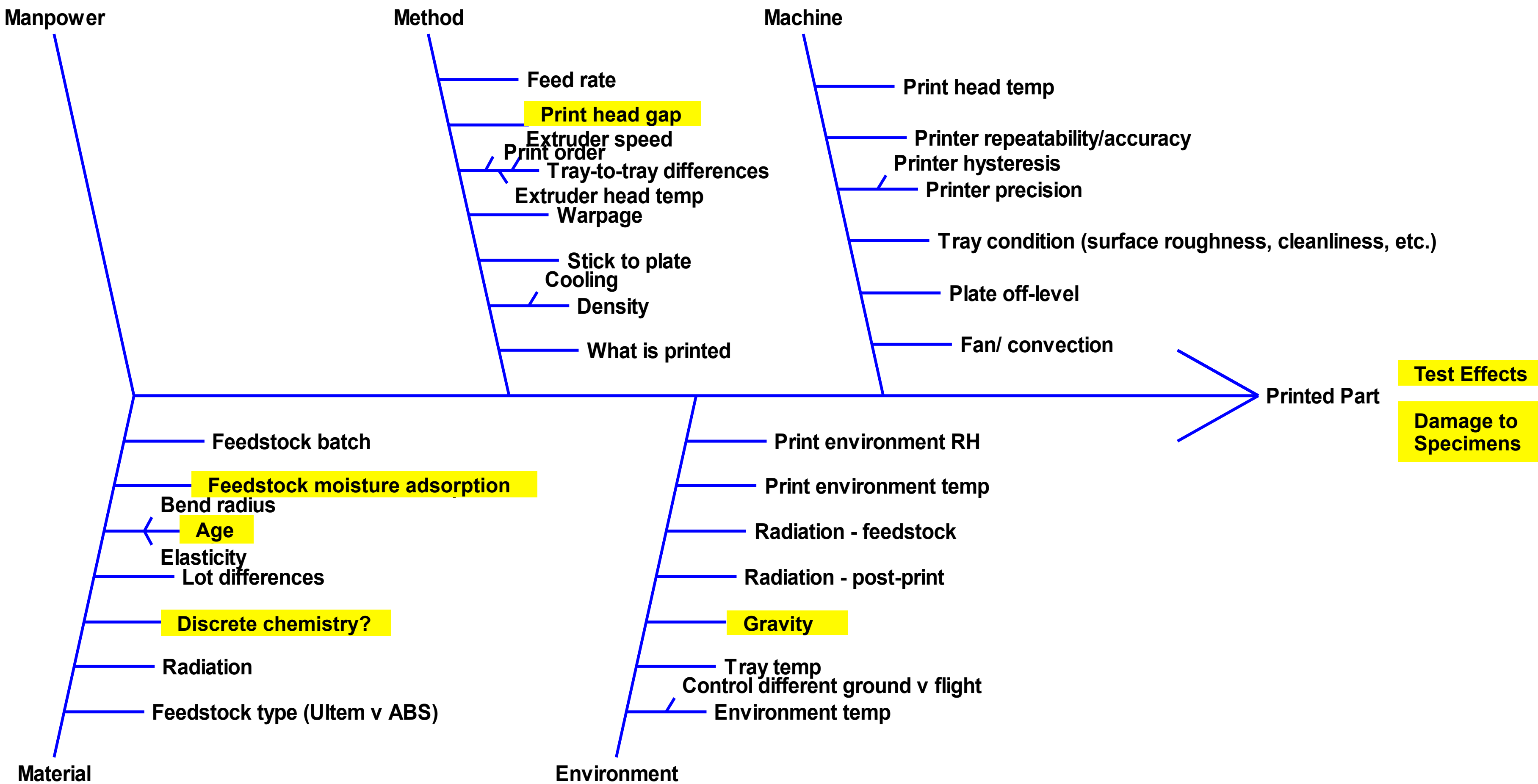
3D Print ISS Technology Demonstration - Preliminary Results

- Optical Microscopy:
  - No clear and consistent differences between flight and ground specimens were observed
- X-ray and CT Scans
  - No significant difference in mean CT (measurement of density from volumetric CT analysis) observed between flight and ground samples
- Structured Light Scanning
  - Almost all of the flight and ground samples exhibited some degree of warpage and shrinkage
  - Most evident in flat parts
- Printer Operations and Process Control Analysis
  - No obvious process change was detected in data using residuals (time series) analysis
  - Features < 2mm exhibited increased error (as designed vs. as built) in range coupons for both flight and ground samples. Above this “threshold” features were consistent with no significant differences between flight and ground samples.
  - Flight samples were generally built with the extruder tip too close to the build surface
  - Distance was held constant for Ground Control prints

Fishbone Diagram of Potential Influences on Results



Fishbone Diagram of Potential Influences on Results



3D Print ISS Technology Demonstration - Preliminary Results

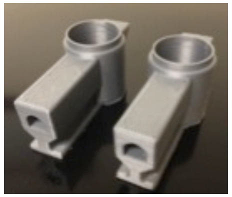
Summary

- The 3D Printer performed flawlessly on ISS
- Lessons Learned have been incorporated into the next generation 3D Printer for ISS – Additive Manufacturing Facility (AMF) by Made In Space
- The team has identified key factors and hypotheses which may explain observed differences in mechanical properties between flight and ground samples
- Plans are being developed to evaluate hypotheses and generate needed additional mechanical properties data through FY16 prints on ISS

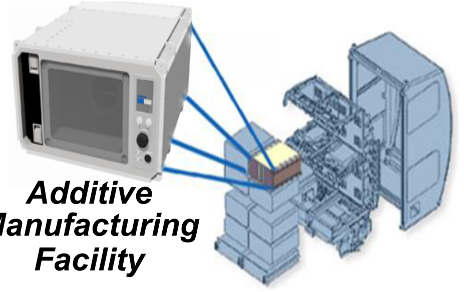
Science & Technology Office

In-Space Manufacturing Elements

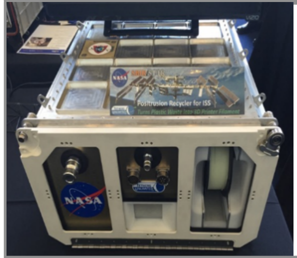
- **Material Characterization Database Development**
  - Objective: Characterize microgravity effects on printed parts and resulting mechanical properties Develop design-level database for microgravity applications.
- **On-demand ISM Utilization Catalogue Development**
  - Objective: Develop a catalogue of approved parts for in-space manufacturing and utilization.
- **AMF - Additive Manufacturing Facility (SBIR Phase II-Enhancement) with Made In Space**
- **In-space Recycler ISS Tech Demonstration Development (SBIR 2014)**
  - Objective: Recycle 3D printed parts into feedstock to help close logistics loop.
- **Launch Packaging Recycling Phase I SBIR (2015)**
  - Objective: Recycle launch packaging materials into feedstock to help close logistics loop (3 proposals selected for award).
- **In-space Printable Electronics Technology Development**
  - Objective: Demonstrate printable electronics technology capabilities on International Space Station
- **ACME - Additive Construction by Mobile Emplacement (STMD GCD)**
  - Joint initiative with the U. S. Army Engineer Research and Development Center – Construction Engineering Research Laboratory (ERDC-CERL) Automated Construction of Expeditionary Structures (ACES) Project
  - Objective: Develop a capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials and minimum number of personnel.



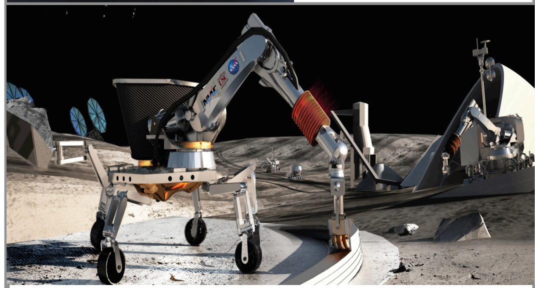
ISM Printed Part for Ground Feasibility Testing



Additive Manufacturing Facility



Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo



Concept of ATHLETE-based autonomous additive construction system on extraterrestrial surface

In-space Manufacturing Exploration Technology Development Roadmap

Science & Technology Office

Earth-based	Demos: Ground & ISS			Exploration	

Plastic Printing Demo

Mat. Char.

3D Print Tech Demo

Recycler

Utilization Testing

AMF

Metal Printing

Fab Lab

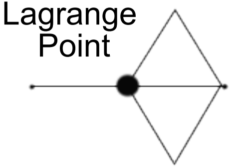
Self-repair/ replicate

Digital Mfctr.

External In-space Mfctr

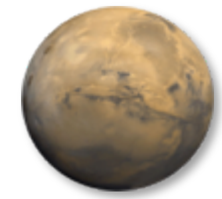
Asteroids

Lagrange Point



Lunar

Mars



Ground Analogs

- Multiple FDM Zero-G parabolic flights (1999-2013)
- System Studies & ground Tests for Multiple Materials & Technologies
- Verification & Cert. Process development
- Material & Printer Characterization Database
- Autonomous Process Dev.
- *Additive Construction: Simulant Dev. &Ground Demos*

2014

- In-space:3D Print: First Plastic Printer on ISS Tech Demo
- NIAC Contour Crafting
- NIAC Printable Spacecraft
- Small Sat in a Day
- AF/NASA Space-based Additive NRC Study
- ISRU Phase II SBIRs
- Ionic Liquids
- Printable Electronics

2015 - 2017

- *3D Print Demo ABS Ops*
- *Add. Mfctr. Facility Ultem Ops (AMF)*
- *In-space*
- *Utilization Catalogue Part Cert & Testing*
- *Recycler Demo*
- *NASA/DARPA External In-space BAA Demo*
- *In-space Material Database*
- *Future Engineer STEM Challenge(s)*

2018 - 2024

ISS: "Fab Lab"

Utilization/Facility Focus

- In-space Recycler Demo
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Embedded Electronics Tech Demo
- Synthetic Biology Demo
- Metal Demo Options
- *ACME Ground Demos*

2025-35

Lunar, Lagrange FabLabs

- Initial Robotic/ Remote Missions
- *Provision feedstock*
- *Evolve to utilizing in situ materials (natural resources, synthetic biology)*
- *Product: Ability to produce, repair, and recycle parts & structures on demand; i.e.. "living off the land"*
- Autonomous final milling to specification

2035+

Planetary Surfaces Points Fab

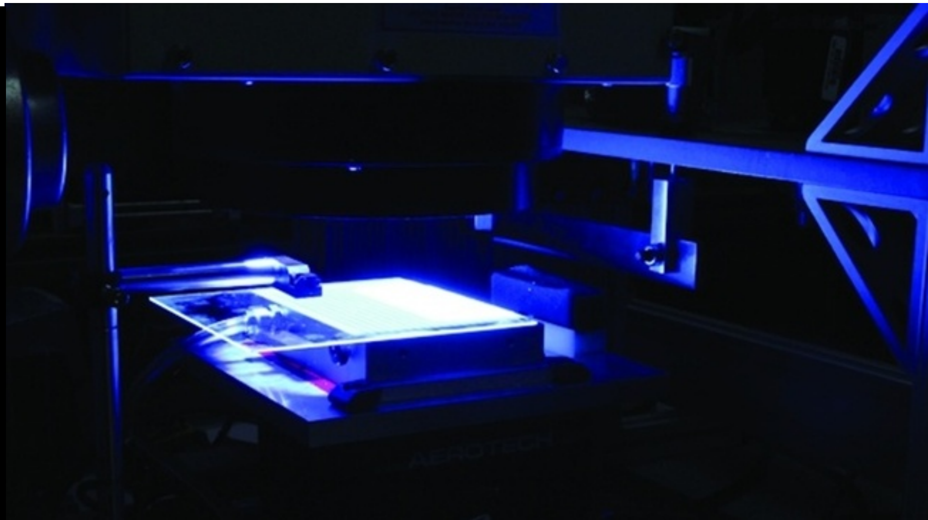
- Transport vehicle and sites would need Fab capability
- *Additive Construction & Repair of large structures*

Mars Multi-Material Fab Lab

- *Provision & Utilize in situ resources for feedstock*
- *FabLab: Provides on-demand manufacturing of structures, electronics, & parts utilizing in-situ and ex-situ (renewable) resources.* Includes ability to inspect, recycle/reclaim, and post-process as needed autonomously to ultimately provide self-sustainment at remote destinations.

** Green text indicates ISM/ISRU collaboration*

ISS Serves as a Key Exploration Test-bed for the Required Technology Maturation & Demonstrations



Additive Manufacturing

at Marshall Space Flight Center

For Space Manufacturing

Advanced Manufacturing Demonstrator: Liquid Propulsion System

Game-Changing Aspects of Prototype Additive Engine

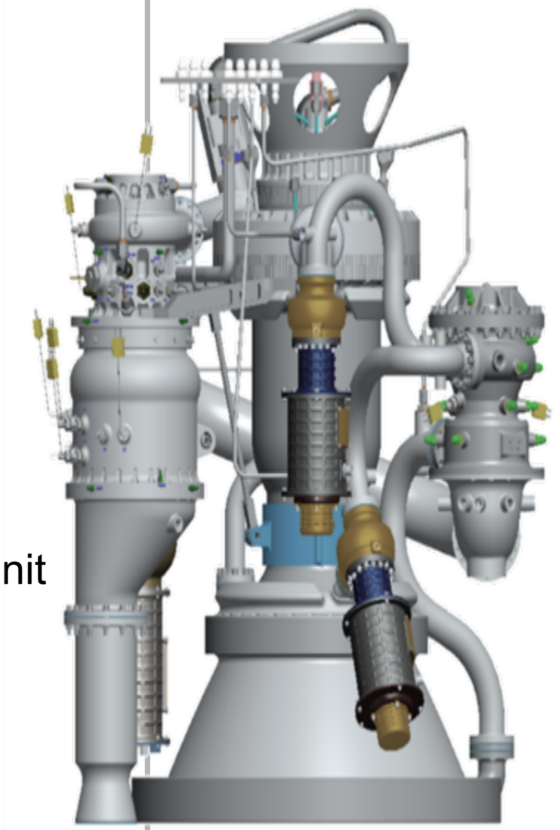
State of the Art for Typical Engine Developments		Prototype Additive Engine
• DDT&E Time – 7-10 years	***1/2 Development Lead Time***	• DDT&E Time – 2-4 years
• Hardware Lead Times – 3-6 Years	***1/6th Production Time***	• Hardware Lead Times – 6 Months
• Testing – Late in the DDT&E cycle		• Testing – Early in the DDT&E cycle
• Engine Cost – $20 - $50 Million	***1/10th Reoccurring Cost***	• Prototype Cost – $3-5 Million

Transforming Liquid Propulsion Systems DDT&E with AM

Additive manufacturing related

Project Objectives

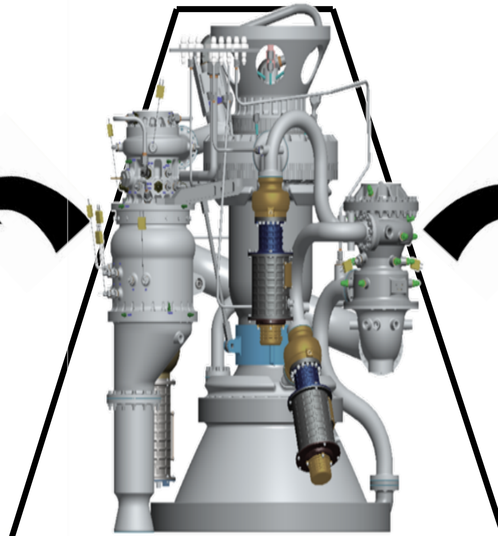
- **Reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle.**
  - Prototype an engine in less than 2.5 years.
  - Use additive manufacturing to reduce part cost, fabrication time, and overall part count.
  - Adopt Lean Development approach.
    - Focus on fundamental/quick turn analysis to reduce labor time and cost and move to first development unit
    - Get hardware into test fast so that test data can be used to influence/refine the design
- **Advance the TRL of additive manufactured parts through component and engine testing.**
- **Develop a cost-effective prototype engine whose basic design can be used as the first development unit for an in-space propulsion class engine.**



Strategic Vision for Future AM Engine Systems

Defining the Development Philosophy of the Future

- **Integrating Design with Manufacturing**
- **3D Design Models and Simulations Increase Producibility**
- **Transforming Manual to Automated Manufacturing**
- **Dramatic Reduction in Design Development, Test and Evaluation (DDT&E) Cycles**



Bridging the gap between the present and future projects that <u>are coming</u>

Building Experience "Smart Buyer" to enable Commercial Partners

Building Foundational Industrial Base

DIRECTEDMFG
AS9100B Certified

INCODEMA
SHAPING THE FUTURE

MORRIS TECHNOLOGIES
Precision. Innovation. Expertise.

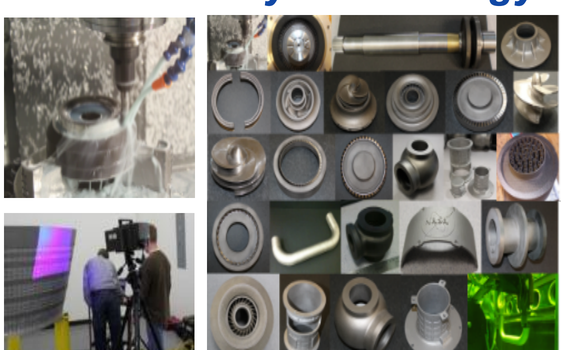
SOLID CONCEPTS®

LINEAR
MOLD & ENGINEERING

RPM INNOVATIONS, INC.

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

Enabling & Developing Revolutionary Technology



Hardware and Testing Accomplishments

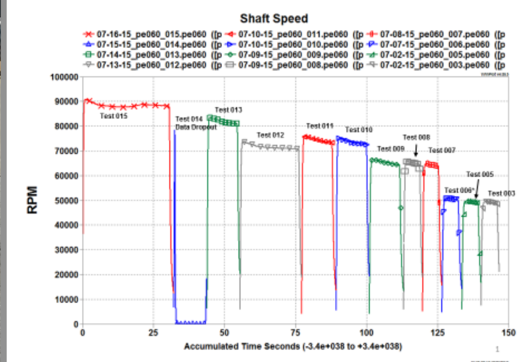
Advanced Manufacturing Demonstrator Test Stand

Fuel Turbopump Performance Test in Hydrogen

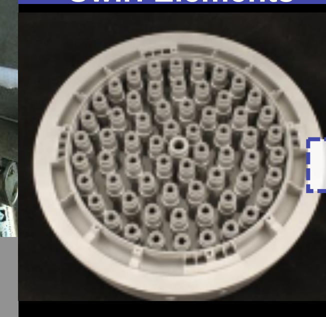
LCUSP MCC Liner

Main Fuel Valve Cryo Test

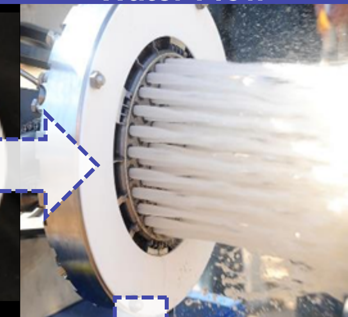
Test Data – Shaft Speed



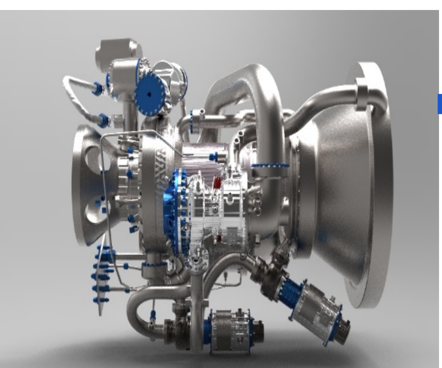
Fuel Scale Injector Swirl Elements



Full Scale Injector Water Flow

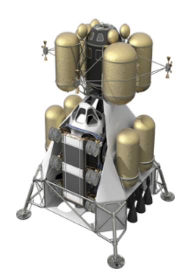


Sub-scale Injector Test

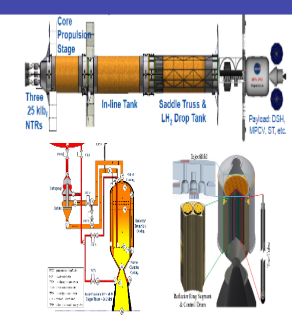


Advanced Manufacturing Demonstrator (AMD)

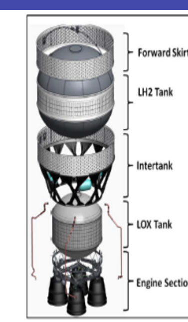
Investment directly benefits prototype engine development and indirectly enables and facilitates technology across multiple current and future activities for NASA and industry.



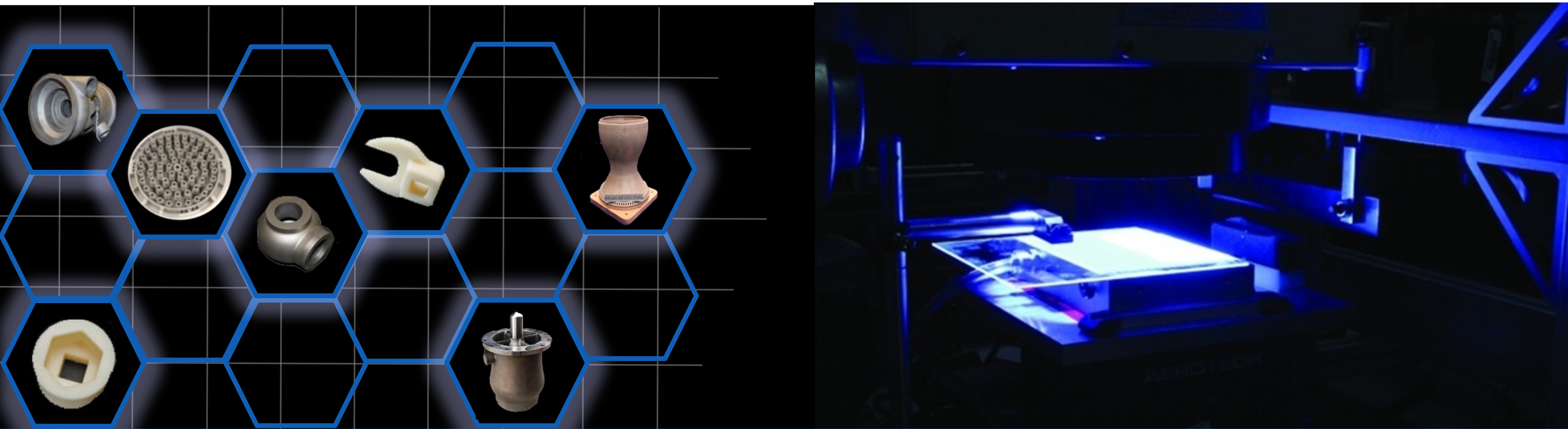
Methane Lander



Nuclear Thermal Propulsion (NTP)



Exploration Upper Stage (EUS)



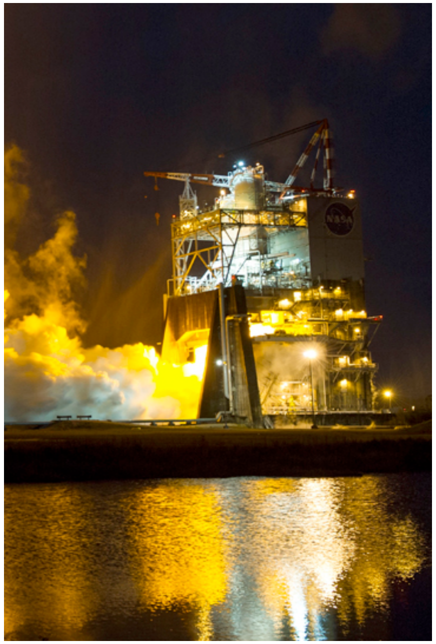
Additive Manufacturing

at Marshall Space Flight Center

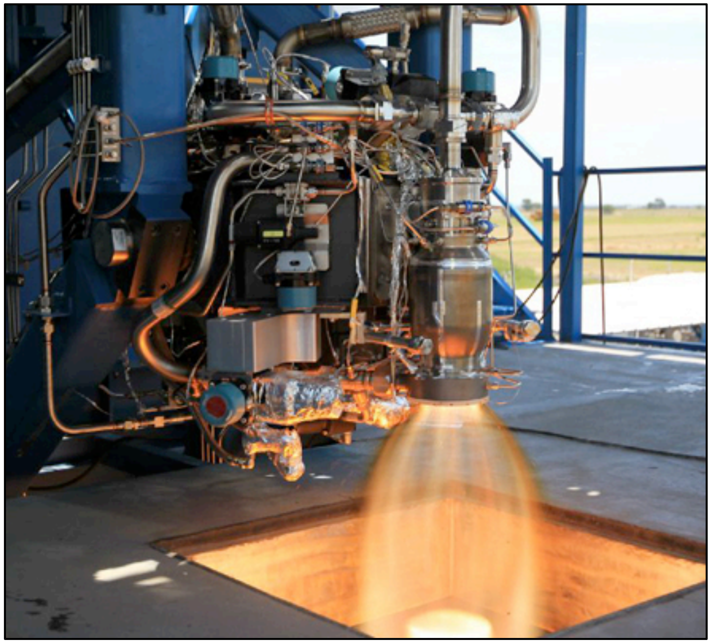
Proposed Certification Approach for Additively Manufactured Spaceflight Hardware

AM in the Human Exploration and Operations Portfolio

Exploration Systems Development
ORION and SLS



Commercial Crew Program
DRAGON V2



Requirement choices dictate how we embrace, foster, and protect the technology and its opportunities

Managing Opportunity and Risk

- **Opportunity**
  - Additive Manufacturing (AM) offers revolutionary opportunities in mechanical design innovation, cost savings, and schedule reduction

- **Risk**
  - Process sensitivity :: unknown failure modes
  - Lack of governing requirements
  - Rapidly evolving technology
  - Too easy, too cheap = ubiquitous, lack of rigor
  - AM related failure tarnishes the technology

MSFC Requirements Approach

1. **Develop a Center-level (MSFC) requirement**
   - Allows for more timely release (targeting January 2016)
   - Review circle much wider than common
     - NASA Centers and NESC (Materials, Structures, NDE, Reliability)
     - Partners (Lockheed Martin, Aerojet Rocketdyne, SpaceX, Boeing)
     - Industry (P&W, Raytheon)
     - Certifying Agencies (FAA, USAF, NAVAIR, AMRDEC)

2. **Revise as needed / Levy as required**

3. **Watch progress of standards organizations and other certifying Agencies**

4. **Incorporate AM requirements at an appropriate level in Agency specifications**
   - Incorporate necessary detail, or
   - Refer to center document or industry standard

Engineering and Quality Standard for AM Spaceflight Hardware

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

Document Contents

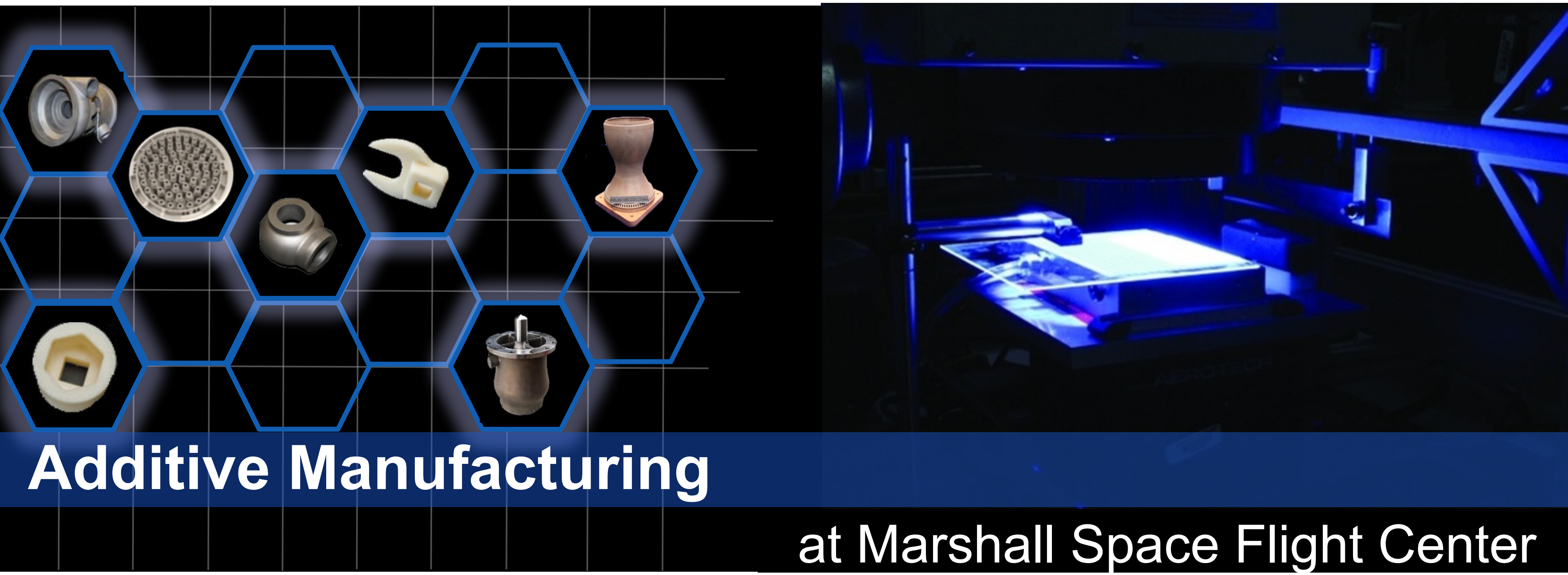
- Governing Standards
- Design for AM
- Part Classification
- Structural Assessment
- Fracture Control
- Qualification Testing
- Material Properties
- **Process Controls**
  - ***Metallurgical Process Control***
  - ***Part Process Control***
  - ***Equipment Vendor Controls***
  - ***Design and Build Vendor Controls***

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

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

National Aeronautics and Space Administration



Additive Manufacturing Structural Integrity Initiative (AMSII)

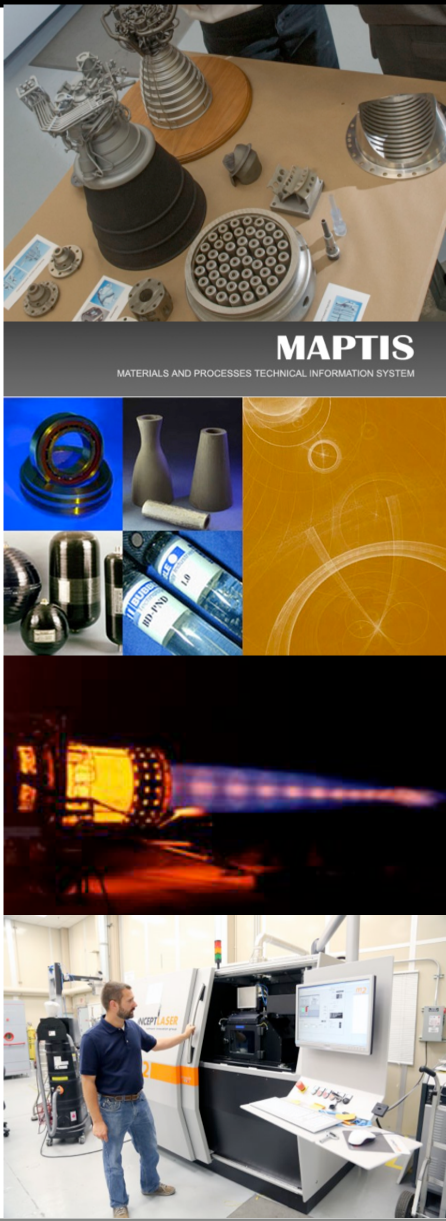
AMSII Project Goal & Objectives

Goal

- **Develop powder bed fusion (PBF) as a reliable and routine alternative to traditional manufacturing methods for human-rated flight hardware.**

Objectives

- **Mature a jointly-defined, resource-loaded technology project to close the knowledge gaps that underpin our drafted AM requirement document.**
  - Effort not to exceed 3 years, $10M.
  - Emphasis on activities required for flight certification.
  - Initial focus on Inconel 718 produced with powder bed fusion technology.
- **Develop an inter-center team to pool knowledge and provide peer review of AM technology development and activities.**
- **Mature NASA-wide or local requirement document(s) in order to enhance standardization of AM for flight hardware.**



Center Roles and Technical Objectives

Lead Center in Blue

Build the standard level of information on AM powder bed fusion processes that is required for certification of any new critical process used for aerospace applications. Better understanding of controlling process parameters and process failure modes will be achieved through completion of this study.

- Certification Requirements – **MSFC**/JSC/KSC (committee) **Objective**: Develop an Agency-wide accepted practice for the certification of AM processes for aerospace hardware.

1. Powder Influence – **GRC**/LaRC/MSFC **Objective**: Understand how basic powder feedstock characteristics influence a PBF part's physical, mechanical, and surface properties.
2. Build Interactions – **MSFC**/GRC/LaRC **Objective**: Use DOEs to understand how basic AM build factors influence part properties. (Answers how we declare the PBF process acceptable & in-control; e.g. microstructural criteria, density criteria, laser/power effects, process FMEA, mitigation of process failure modes)
3. Characteristic Defects – **LaRC**/GRC/MSFC **Objective**: Identify, catalog, and reproduce defects characteristic of the AM process.
4. Thermal Processing – **GRC**/LaRC/MSFC **Objective**: Establish an understanding of how post-build thermal treatments affect build quality, microstructural evolution, and mechanical properties.
5. Surface Improvement – **LaRC**/MSFC **Objective**: Understand how as-built and improved AM surface texture influence part performance and fatigue life.
6. Characterization in Environment – **MSFC**/GRC/LaRC **Objective**: Understand mechanical behavior of AM Inconel 718 in representative aerospace environments.
7. Design Engineering – **MSFC** **Objective:** Demonstrate the certification process for AM propulsion components. Increase TRL of propulsion components through testing in operational environment.

Related Task: NASA NDE Working Group Additive Manufacturing Proposed Tasks – Various Centers **Objective**: Assessment of NDE Capability for AM parts and creation of NDE standards and models. (sponsored by OSMA)

Project designed to leverage Centers' critical skills, knowledge, and expertise.

Science & Technology Office

Summary

In Space Manufacturing - Don't leave home (planet) without it!

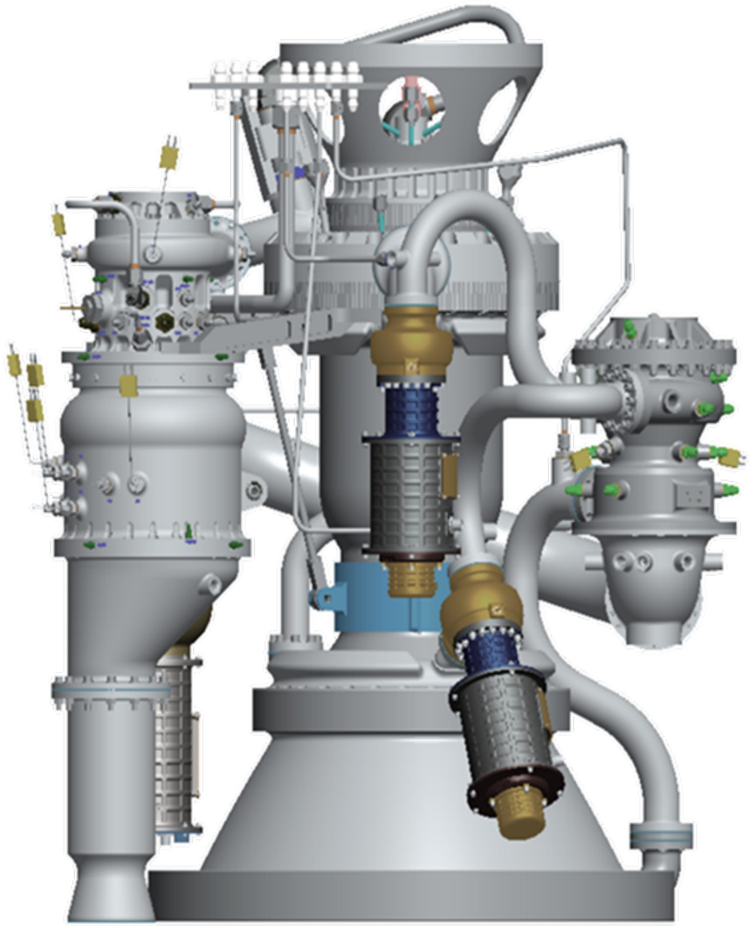
- 3D Print ISS Tech Demo has been fully successful as the first step in becoming Earth independent
- MSFC will develop design databases for the selected materials and design parts and tools to be printed on orbit in collaboration with JSC ISS Crew Tools Office
- We will follow the roadmap, developing new ISS Tech Demos for the Recycler; Printed Electronics; Alternate, Stronger Nonmetallic Materials; Metallic Materials; and External (to ISS) Fabrication in preparation for Proving Ground utilization.

For Space Manufacturing

- **AMD-LPS is catalyst for culture change**
  - Demonstrated game changing aspects of cost and schedule reduction
  - Dramatic reduction in DDT&E cycle time
  - Technology testbed for future developments
- **Certification approach for additively manufactured rocket engine components developed by MSFC**
  - Center-level AM requirements released for broad review in July 2015
  - Requirements allow innovation while managing risk
  - Defines the expectations for engineering and quality control in developing critical AM parts
- **Additive Manufacturing Structural Integrity Initiative (AMSII) is an Agency level cooperative effort to help close knowledge gaps in certification requirements to better manage AM risk**

BACK UP

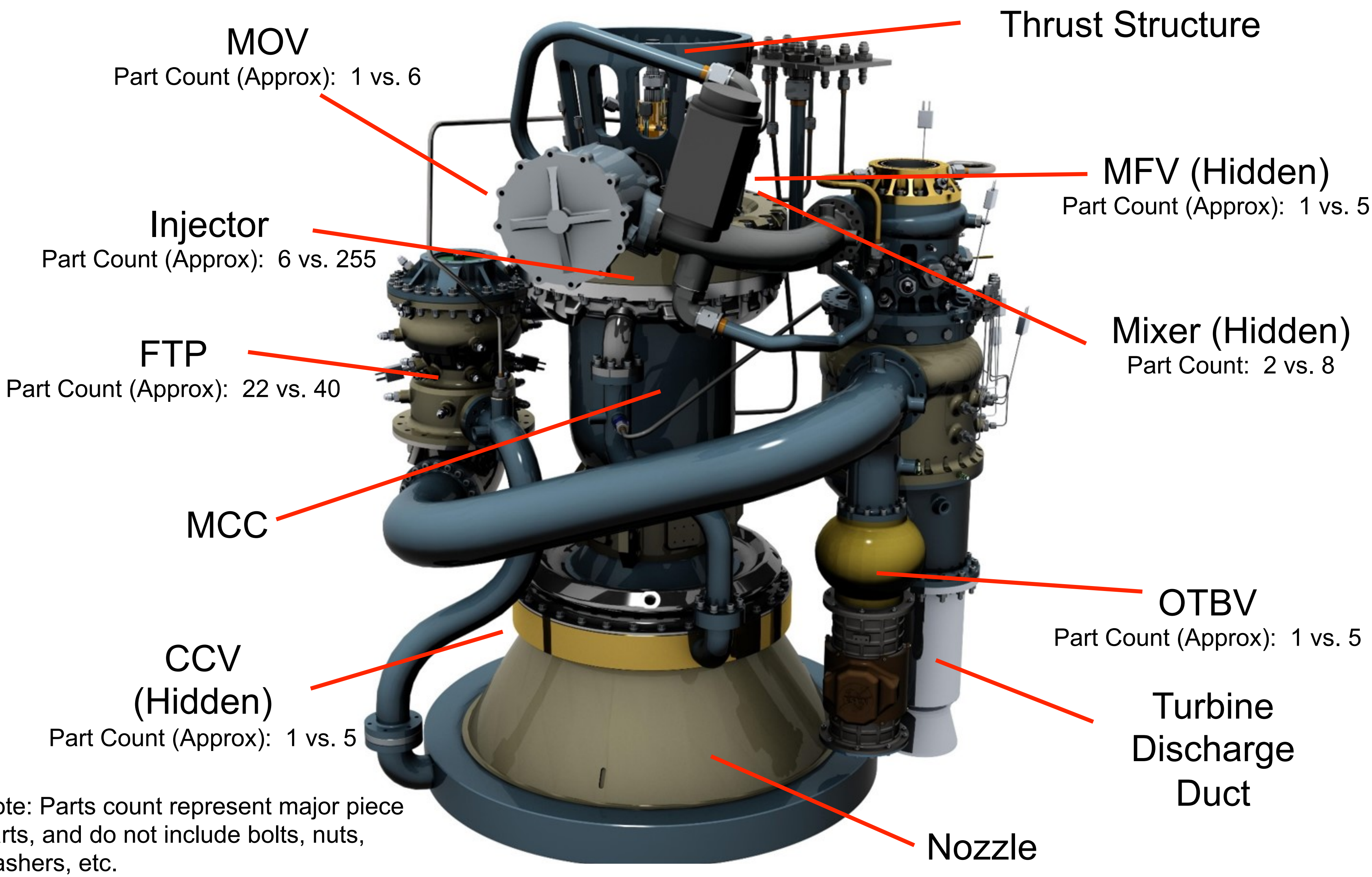
Additive Manufacturing Demonstrator - Basic Characteristics



Engine Assembly LPS00001-02

Vision Engine	Upper stage or In-Space
Cycle	Open Expander
Propellants	LOX/LH2
Thrust, Primary	35 klbf
Thrust, Secondary	25 klbf
Isp, Vacuum	Greater than 450 s
Inlet MR	5.88
Pc, ns	1400 psi
AR	27
Envelope	90” Height, 70” Diameter
Starts	5
Op. Life	3500 sec
Turbopump Configuration	Dual pumps, series turbines, no boost pumps

Expected Reduction in Parts Count for Major Hardware



Note: Parts count represent major piece parts, and do not include bolts, nuts, washers, etc.

Material Properties

- **Material properties often confused with certification**
  - Certification >> material properties
- **Highly "localized user" process requires different thinking**
- **Shift emphasis away from exhaustive, up-front material allowables intended to account for all process variability**
- **Move toward ongoing process monitoring with thorough, intelligent witness sampling of each build**
- **Hybrid of Statistical Process Control and CMH-17 approach for process-sensitive composite material equivalency**
- **Utilize a QMP to develop a *Process Control Reference Distribution* (PCRD) of material properties that reflects not the design values, but the actual mean and variability associated with the controlled AM process**
- **Enforce suite of design values compatible with PCRDs**
- **Accept parts based on comparison to PCRD, not design values**
- **PCRDs are continuously updated, design suite must be monitored and determined judiciously early on**
- **Allows for adoption of new processes without invalidating large allowables investments**