National Aeronautics and
Space Administration

NASA's Additive Manufacturing Development Materials Science to Technology Infusion - Connecting the Digital Dots

Science in the Age of Experience Conference / Additive Manufacturing Symposium

May 15, 2017

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Principal Technologist
NASA, Space Technology Mission Directorate

The Crucial Role of Additive Manufacturing at NASA

Abstract:

At NASA, the first steps of the Journey to Mars are well underway with the development of NASA's next generation launch system and investments in research and technologies that should increase the affordability, capability, and safety of exploration activities.

Additive Manufacturing presents a disruptive opportunity for NASA to design and manufacture hardware with new materials at dramatically reduced cost and schedule. Opportunities to incorporate additive manufacturing align very well with NASA missions and with most NASA programs related to space, science, and aeronautics. The Agency also relies on many partnerships with other government agencies, industry and academia.

Agenda

- **NASA's Journey to Mars – Where will Additive Manufacturing Contribute?**
- **Background**
- **National Landscape**
- **In Space Manufacturing Initiative (ISM)**
- **Additive Manufacturing of Liquid Rocket Engine Components**
- **Proposed Engineering and Quality Standard for Additively Manufactured Spaceflight Hardware**

Space Technology…
…. an Investment for the Future

- Enables a **new class of NASA missions** beyond low Earth Orbit.
- **Delivers innovative solutions** that dramatically improve technological capabilities for NASA and the Nation.
- Develops technologies and capabilities that make NASA's missions **more affordable and more reliable.**
- Invests in the economy by **creating markets and spurring innovation** for traditional and emerging aerospace business.
- **Engages the brightest minds** from academia in solving NASA's tough technological challenges.

Addresses National Needs

A generation of studies and reports (40+ since 1980) document the need for regular investment in new, transformative space technologies.

Value to NASA **Value to the Nation**

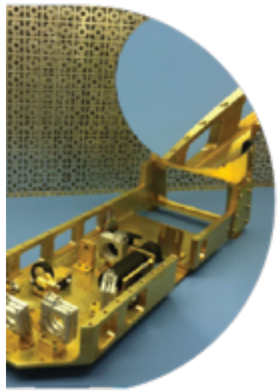
Who:

The NASA Workforce
Academia
Small Businesses
The Broader Aerospace Enterprise

STMD Thrust Areas

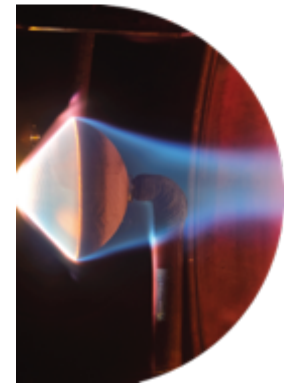
Space Technology focus investments in 7 thrust areas that are key to future NASA missions and enhance national space capabilities.

Space Power and Propulsion



High-Bandwidth Comm, Deep Space Navigation, Avionics

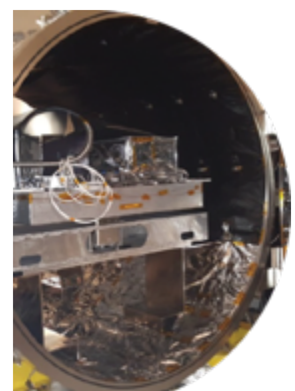
Advanced Life Support & Resource Utilization



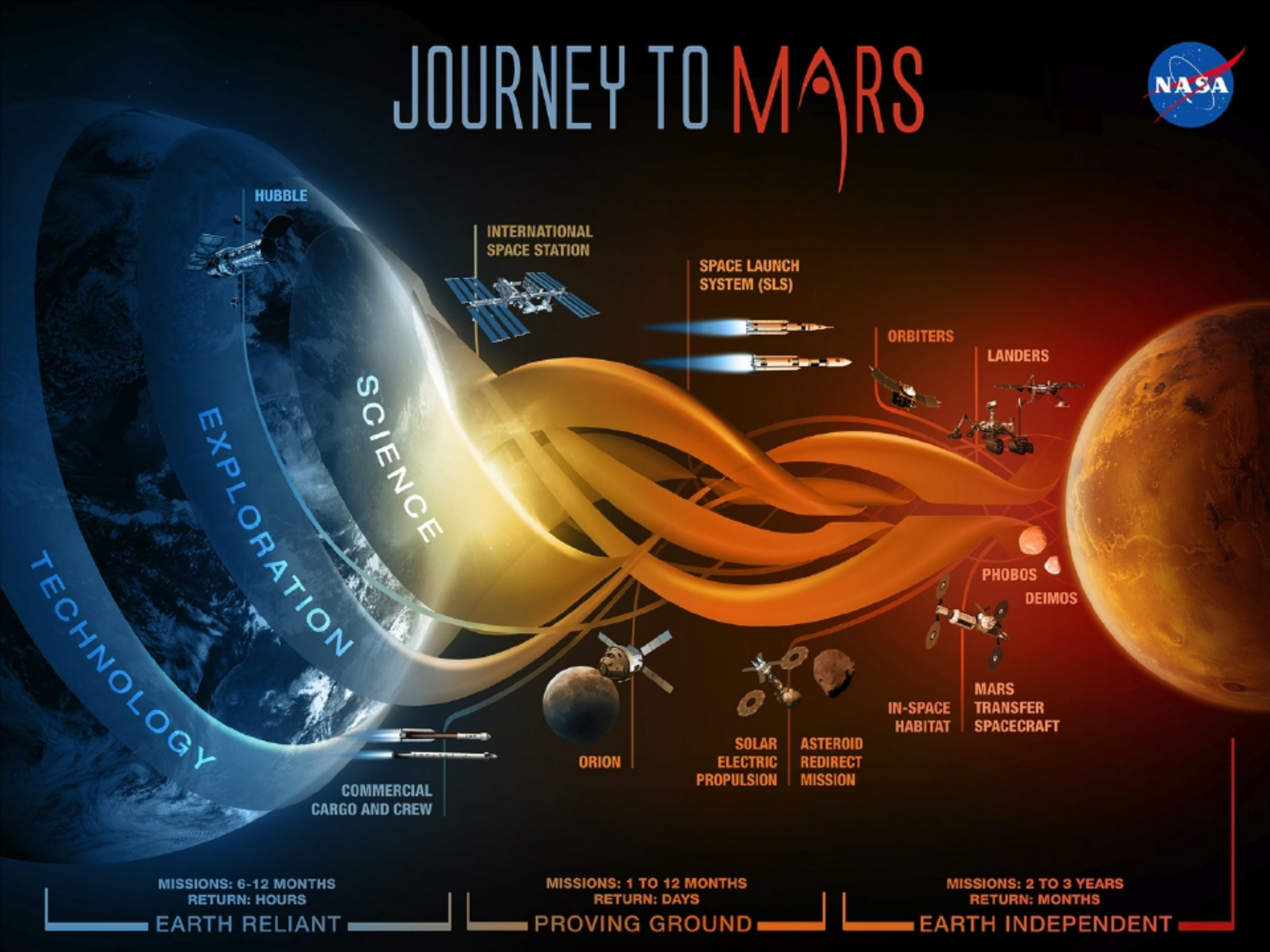
Entry Descent and Landing Systems

Autonomy & Space Robotic Systems

Lightweight Structures & Manufacturing

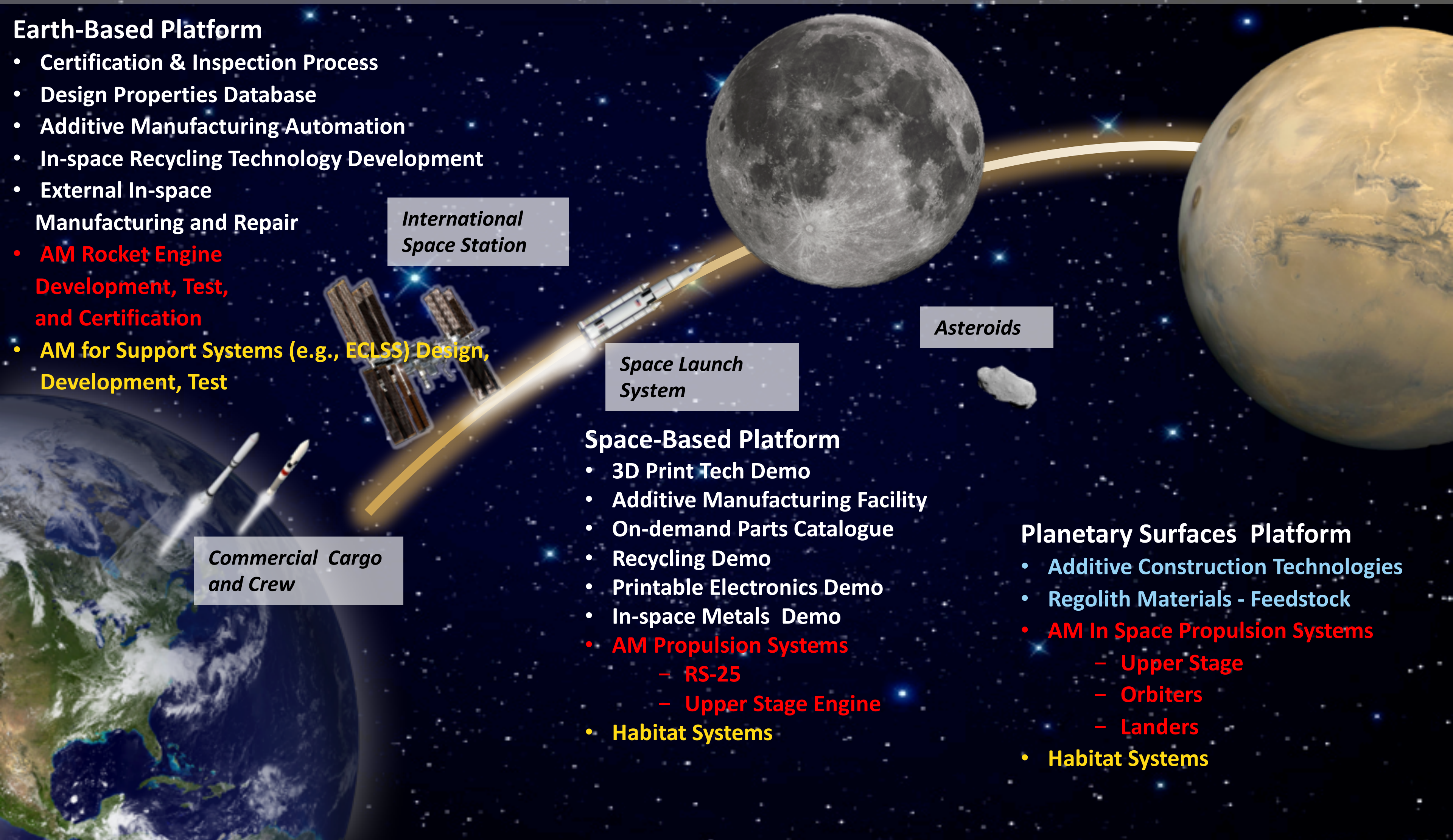


Space Observatory Systems


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

Additive Manufacturing Path to Exploration

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

Manufacturing USA
National Network for Manufacturing Innovation

Executive Office of the President

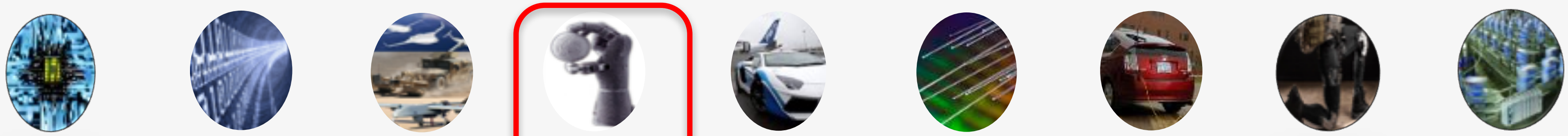
Advanced Manufacturing Partnership (AMP/PCAST)

Advanced Manufacturing National Program Office (hosted by DOC - NIST)

NSTC - Advanced Manufacturing Subcommittee

Manufacturing USA: Nat'l Network for Mfg Innov

Nine Manufacturing USA Institutes Established



NextFlex	DMDII	LIFT	America Makes	IACMI	AIM Photonics	Power America	AFFOA	Smart Manufacturing
Hybrid Electronics	*Digital Mfg.*	*Light/Modern Metals*	*Additive Mfg.*	*Adv. Composites*	*Integrated Photonics*	*Wide bandgap semis*	*Technical textiles*	*Adv. sensors, controls*
San Jose, CA	Chicago, IL	Detroit, MI	Youngstown, OH	Knoxville, TN	Rochester, NY	Raleigh, NC	Cambridge, MA	Los Angeles, CA

Since launching in 2012:

- $600M+ Fed matched by $1.3B+ non-Fed
- 1,300+ companies, universities, and non-profits members
- 30+ states

More Competitions underway

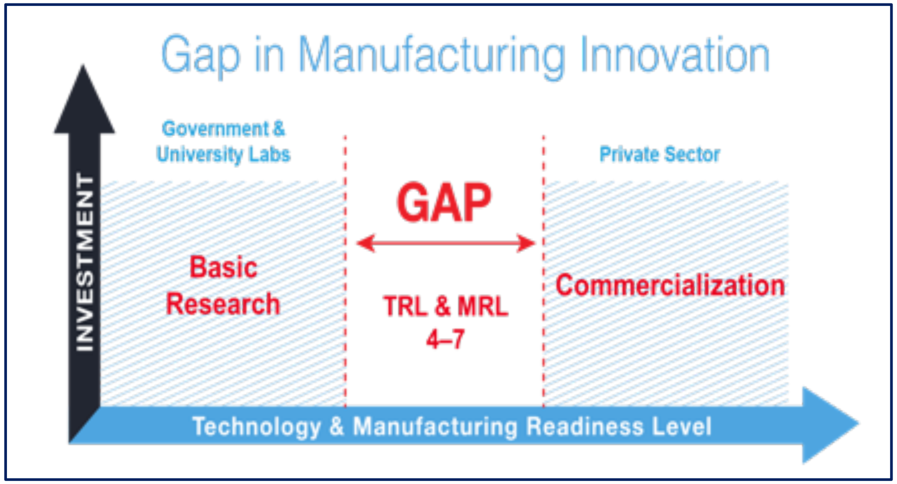
2 competitions underway	*2 competitions underway*	*Open topic(s) competition*

America Makes - The National Additive Manufacturing Innovation Institute

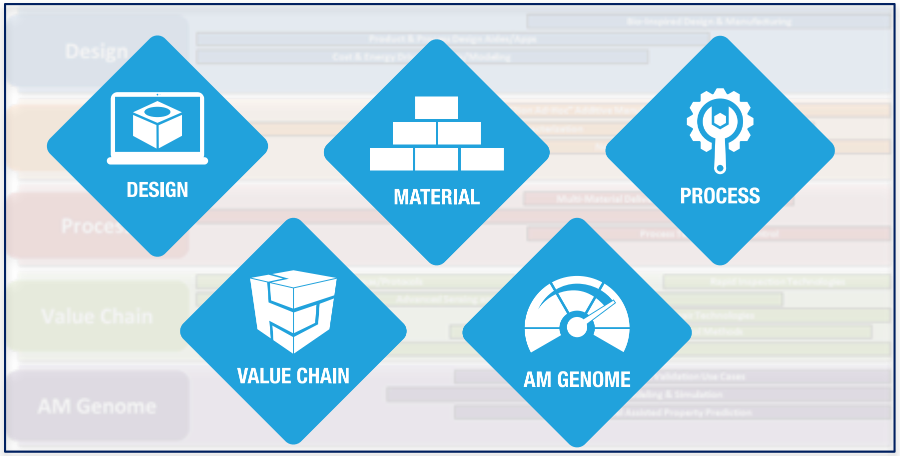
Overview

- Est. August 2012; Lead: National Center for Defense Manufacturing and Machining (NCDMM)
- Headquartered in Youngstown, OH with a satellite center at the University of Texas, El Paso
- Consortium of ~176 member organizations
- Technology Portfolio: ~ 60 projects, ~ 100M combined public and private funding for additive manufacturing R&D

Vision



Technology Roadmap

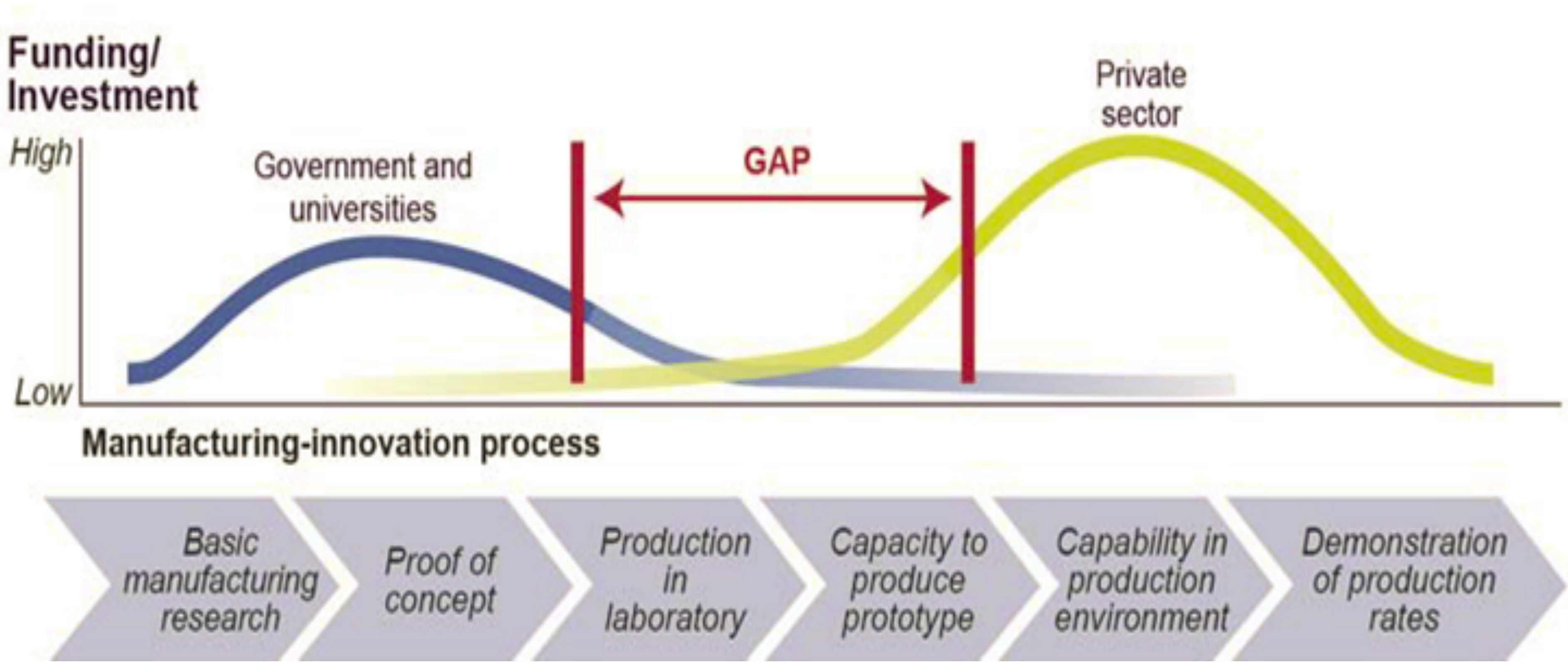


Public / Private Partnership

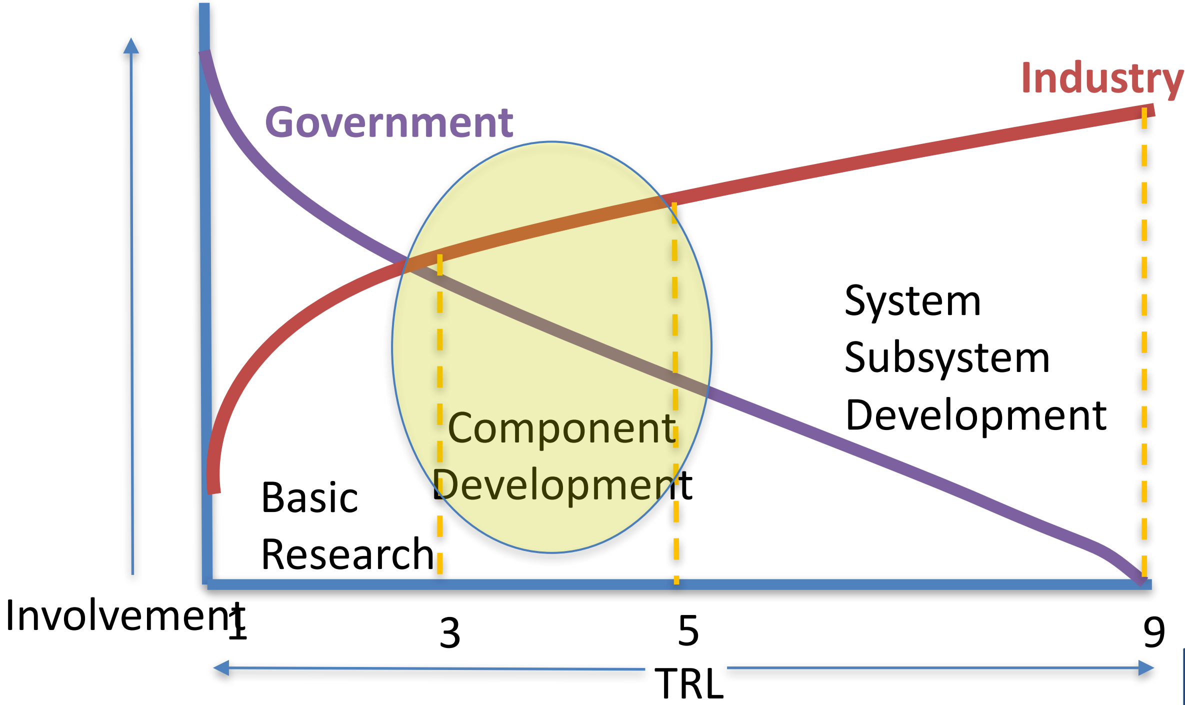
Multi-Agency Collaboration

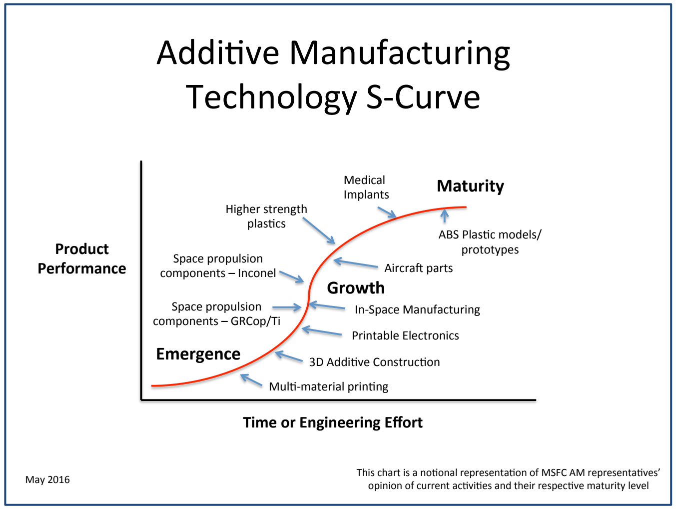
- Partnership between industry, government and academia, led by the Defense-wide Manufacturing Science & Technology (S&T) team.
- Provides a platform for all members, regardless of specialty or organization size, the opportunity to collaborate together.

Filling the Gap from Low TRL to Production



Advanced Manufacturing

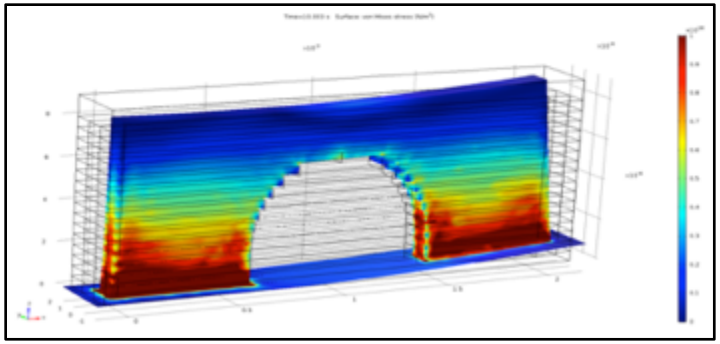




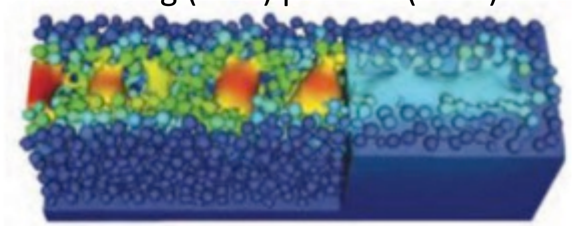
NASA AM Capability

The Digital Twin

- NASA continues to show progress in developing additive manufacturing materials and process models.
  - Demonstrated 3-D models for modeling part distortion and stresses in selective laser melting additive part manufacturing resulting from given process parameters.
  - Developed and demonstrated in-situ monitoring techniques for SLM processing and defined requirements for implementing closed loop control.
  - Thermal models of the melt pool were demonstrated to reduce the process parameters development by over 80% in one test case.
- Volumetric residual stress measurements were completed at Oak Ridge National Laboratories (ORNL) on SLM produced material.



Models of advancing solid liquid front for Selective Laser Melting (SLM) process (LLNL)



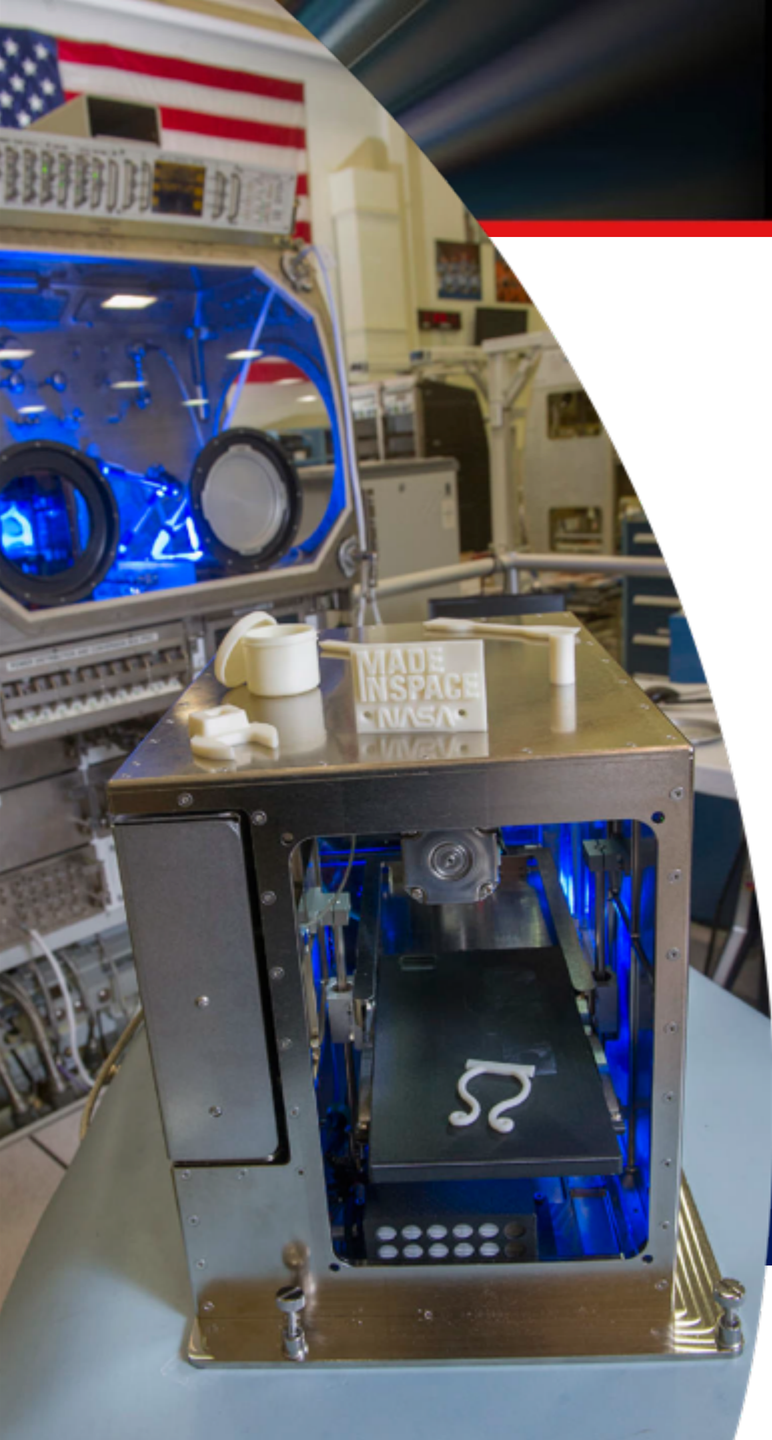
(Univ. California Davis)

In-Space Manufacturing

Preparing for the Journey to Mars – and Beyond

December 8, 2016

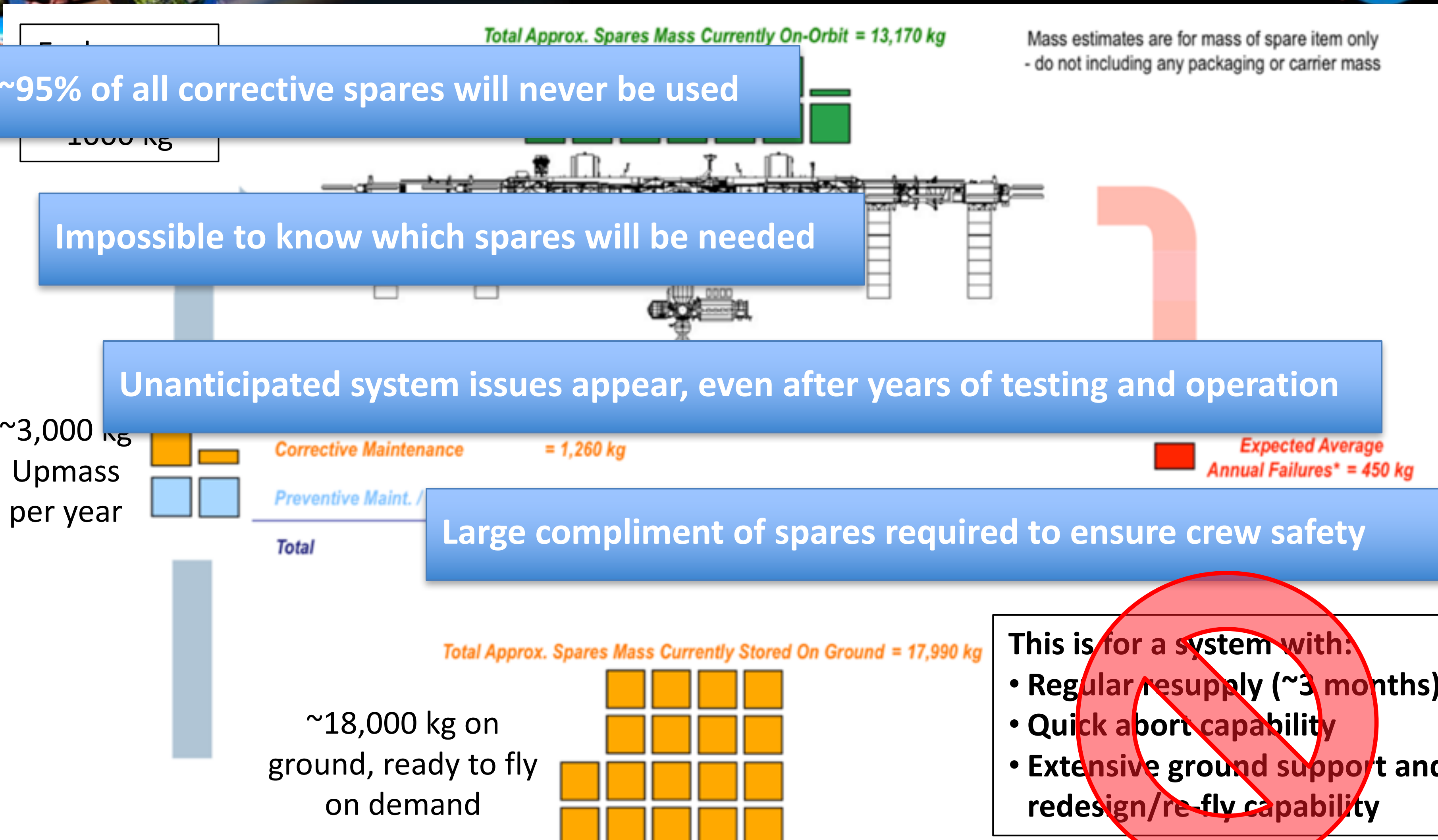
First 3D Printer in Space



ISM Task 1

Maintenance Logistics Challenges

- ~95% of all corrective spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues appear, even after years of testing and operation
- Large compliment of spares required to ensure crew safety



This is for a system with:

- Regular resupply (~3 months)
- Quick abort capability
- Extensive ground support and redesign/re-fly capability

Current maintenance logistics strategy
will not be effective **for long-duration missions beyond LEO**

Cirillo et al. 2011

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

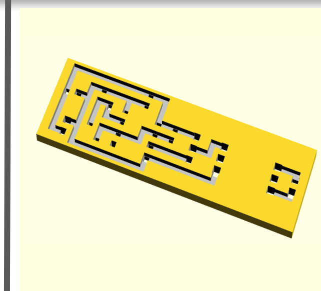
IN-SPACE RECYCLING

- 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

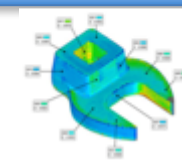
- Develop Multi-material Fabrication Laboratory Rack as 'springboard' for Exploration missions
- In-space Metals ISS Demo
- nScrypt Multi-material machine at MSFC for R&D

PRINTED ELECTRONICS



- MSFC Conductive & Dielectric Inks patented
- Designed & Tested RFID Antennae, 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

- Develop design-level database for micro-g applications
- Includes materials characterization database in MAPTIS
- Design & test high-value components for ISS & Exploration (ground & ISS)

Collaborative Additive Construction Projects Status

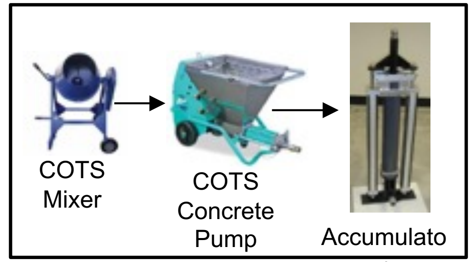
Additive Construction with Mobile Emplacement (ACME)

Planetary Regolith-based Concrete

Candidate Binder Materials

- Sorel-type cement (Mg0-based)
- Sulfur cement
- Polymers / trash
- Portland cement

Manual feed



ACME 2 Nozzles

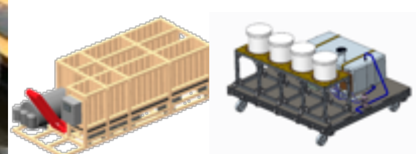
Subscale Optimized Planetary Structure

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

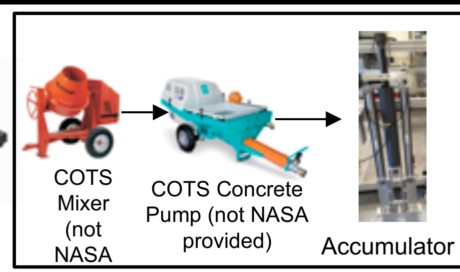
ACME 3

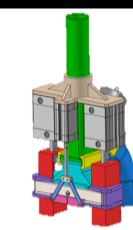
ACE3 3

Portland Cement



Storage Subsystems





ACES 2 Nozzle

Guard Shack
(6' x 6' x 8')

Synergistic technologies for planetary and terrestrial use

3D Printed Habitat Challenge

In-Space Manufacturing (ISM) Technology Goals

- Identify candidate binder for use in Mars/planetary construction Mars Regolith, in-situ resource material.

- Determine optimum binder/regolith ratios and print with that composition to improve strength and durability

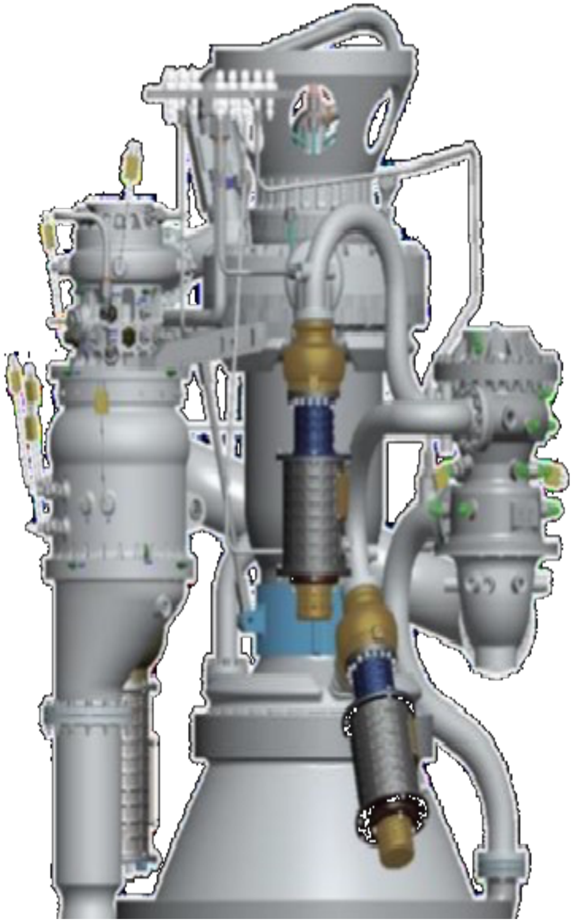
- Advance technology for space and terrestrial 3DP Structures and Habitats
  - Ordinary Portland cement
  - Sorel-type cement
  - Sulfur binders
  - Sintering/melting materials
  - In-Situ Resource Utilization (remote areas)
  - Other potential binders, etc…

Advanced Manufacturing Demonstration

Liquid Propulsion System

December 8, 2016

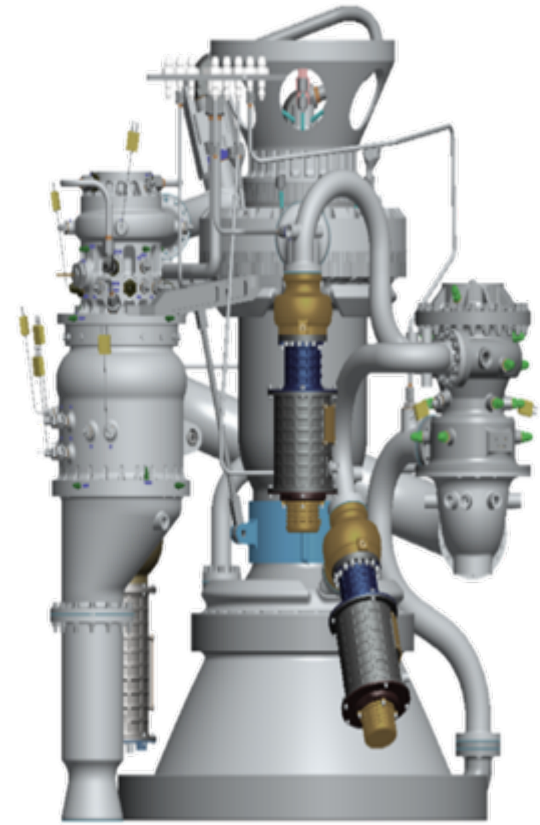
Strategic Vision for Future AM Engines



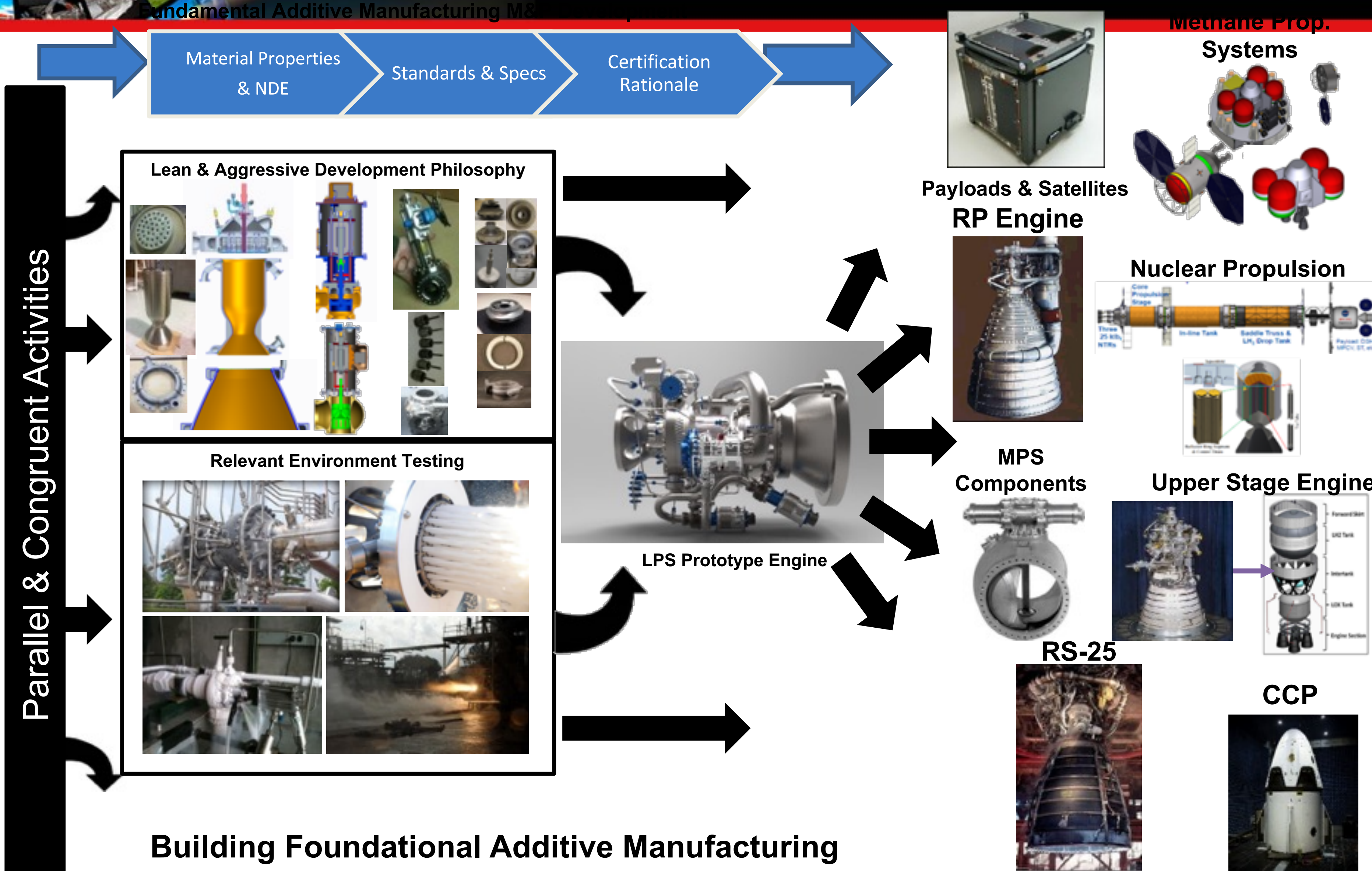
Typical Engine Developments	Prototype Additive Engine
DDT&E Time	
7-10 years	2-4 Years
HW Lead Time	
3-6 Years	6 Months
Prototype Costs	
$20-50 Million	$3-5 Million

Transforming Liquid Propulsion Systems DDT&E with AM

- 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.



Future Outlook



Building Foundational Additive Manufacturing Industrial Base

Certification of AM Components

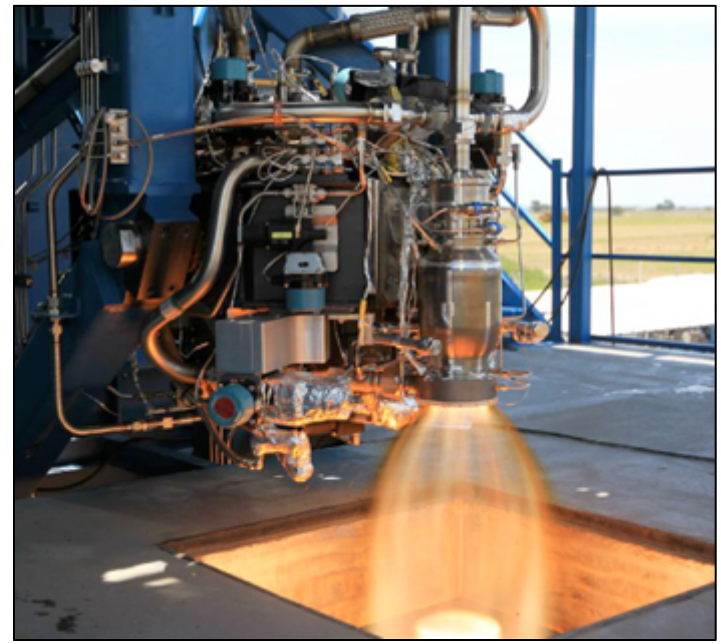
Liquid Propulsion System

December 8, 2016

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

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.

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.

- **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.

National Aeronautics and
Space Administration

Thank you!

Technology Drives Innovation
www.nasa.gov/spacetech