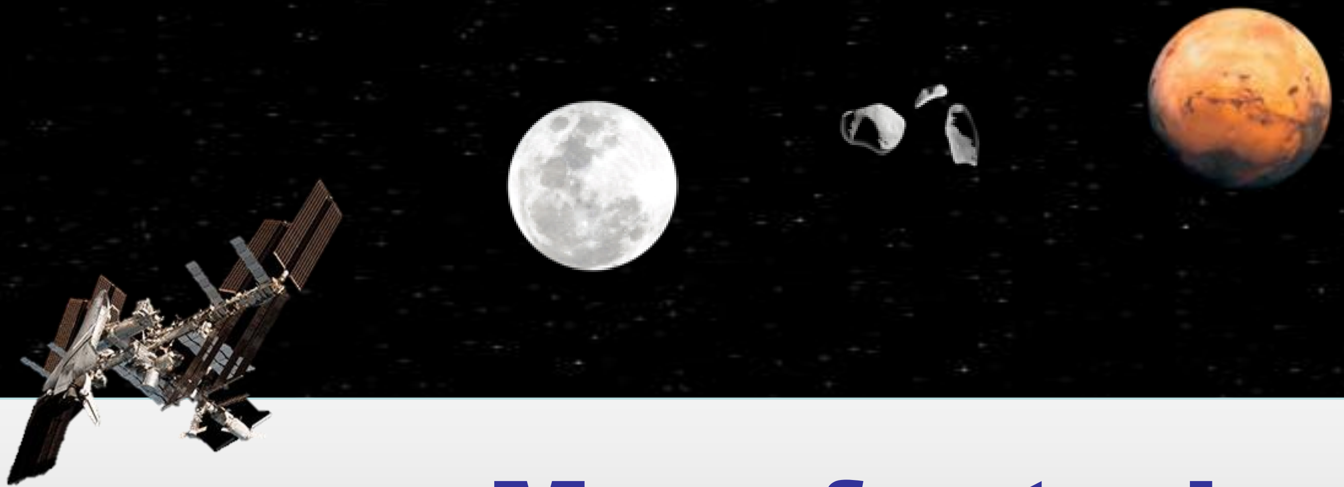

In-space Manufacturing (ISM):
Pioneering Space Exploration
2015 Bay Area Maker Faire

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Why?

- ISM Objective: Develop and enable the manufacturing technologies and processes required to provide on-demand, sustainable operations for Exploration Missions. This includes development of the desired capabilities, as well as the required processes for the certification, characterization & verification that will enable these capabilities to become institutionalized via ground-based and ISS demonstrations.

TECHNOLOGIES

+

SKILLS & PROCESSES

Design
Optimize

Characterize

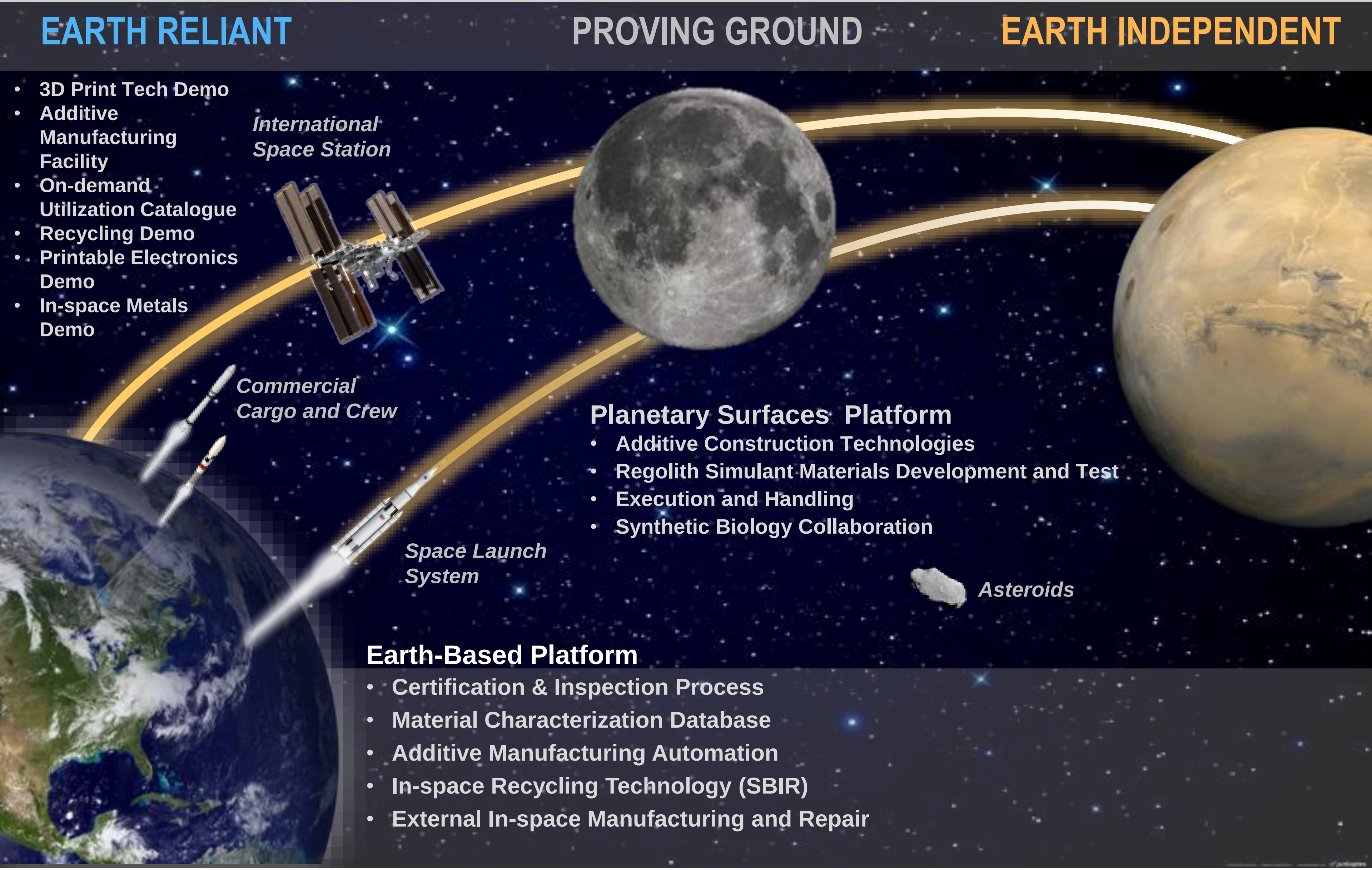
Certify

=

On-demand Manufacturing Capability for Exploration Missions

Images courtesy of Creative

In-space Manufacturing Path to Exploration



In-space Manufacturing Technology Development Roadmap

Earth-based	International Space Station		Exploration

Earth-based


Pre-2012

Ground & Parabolic centric:
- Multiple FDM Zero-G parabolic flights
- Trade/System Studies for Metals
- Ground-based Printable Electronics/Spacecraft
- Verification & Certification Processes under development
- Materials Database
- Cubesat Design & Development

International Space Station

3D Print Tech Demo

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**

Plastic Printing Demo

Add Mfctr. Facility

Recycler

SmallSats

Printable Electronics

Metal Printing

Self-repair/ replicate

External In-space Mfctr

2015 2016

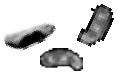
- ***3D Print Tech Demo***
- ***Future Engineer Challenge***
- ***Utilization Catalogue***
- ***ISM Verification & Cert Process Development***
- ***Add. Mfctr. Facility (AMF)***
- ***In-space Recycler SBIR***
- ***In-space Material Database***
- ***External In-space 3D Printing***
- ***Autonomous Processes***
- ***Additive In-space Repair***

2017 2018

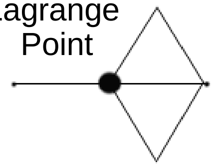
ISS: *Utilization/Facility Focus*
- In-space Recycler Demo
- Integrated Facility Systems for stronger types of extrusion materials for multiple uses including metals & various plastics
- Printable Electronics Tech Demo
- Synthetic Biology Demo
- Metal Demo Options

Exploration

Asteroids



Lagrange Point



Lunar

Mars

2020-25

Lunar, Lagrange FabLabs
- Initial Robotic/Remote Missions
- Provision some feedstock
- Evolve to utilizing in situ materials (natural resources, synthetic biology)
- Product: Ability to produce multiple spares, parts, tools, etc. “living off the land”
- Autonomous final milling to specification

2025

Planetary Surfaces Points Fab
- Transport vehicle and sites would need Fab capability
- Additive Construction

2030 - 40

Mars Multi-Material Fab Lab
- Utilize in situ resources for feedstock
- Build various items from multiple types of materials (metal, plastic, composite, ceramic, etc.)
- Product: Fab Lab providing self-sustainment at remote destination

ISS Technology Demonstrations are Key in ‘Bridging’ Technology Development to Full Implementation of this Critical Exploration Technology.

Step #1: First 3D Printer in Space!

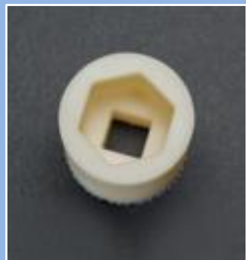
- The 3D Print Tech Demo launched on SpaceX-4 (9/21/14) and was installed in the Microgravity Science Glovebox on ISS
- To date, it has printed 21 parts in space (14 unique designs); the printer functioned nominally.
- First part “emailed” to Space: 3D Print of a ratchet tool demonstrated on-demand capability by uplinking a part file that was not pre-loaded to the 3D Printer.
- The first flight samples were received at NASA MSFC on 3/17/15
- Results to be published late 2015

Images courtesy of NASA

3D Printer International Space Station Technology Demonstration Status

Mechanical Property Test Articles

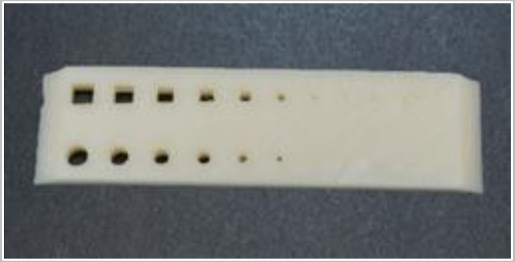


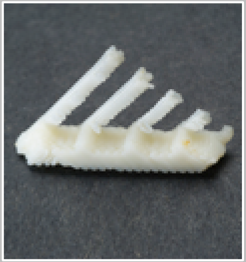



Functional Tools




Printer Performance Capability




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.
- MSFC team has performed initial characterization on ABS and ULTEM.
- B-basis dataset received from RP+M for ULTEM through America Makes project
- MSFC will generate design property database from ground samples produced using the flight spare 3D printer.
- Phase II operations for additional on-orbit prints of engineering test articles are being planned with ISS for later this year.
- 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 materials and process experts and space system designers and JSC ISS Crew Tools Office
- Parts being considered include crew tools, payload components, medical tools, exercise equipment replacement parts, cubesat components, etc.
- First parts are in design and ground test process.

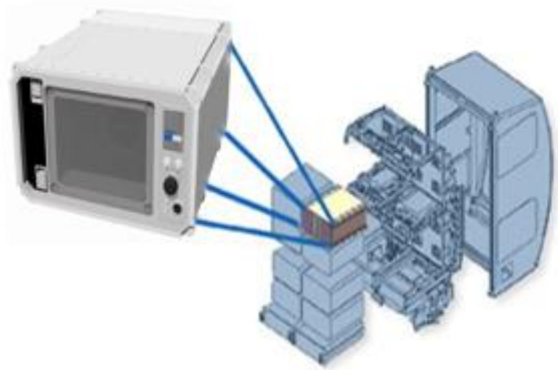
ISM Characterization of Materials and Process Variability (above)

Housekeeping Vacuum Crevice Tool

EVA Suit Fan Shipping Container: Design Clearances had to be relaxed for part to be printed on one FDM printer (red) vs. another in order for the parts to be assembled.

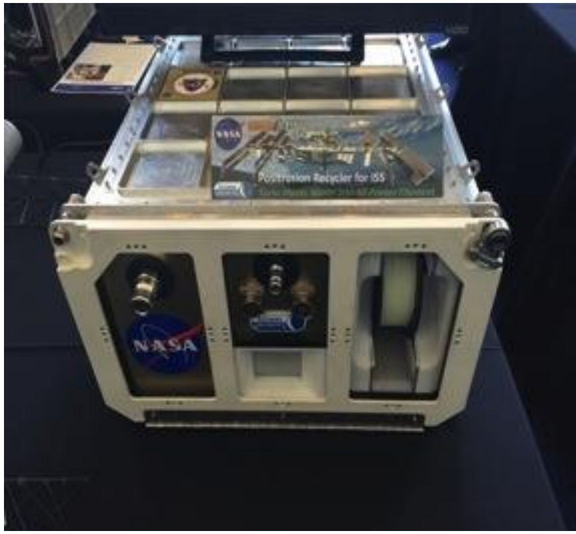
In Space Manufacturing Technology Infusion

- **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
    - Increased build volume
  - Anticipated launch late CY2015



Additive Manufacturing Facility (AMF)

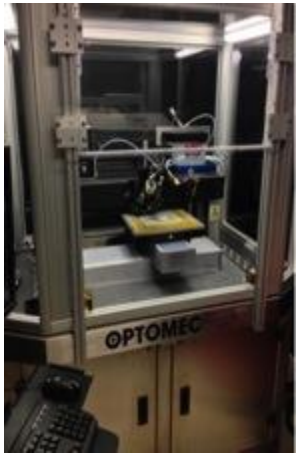
- **In-space Recycler ISS Technology Demonstration Development (SBIR 2014)**
  - Objective: Recycle 3D printed parts into feedstock to help close logistics loop.
  - Phase I recycler developments completed by Made In Space and Tethers Unlimited.
  - Phase II SBIR (2014) awarded to Tethers Unlimited.
  - Final deliverable will result in flight hardware for the In-space Recycler for proposed ISS Technology Demonstration in FY2017.
- **Launch Packaging Recycling Phase I SBIR (2015)**
  - Objective: Recycle launch packaging materials into feedstock to help close logistics loop



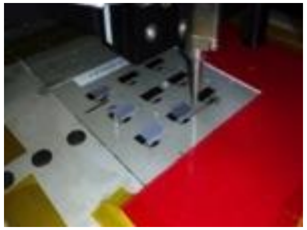
Tethers Unlimited SBIR to Develop ISS Recycler Tech Demo

In-Space Manufacturing Elements

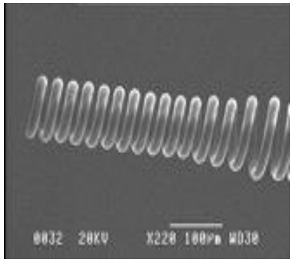
- **In-space Printable Electronics Technology Development**
  - Development of inks, multi-materials deposition equipment, and processes
  - Collaborating with Xerox Palo Alto Research Center (PARC) on Printable Electronics technologies developed at MSFC and Xerox PARC.
  - NASA Ames Research Center developing plasma jet printable electronics capability
  - Jet Propulsion Lab (JPL) has Advanced Concepts project to develop “printable spacecraft”
  - Printable Electronics Roadmap developed targeting ISS technology demonstrations including RF sensors/antennae, in-space printed solar panel, and printable cubesats
- **In-space Multi-Material Manufacturing Technology Development**
  - In-space Adaptive Manufacturing (ISAM) project with Dynetics utilizing the Hyperbaric Pressure Laser Chemical Vapor Deposition (HP-LCVD)
  - HP-LCVD technology holds promise for a novel solution to manufacturing with multiple materials (including metallics) in microgravity.
  - Phase I deliverable is small spring similar to design utilized on ISS







Printable Electronic Technologies

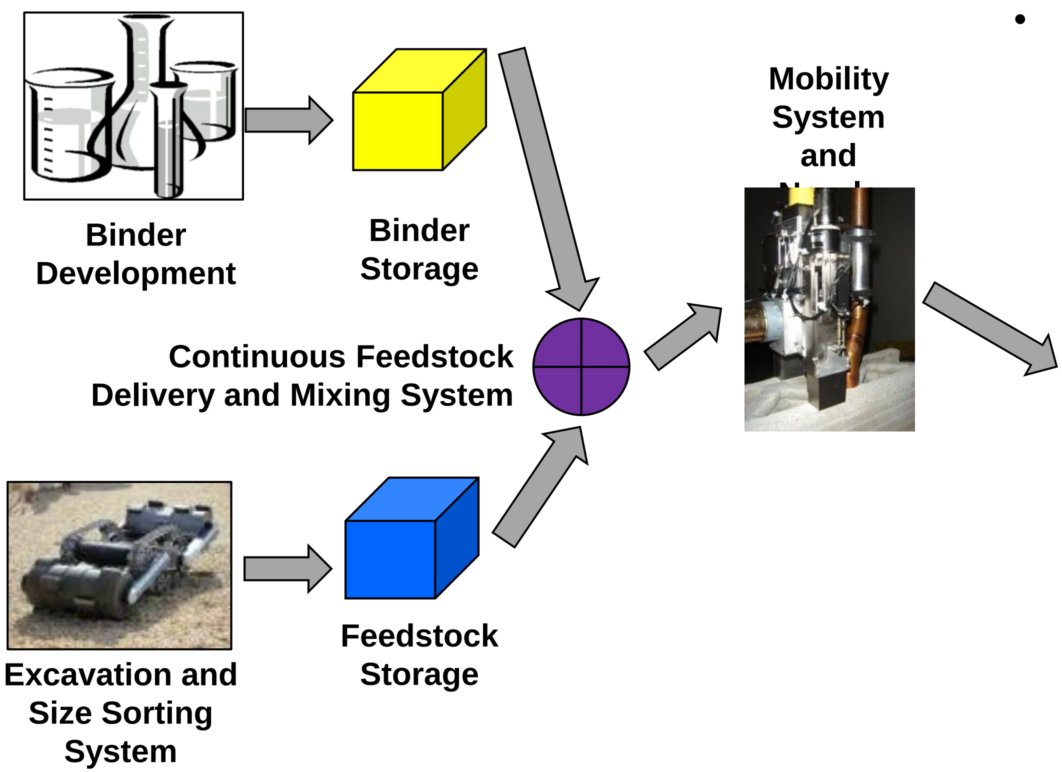


Spring Created by Adaptive Manufacturing

Additive Construction by Mobile Emplacement (ACME)

- 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.
- Goal: Produce half- scale and full-scale structures with integrated additive construction system at a lab or planetary analog site (September 2017)

- Funded by NASA/GCDP and U.S. Army Corps of Engineers (USACE)
- Partnerships between MSFC, KSC, Contour Crafting Corporation (CCC), and the Pacific International Space Center for Exploration Systems (PISCES)



NASA In-Space Manufacturing Challenges

Future Engineers Program: National challenge conducted jointly by NASA and American Society of Mechanical Engineers (ASME)

- Competition was held in two divisions, Junior (K-12) and Teen (13-18)
- First Challenge was to design a tool that astronauts could use on ISS. Teen winner's part will be printed on ISS later this year.
- The Space Container Challenge was announce on 5/12.
- Discussions underway for a joint NASA/IndyCar Challenge

Future Engineers Winning Part – Multi-purpose Maintenance Tool (MPMT)

NASA GrabCAD Handrail Clamp Assembly Challenge

- GrabCAD has a community of nearly 2 million designers
- Challenge was to design a 3D Printed version of the Handrail Clamp Assembly commonly used on ISS
- Nearly 500 entries in three weeks
- Five winners were selected

ISS Handrail Clamp Assembly GrabCAD (left) & traditional (right)

TEEN ENGINEERS

13-19 YEARS OLD

GRAND PRIZE:
Tour of the Space Shuttle Endeavor with an Astronaut in Los Angeles, CA

FOUR FINALIST PRIZES:
A One-Week Space Camp Scholarship

TEN SEMIFINALIST PRIZES:
A $50 3D Printing Gift Certificate

* 13-19 years old as May 12, 2015

JUNIOR ENGINEERS

5-12 YEARS OLD

GRAND PRIZE:
A 3D Printer For Your School

FOUR FINALIST PRIZES:
A One-Week Space Camp Scholarship

TEN SEMIFINALIST PRIZES:
A $50 3D Printing Gift Certificate

* 5-12 years old as May 12, 2015

WWW.FUTUREENGINEERS.ORG

PROGRAM DATES

PROGRAM LAUNCH	ENTRIES CLOSE	TEN SEMIFINALISTS ANNOUNCED	FOUR FINALISTS ANNOUNCED	FINALIST INTERVIEW	WINNERS ANNOUNCED
12 MAY	02 AUGUST	02 SEPTEMBER	16 SEPTEMBER	30 SEPTEMBER	07 OCTOBER

In-space Manufacturing Summary

In order to provide meaningful impacts to Exploration Technology needs, the ISM Initiative Must Begin to Influence Exploration Systems Design Now.

- **In-space Manufacturing offers:**
  - Dramatic paradigm shift in the development and creation of space architectures
  - Efficiency gain and risk reduction for low Earth orbit and deep space exploration
  - “Pioneering” approach to maintenance, repair, and logistics will lead to sustainable, affordable supply chain model.
- **In order to develop application-based capabilities in time to support NASA budget and schedule, ISM must be able to leverage the significant commercial developments.**
  - Requires innovative, agile collaborative mechanisms (contracts, challenges, SBIR’s, etc.)
  - NASA-unique Investments to focus primarily on adapting the technologies & processes to the microgravity environment.
- **We must do the foundational work – it is the critical path for taking these technologies from lab curiosities to institutionalized capabilities.**
  - Characterize, Certify, Institutionalize, Design for AM
- **Ideally, ISS US Lab rack or partial rack space should be identified for In-space Manufacturing utilization in order to continue technology development of a suite of capabilities required for exploration missions, as well as commercialization on ISS.**

BACKUP

3D Printing in Zero-G Tech Demo Objectives

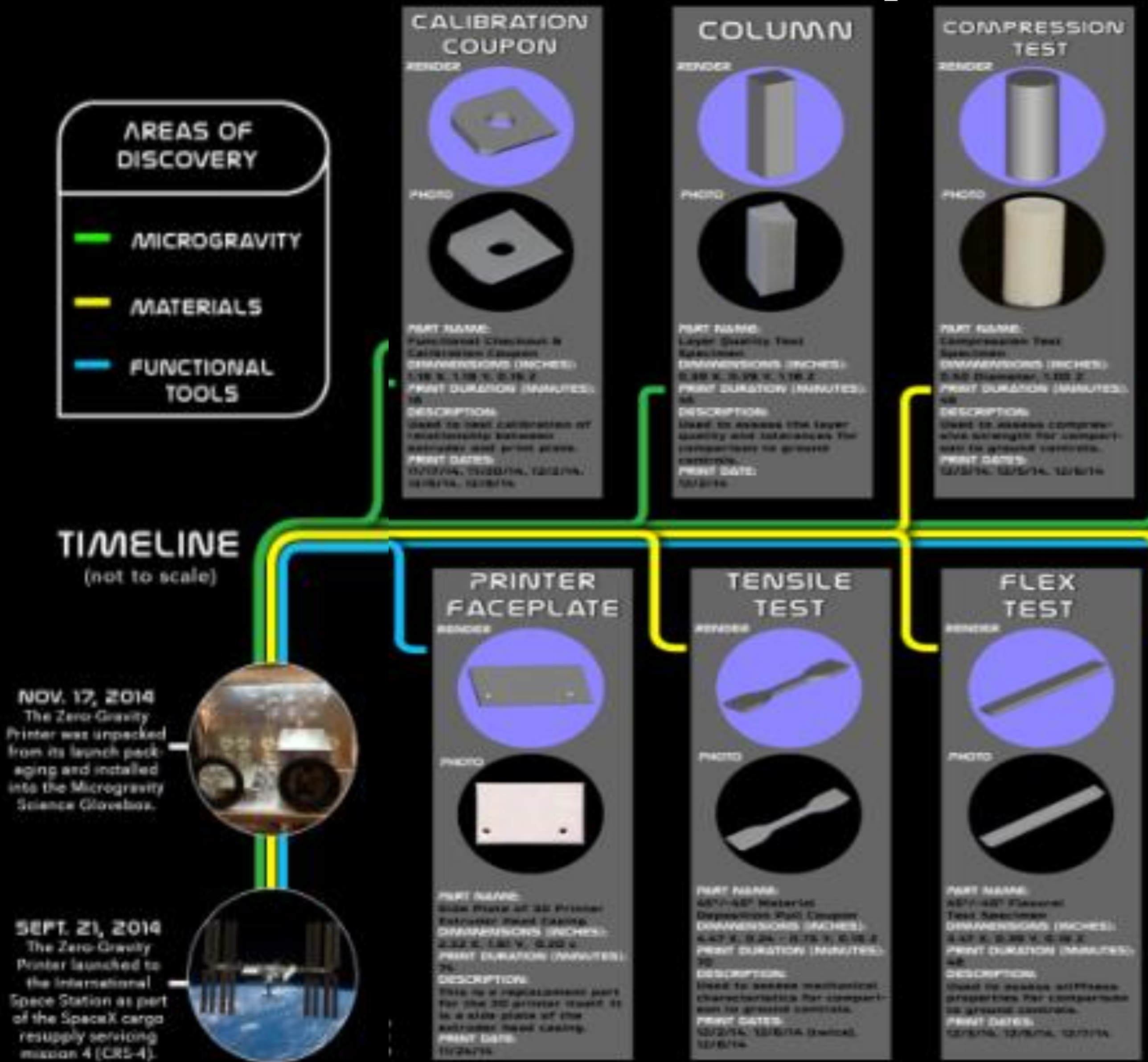


Image courtesy of MIS

- The objective of the first phase of the technology demonstration is to confirm that ***Printer and Processes work in microgravity*** via printing of Test Articles & post-flight analyses.
- The objective of the second phase is to ***Demonstrate functionality of utilization parts*** such as crew tools and ancillary hardware.
- First parts printed returned on SPX-5 and will be sent to MSFC for detailed analyses and testing. All results will be published.

3D Printing in Zero-g Tech Demo Status

- To date, 21 parts have been printed of 14 unique objects. These included engineering test coupons, a microgravity test coupon, & utilization examples.
- Engineering Test Coupons:
  - Column: layer quality & tolerance
  - Tensile: mechanical characteristics
  - Compression: compressive strength
  - Flex: stiffness properties
  - Hole & Feature Resolution: geometric accuracy & tolerances for positive & negative range
  - Torque: torque strength
- Overhang Structure: would be difficult, if not impossible, to print in gravity w/out supports
- Utilization Examples:
  - Crowfoot Tool
  - Sample Container
  - Cubesat Clip
  - Ratchet (test of on-demand capability)