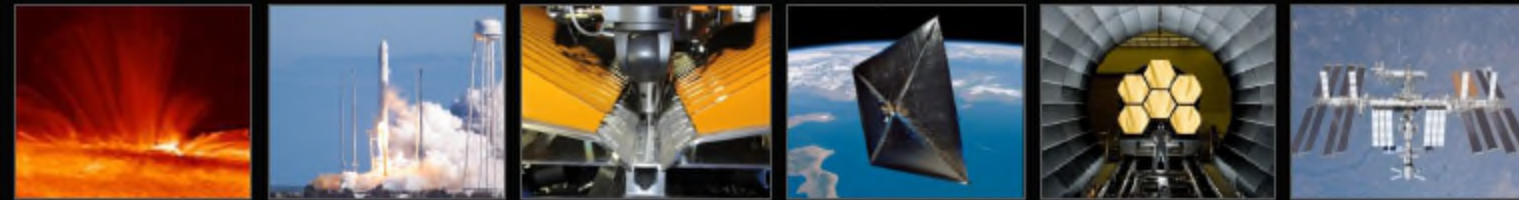




NASA's In Space Manufacturing Initiative and Additive Manufacturing Development and Quality Standards Approach for Rocket Engine Space Flight Hardware

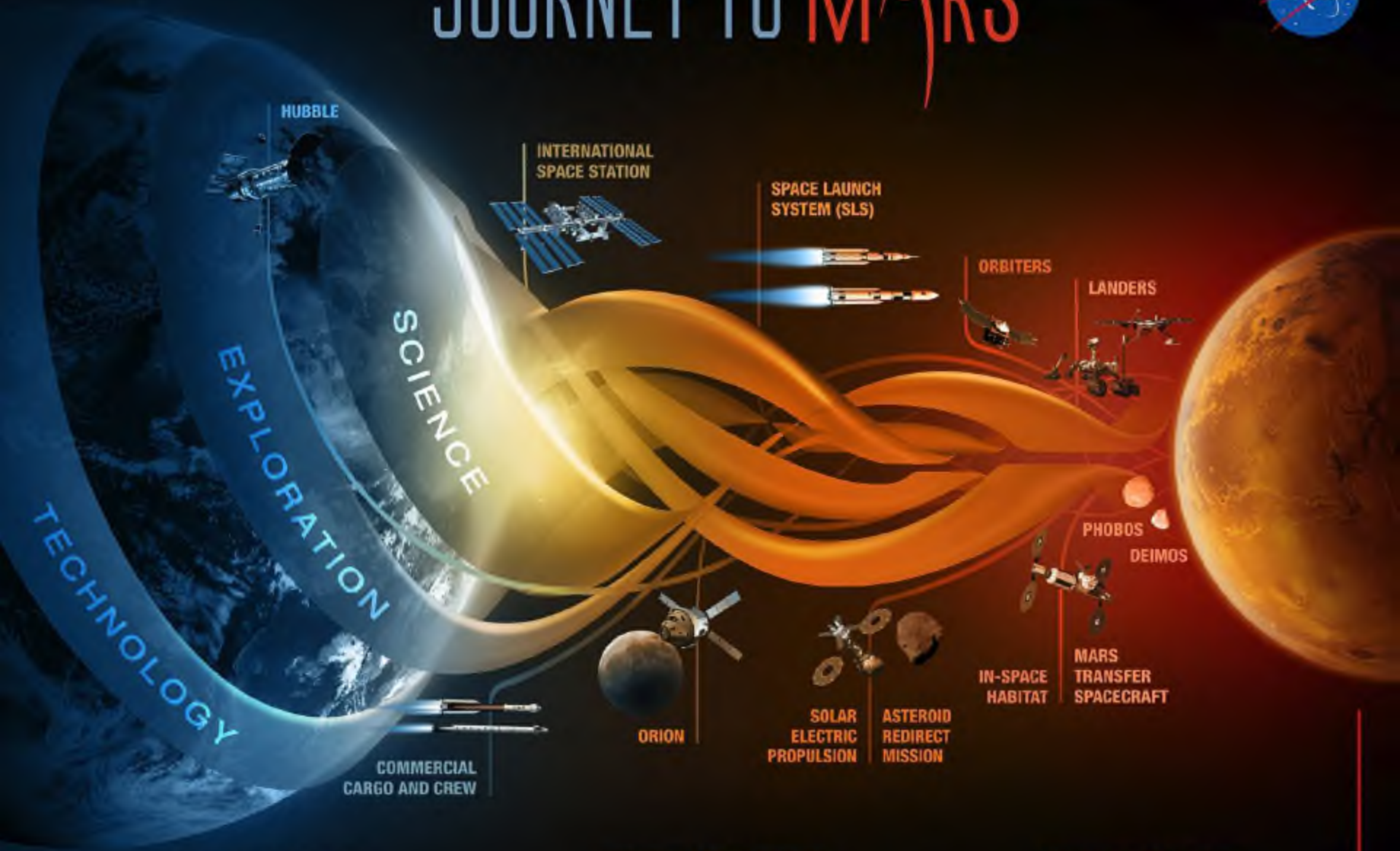
Additive Manufacturing for Defense and Aerospace 2016 Summit
March 29-30, 2016
London, United Kingdom

marshall



- " **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
 - " Additive Construction with Mobile Emplacement (ACME) and Additive Construction for Expeditionary Structures (ACES)
 - " External In-Space Manufacturing and Assembly Projects
 - " ISM Roadmap
- " **Additive Manufacturing of Liquid Rocket Engine Components**
 - " Additive Manufacturing Demonstrator: Liquid Propulsion System
 - " Proposed Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware
 - " Additive Manufacturing Structural Integrity Initiative (AMSII)
- " **Summary**

JOURNEY TO MARS



HUBBLE

INTERNATIONAL SPACE STATION

SPACE LAUNCH SYSTEM (SLS)

ORBITERS

LANDERS

SCIENCE

EXPLORATION

TECHNOLOGY

COMMERCIAL CARGO AND CREW

ORION

SOLAR ELECTRIC PROPULSION

ASTEROID REDIRECT MISSION

PHOBOS
DEIMOS

IN-SPACE HABITAT

MARS TRANSFER SPACECRAFT

MISSIONS: 6-12 MONTHS
RETURN: HOURS

MISSIONS: 1 TO 12 MONTHS
RETURN: DAYS

MISSIONS: 2 TO 3 YEARS
RETURN: MONTHS

EARTH RELIANT

PROVING GROUND

EARTH INDEPENDENT

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

International Space Station

Space Launch System

Asteroids

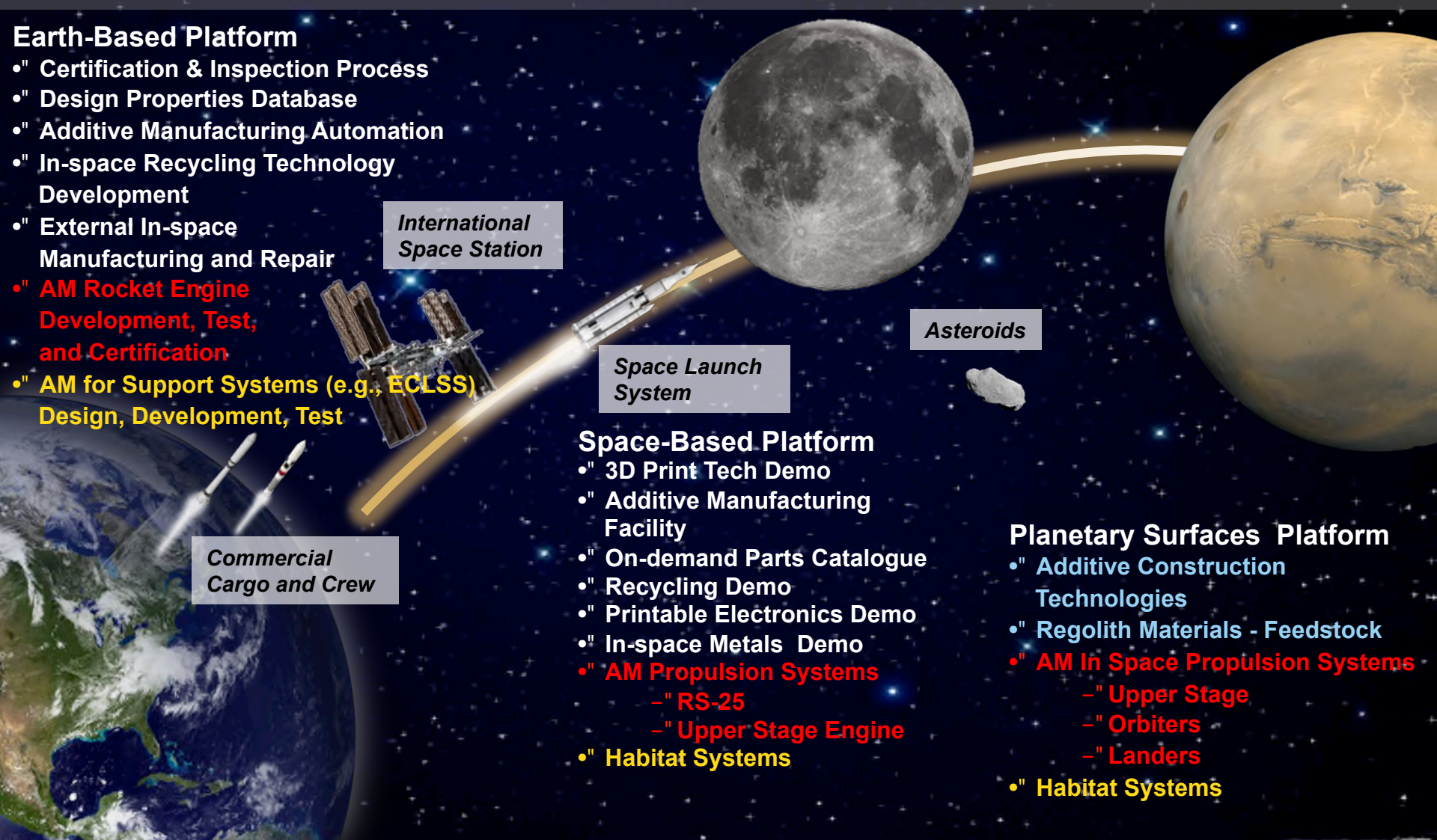
Commercial Cargo and Crew

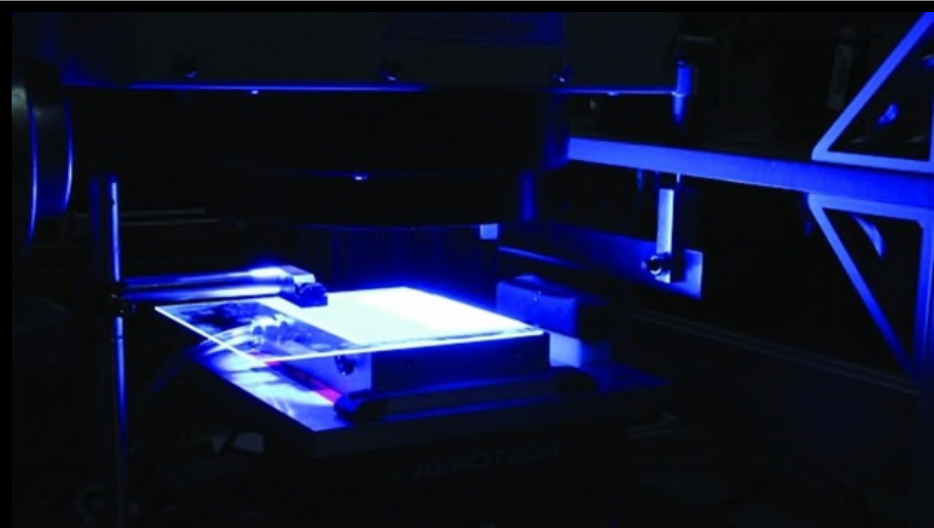
Space-Based Platform

- 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



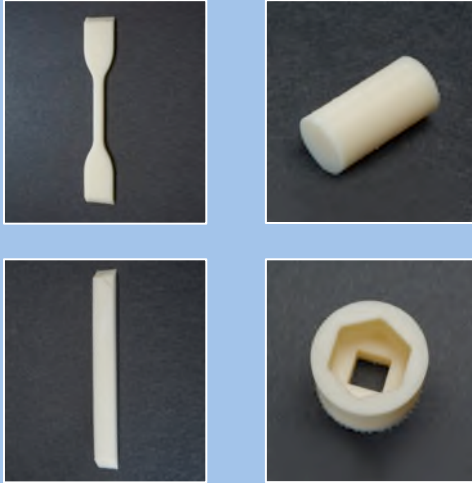


Additive Manufacturing

at Marshall Space Flight Center

In Space Manufacturing Initiative

Mechanical Property Test Articles



Functional Tools



- " A total of 21 parts were printed on ISS, including the uplinked ratchet handle.
- " Inspection and testing of all articles included:
 - Structured light scanings
 - X-ray and CT scan
 - Density
 - Mechanical testing
 - Microscopy
- " Mechanical property differences observed between flight and ground samples
- " Additional ISS prints in Spring 2016 will enable additional mechanical properties data and support hypotheses evaluation
- " Lessons Learned have been incorporated into the next generation 3D Printer for ISS – Additive Manufacturing Facility (AMF) by Made In Space

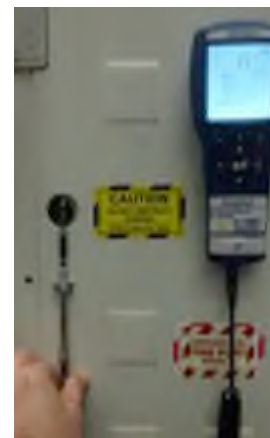
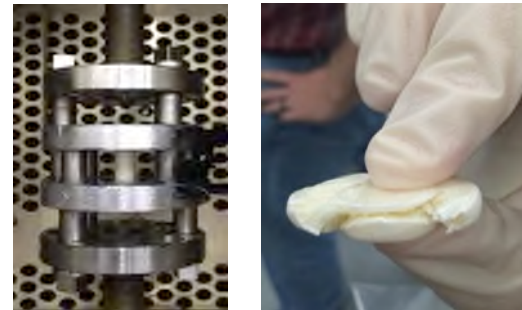
Material Characterization Database Development

- 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)

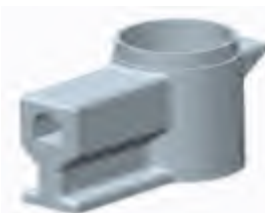
On-demand ISM Utilization Catalogue Development

- 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
- Documenting on-orbit printing process with users and ISS Program (safety, human factors, etc.)
- Developing V&V/Quality Control/Certification process and process for Candidate Part inclusion in catalogue

Compression Testing of Mechanical Flight Sample 7/21/15



**OGS AAA
Inlet Adaptor**



**Freedom
360
Virtual
Reality
Rig**



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

- "Commercial printer for use on ISS
- "Incorporates lessons learned from 3D Printer ISS Tech Demo
- "Expanded materials capabilities: ABS, ULTEM, PEEK
- "Anticipated launch in Spring 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 (2014) awarded to Tethers Unlimited for the In-space Recycler for proposed ISS Technology Demonstration in FY2017



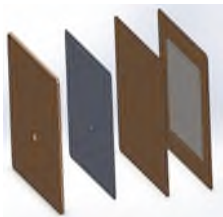
Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo

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

- "Collaborating with Xerox Palo Alto Research Center (PARC), NASA Ames Research Center, and AMRDEC
- "Roadmap developed targeting ISS technology demonstration
- "Printing a Radio Frequency Identification (RFID) antenna for assessment on the RFID Enabled Autonomous Logistics Management Tech Demo
- "Additive ultracapacitors have been developed, tested, & patented utilizing MSFC Innovation Funds

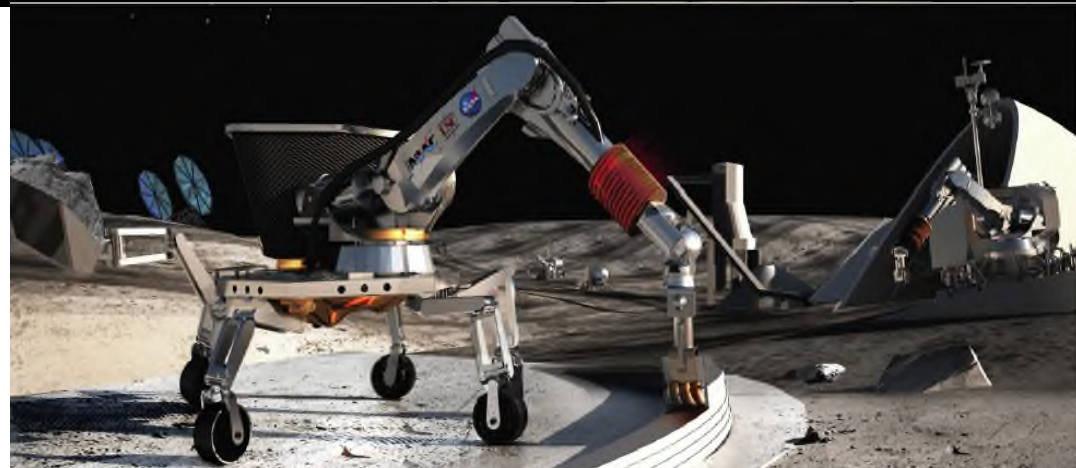


3D Printed RFID Antenna, layers



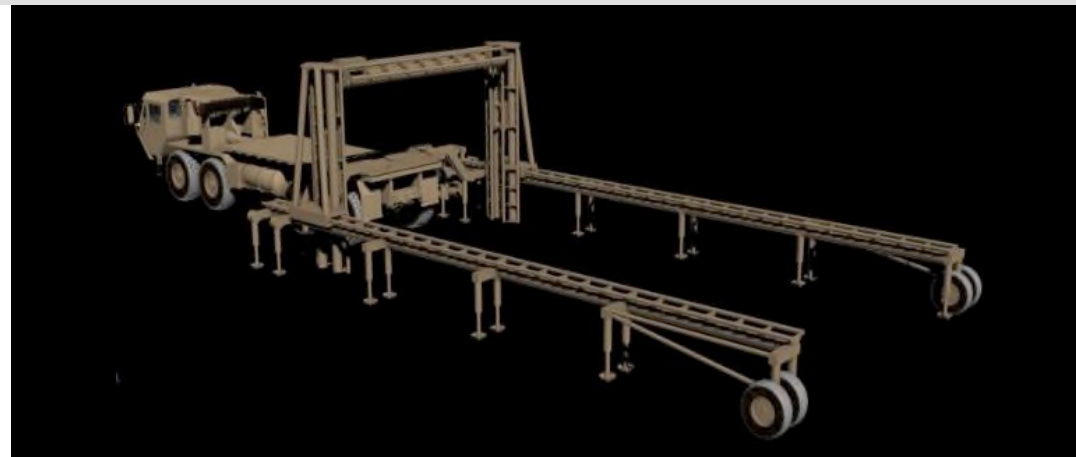
Printed/packaged ultracap device

Additive Construction with Mobile Emplacement (ACME)

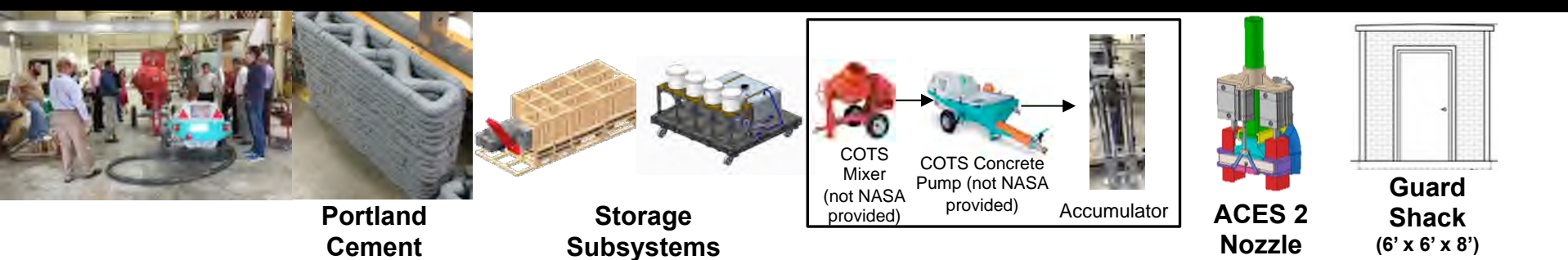
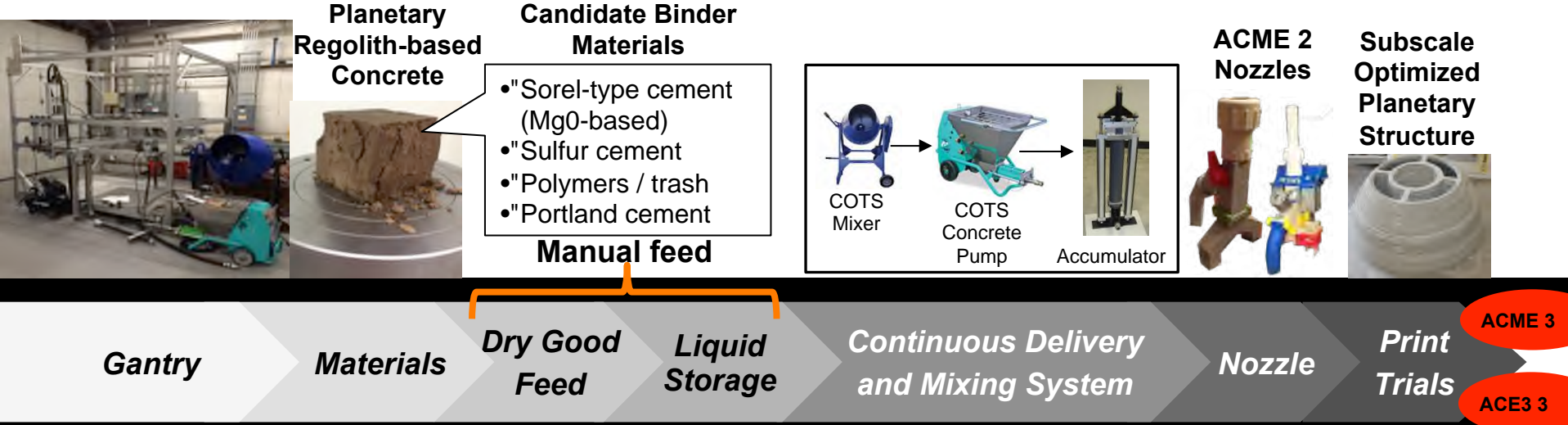


Shared Vision: Capability to print custom-designed expeditionary structures on-demand, in the field, using locally available materials.

Automated Construction of Expeditionary Structures (ACES)



Additive Construction with Mobile Emplacement (ACME)

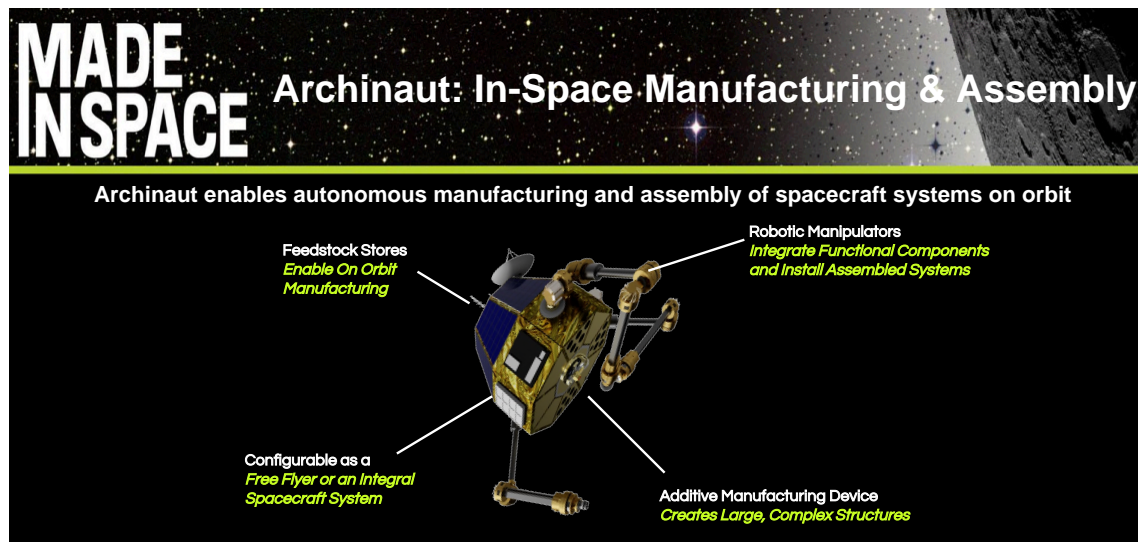


Automated Construction of Expeditionary Structures (ACES)

Synergistic technologies for planetary and terrestrial use




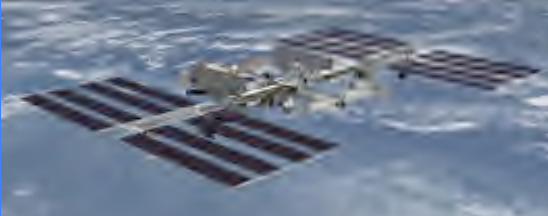

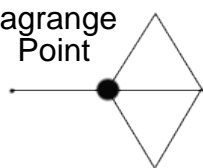


Space Technology Mission Directorate's Tipping Point Projects – Robotic In-Space Manufacturing and Assembly of Spacecraft and Space Structures

- " **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**

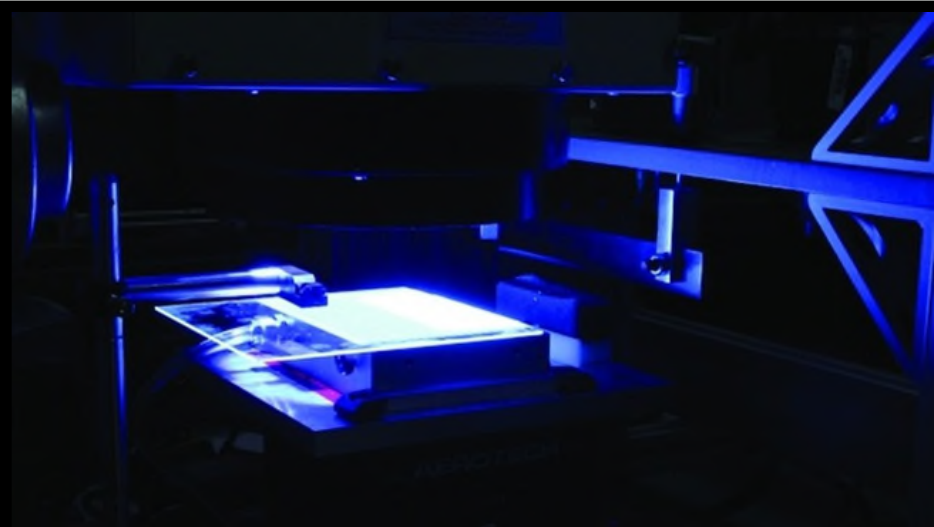


External In-Space Manufacturing (EISM) is a joint program between the Defense Advanced Research Projects Agency (DARPA) Tactical Technology Office and the NASA Advanced Exploration Systems (AES) Office

- " Broad Area Announcement solicitation to be released in Spring 2016

| Earth-based | Demos: Ground & ISS | | | Exploration | | |
|---|---|--|---|---|---|---|
|   |  Plastic Printing Demo Mat. Char. 3D Print Tech Demo |  Recycler Utilization Testing AMF | Metal Printing Self-repair/ replicate Fab Lab Digital Mfctr. External In-space Mfctr | Asteroids  Lagrange Point  | Lunar  | Mars  |
| Ground Analogs | 2014 | 2015 - 2017 | 2018 - 2024 | 2025-35 | 2035+ | |
| <ul style="list-style-type: none"> " 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 | <ul style="list-style-type: none"> " 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 | <ul style="list-style-type: none"> " 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) | ISS: "Fab Lab" Utilization/Facility Focus <ul style="list-style-type: none"> " 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 | Lunar, Lagrange FabLabs <ul style="list-style-type: none"> " 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 | Planetary Surfaces Points Fab <ul style="list-style-type: none"> " Transport vehicle and sites would need Fab capability " Additive Construction & Repair of large structures | Mars Multi-Material Fab Lab <ul style="list-style-type: none"> " 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. |
| <p style="text-align: center;">ISS Serves as a Key Exploration Test-bed for the Required Technology Maturation & Demonstrations</p> | | | | | | |

* Green text indicates ISM/ISRU collaboration



Additive Manufacturing

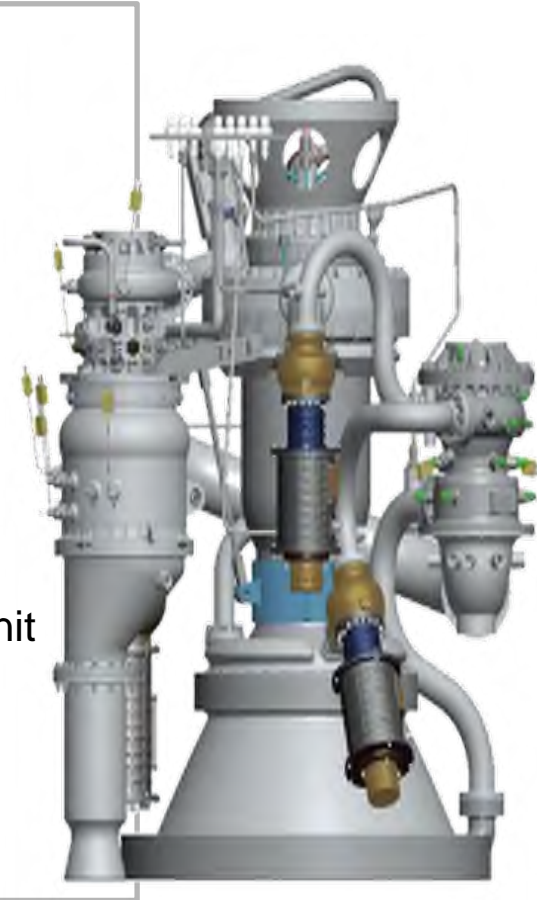
at Marshall Space Flight Center

Advanced Manufacturing Demonstrator: Liquid Propulsion System

Additive manufacturing related

Project Objectives

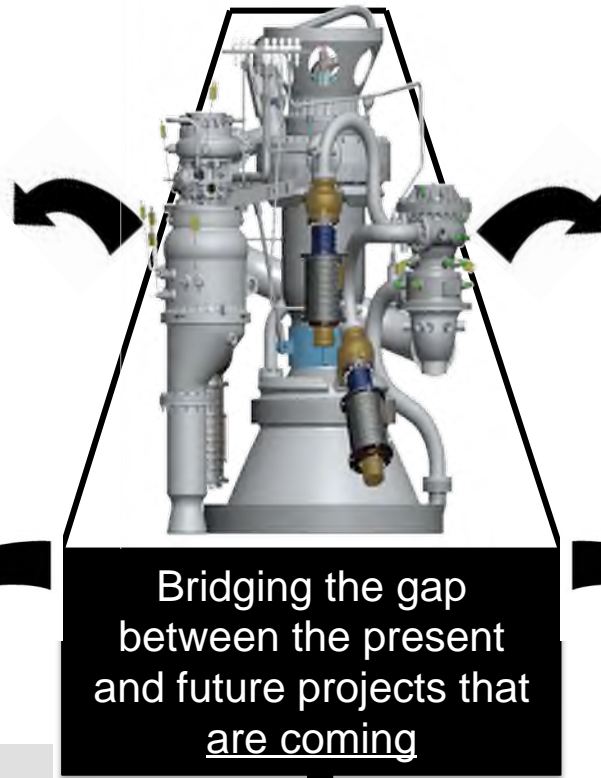
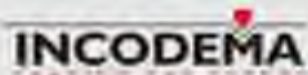
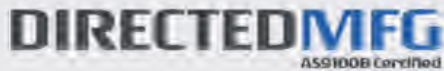
- " **Reduce the cost and schedule required for new engine development and demonstrate it through a complete development cycle.**
 - " Prototype an engine in less than 2.5 years.
 - " Use additive manufacturing to reduce part cost, fabrication time, and overall part count.
 - " Adopt Lean Development 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.**



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

Building Foundational Industrial Base



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



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

Building Experience "Smart Buyer" to enable Commercial Partners

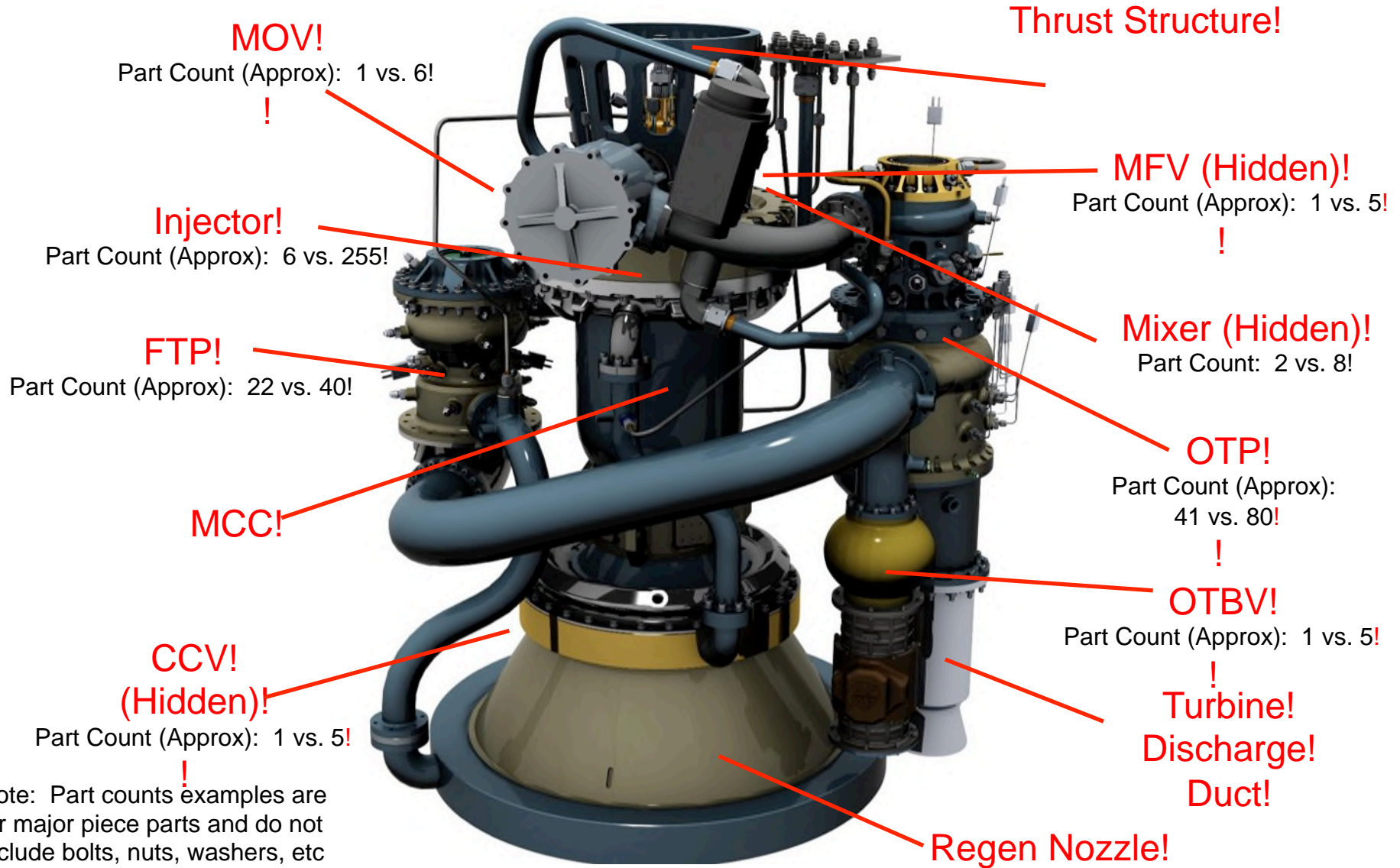


Enabling & Developing Revolutionary Technology

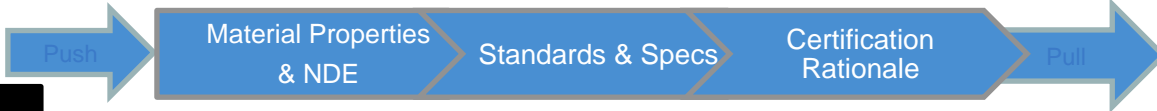


| State of the Art for Typical Engine Developments | Prototype Additive Engine |
|--|--|
| <ul style="list-style-type: none"> •" DDT&E Time <ul style="list-style-type: none"> –" 7-10 years | <ul style="list-style-type: none"> •" DDT&E Time <ul style="list-style-type: none"> –" 2-4 years |
| <ul style="list-style-type: none"> •" Hardware Lead Times <ul style="list-style-type: none"> –" 3-6 Years | <ul style="list-style-type: none"> •" Hardware Lead Times <ul style="list-style-type: none"> –" 6 Months |
| <ul style="list-style-type: none"> •" Testing <ul style="list-style-type: none"> –" Late in the DDT&E cycle | <ul style="list-style-type: none"> •" Testing <ul style="list-style-type: none"> –" Testing occurs early in the DDT&E cycle |
| <ul style="list-style-type: none"> •" Engine Cost <ul style="list-style-type: none"> –" \$20 - \$50 Million | <ul style="list-style-type: none"> •" Prototype Cost <ul style="list-style-type: none"> –" \$3-5 Million |
| <ul style="list-style-type: none"> •" Applicability <ul style="list-style-type: none"> –" Design for particular mission by a particular contractor –" Often proprietary | <ul style="list-style-type: none"> •" Applicability <ul style="list-style-type: none"> –" Provide relevant data to multiple customers (SLS, Commercial partners, other government agencies) –" Flexible test bed configuration can accommodate other's hardware / design concepts |

Reduction in Parts Count for Major Hardware



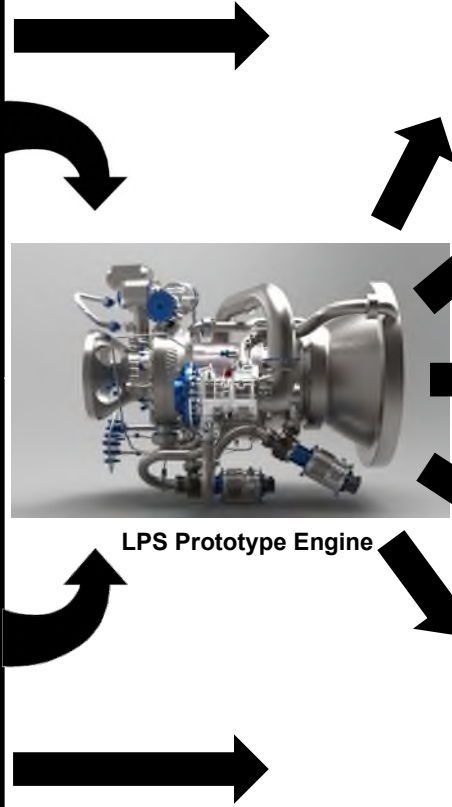
Fundamental Additive Manufacturing M&P Development



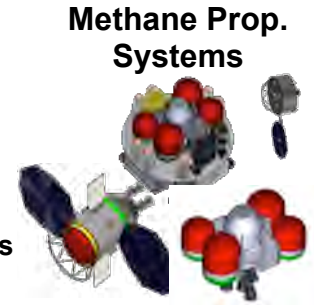
Parallel & Congruent Activities

Lean & Aggressive Development Philosophy

Relevant Environment Testing



Payloads & Satellites RP Engine



Methane Prop. Systems



Nuclear Propulsion



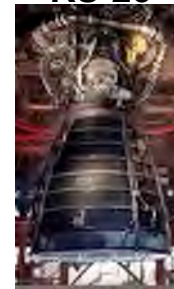
MPS Components



Upper Stage Engine



RS-25

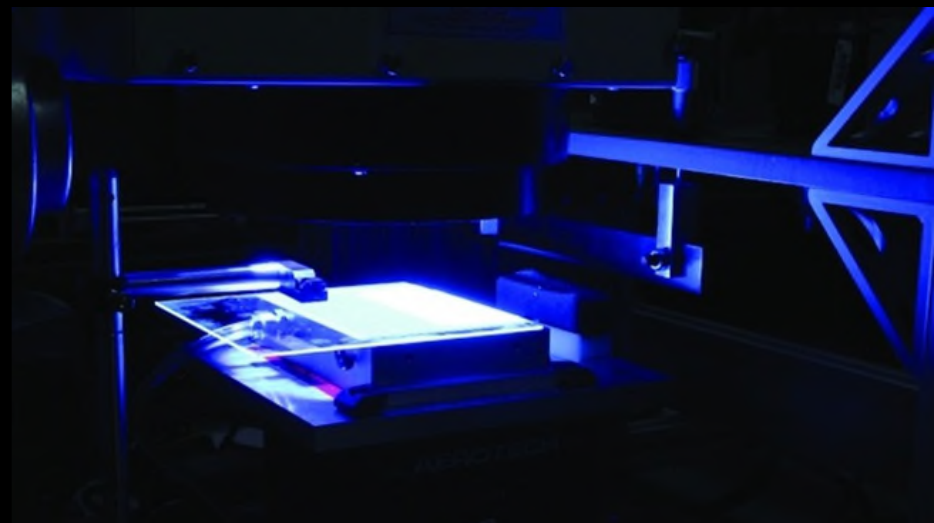


CCP



Building Foundational Additive Manufacturing Industrial Base





Additive Manufacturing

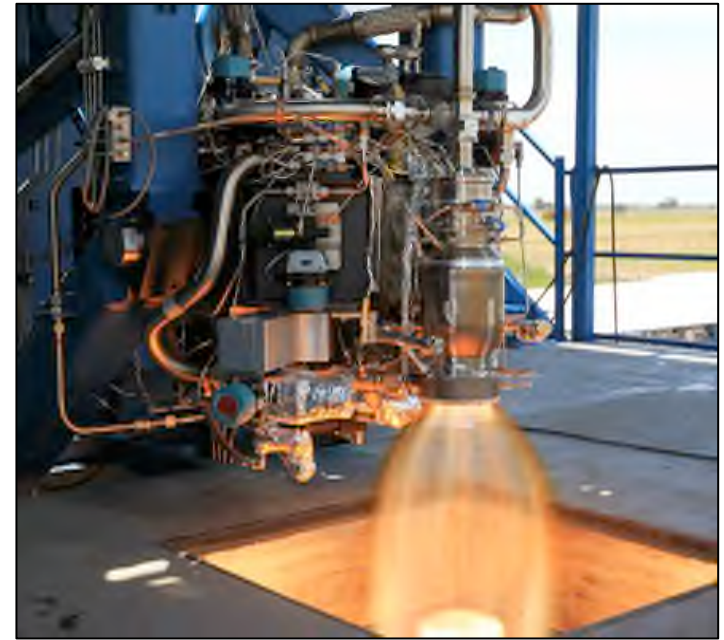
at Marshall Space Flight Center

Proposed Certification Approach for Additively Manufactured Rocket Engine Spaceflight Hardware

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**

- " **Opportunity**

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

- " **Risks**

- " Lack of governing requirements (M&P)
- " Process control – how to ensure AM process is repeatable, reliable, and in control (M&P, PM)
- " Process sensitivity :: unknown failure modes (M&P, PM)
- " Inspection and acceptance testing (PM)
- " Rapidly evolving technology(M&P, PM)
- " Too easy, too cheap = ubiquitous, lack of rigor (M&P)
- " AM related failure tarnishes the technology (M&P)



National Aeronautics and
Space Administration

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

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

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**

- " ***Tailoring***
- " Governing standards
- " AM Design
- " ***Part Classification***
- " Structural Assessment
- " Fracture Control
- " Qualification Testing
- " Part Development Plans
- " ***Process Controls***
- " ***Material Properties***
- " Finishing, Cleaning, Repair Allowances
- " Part Inspection and Acceptance

- " **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.

(AMSII) Project Overview

- " **Goal for Certification of AM flight hardware at NASA**
 - " Implement a unified, data-driven, cross-program approach to the certification of structural AM spaceflight hardware.
- " **AMSII Project Objectives**
 - " Provide the foundational knowledge required to qualify the Selective Laser Melting (SLM) process for structural hardware in spaceflight applications.
 - " Validate the qualification and certification methodology presented in the MSFC draft, *Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware*.
- " **Participants**
 - " ARC, GRC, LaRC, MSFC, NASA NDE Working Group (NNWG)
- " **Tasks**
 - 1." Establish feedstock controls and maximum recycle limits for Alloy 718 powder. Identify powder control metrics for inclusion in standard.
 - 2." Apply statistical process controls to powder fusion systems. Evaluate methodology at commercial vendors having mature SLM alloy 718 processes
 - 3." Derive statistically-based design allowables for SLM alloy 718 and compare with traditional A-basis methodology. Publish design allowables for SLM alloy 718 based on a minimum five powder lots.
 - 4." Design and build analogue engine articles to evaluate platform-to-platform variability; establish "first article" inspection methodology; and interrogate critical features.
 - 5." Characterize defect structures of SLM alloy 718 material built within and at the limits of the process window. Provide test articles to NNWG for NDE studies. Evaluate in-situ process monitoring methods to detect defects and/or build anomalies.

- " **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
- " **Additive construction offers significant potential for expeditionary structures for the Army and NASA and, in addition, commercial, humanitarian assistance and disaster relief possibilities. Excellent opportunity for demonstration of public/private partnerships.**

- " **AMD-LPS is catalyst for culture change**
 - " Demonstrated game changing aspects of cost and schedule reduction
 - " Dramatic reduction in Design, Development, Test and Evaluation (DDT&E) cycle time
 - " Established 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 designed to address foundational knowledge gaps in certification requirements to better manage AM risk**