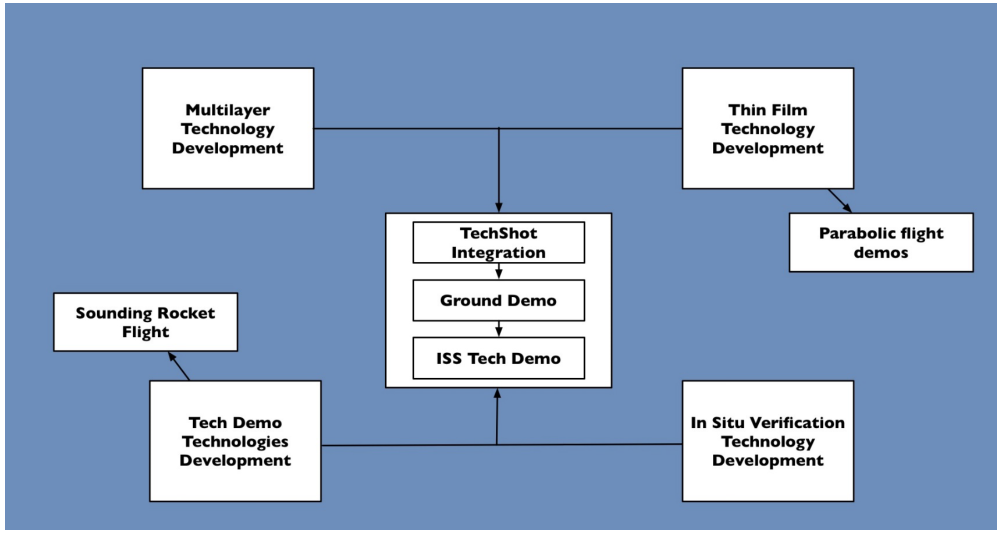
National Aeronautics and Space Administration

Annual Program Review
Game Changing Development Program

Curtis Hill | FY21 On-Demand Manufacturing of Electronics (ODME) | 09.15.21

On-Demand Manufacturing of Electronics (ODME) Overview

- **Technology Product Capability**
  - On-Demand Manufacturing of Electronics (ODME) has the critical function of building crew and structural monitoring systems and sensors in orbit.
- **Technical Capabilities**
  - Development of Multilayer Technology for Flexible Electronics
  - Development of Thin Film Technology for Microgravity
  - Development of In-Situ Verification Technology
  - Development of ODME Flight Demo for ISS
- **Exploration & Science Applicability**
  - Applicable to current ISS operations
  - Applicable to Artemis II, Lunar Surface Habitat
  - Applicable to MTM and future missions

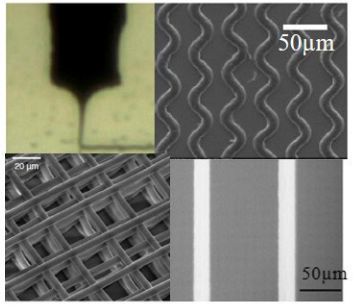


Overview of ODME Technical Approach

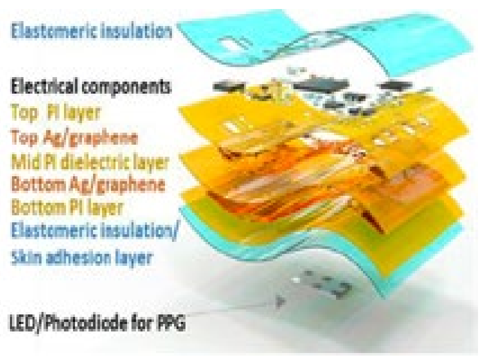
On-Demand Manufacturing of Electronics (ODME) Overview

On-Demand Printed Electronics Capability Development:

- **Development of Thin Film Deposition Capability in Microgravity**
  - The objective of the Thin Film Deposition Technology development is to evaluate alternate thin film deposition systems for the best system to print printed electronics and sensors in microgravity.
  - A threshold value of a 300 microns resolution (minimum printable feature size) was chosen because this is the solution with the minimum complexity required to fabricate electronic devices in microgravity. The Project Goal is to demonstrate fabrication processes with 100 micron or better resolution. Current State-of-the-Art (SOA) of printed resolution of electronic materials is between 30 and 50 microns for analogous ground-based processes.
- **Development of Multilayer Technology for Microgravity**
  - The objective of the Multilayer Technology development is to develop materials, processes, and equipment modifications as necessary for the stacking of circuitry layers of printed electronics. This will enable a much wider range of potential applications and printed electronic capability.
  - A threshold fabrication ability of a single layer printed "board" was chosen because this is the solution with the minimum complexity required to fabricate electronic devices in microgravity. The Project Goal is to demonstrate fabrication of multi-layered electronic devices in microgravity.
- **Development of Validation and Verification In-Situ Capability for Flight Demo**
  - The objective of the Validation & Verification development is to develop test procedures, software, and hardware to effectively test function and operation of the ODME printed flight demo on ISS.
  - The development of In-situ Verification is a two-year project to develop and evaluate optimum methods, hardware, and integration to the 3D printer operation, in order to effectively validate the operation of flexible hybrid electronics sensors and devices.



Electrohydrodynamic inkjet deposition for microgravity

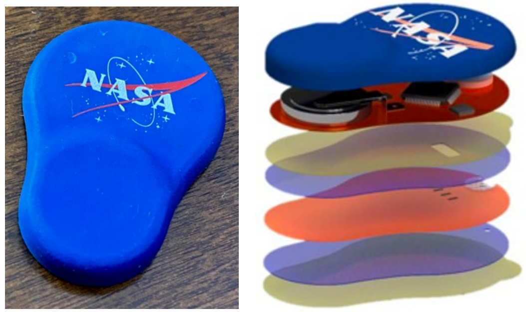


Multilayer thin film printed device work with Georgia Tech

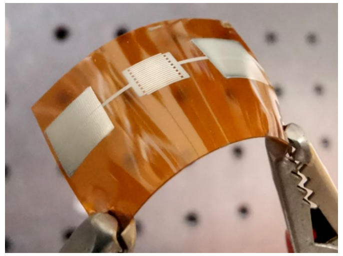
On-Demand Manufacturing of Electronics (ODME) Overview

On-demand printed electronics capability development:

- **Flight Demo Technologies Development -**
  - The objective of Flight Demo technologies development is to develop the necessary technologies for a successful demonstration of printed electronics and sensors in microgravity. These technologies includes sensor development, development of post-processing technologies, wireless communications, energy and power for self-powered sensor operation, and in situ verification of the completed devices. This is our core ODME development integrating all the other development efforts.
  - The flight demo device is a flexible wearable multi-sensor device being developed in a collaboration with NextFlex and multiple NASA Centers as the AstroSense wearable device.
  - The development of Flight Technologies includes the multi-Center and outside collaborators development of associated technologies for the device, including:
    - Development of multiple environmental and biosensor technologies
    - Development of on-demand printed power harvesting technologies
    - Development of on-demand printed energy storage technologies
    - Development of laser sintering post-processing capability
    - Development of next-generation 3D printing hardware for multi-material high precision deposition of nanomaterials for electronics and sensors.

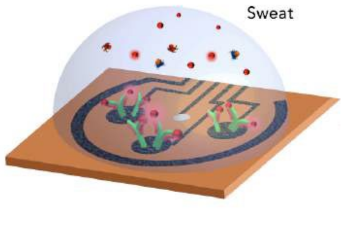


AstroSense wireless wearable sensor (cortisol, temp, humidity)



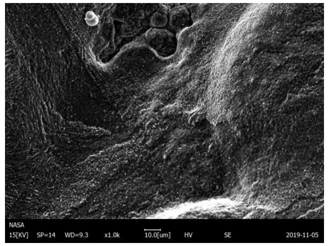
Printed CO_2 sensor for Crew Health Monitoring

Flexible, printed supercapacitor for energy storage



Printed cortisol biosensor for monitoring astronaut stress

nScrypt Next-Generation Deposition Heads



Laser sintered Ti64

ODME Accomplishments

Status on GCD Objectives

1. Feasibility Study of ODME ISS Flight Demo Hardware Development
   - Study completed May 26 with presentation to Doug Willard, GCD PEM
   - Flight Demo Paths evaluated:
     - Demo of ODME capability with TechShot FabLab *(funded and in process with TechShot IDIQ Task for FY21)*
     - Independent ODME system *(ground-based nScrypt development system specified and PR in process for FY21 purchase)*
2. Development of Thin Film Deposition Technology
   - Two projects funded and in process for FY21
     - **Space Foundry Inc.** – Phase II SBIR for development of Plasma Jet Deposition technology
     - **Iowa State University** – EPSCoR for development of Electrohydrodynamic Inkjet Deposition technology
     - See following slide for Parabolic Flights planned in 2021. Downselect of technology following parabolic flights.
3. Development of Multilayer Fabrication for Flexible Electronics
   - Two projects funded and in process for FY21
     - **Auburn University** – Year 1 of 3 project to develop materials & processes for Multilayer Flexible Electronics
     - **Georgia Tech University** – Current CAN project in work, and follow-on project funded by ODME for start in FY22. Development of flexible, multilayer wearable sensors

ODME Accomplishments

Status on GCD Objectives, continued

4. Development of Validation & Verification of ODME Printed Devices
   - Collaborative multi-year project with **Auburn University** to develop verification and testing of materials and sensors, and eventual development of hardware and software to test printed devices on ISS Flight Demo.
5. Flight Demo Technologies Development
   - Re-started NextFlex project (AstroSense) for development of Crew Health Wearable biosensor device. FY21 development of Sensing Potentiostat. FY22 delivery of Beta Wearable Sensor Devices.
   - Flight Demo Technology Projects:
     - **Internal NASA**
       - **MSFC:**
         - Development of post-processing methods (laser sintering & photonic sintering)
         - Materials development of electronic inks for collaboration support
         - Development of micro-milling processes for advanced coatings & energy storage devices
         - Testing & verification of sensors, materials, & processes
         - Development of power-harvesting & energy storage technologies
       - **ARC**
         - Aptamer-based cortisol sensor for incorporation into AstroSense
         - Printed colorimetric CO_2 sensor
         - On-demand printed supercapacitor
         - On-demand printed bone density sensor

ODME Accomplishments

Status on GCD Objectives, continued

5. Flight Demo Technologies Development
   - Flight Demo Technology Projects:
     - **Internal NASA**
       - **GSFC:**
         - Sounding rocket test flight coordination
         - Development of printed superconducting devices
         - Test & characterization of flexible batteries for printed electronics
       - **JSC:**
         - Development of HYDRA next-generation RFID antenna network
         - Development of RFID sensors and sensing technology

ODME Accomplishments

Status on GCD Objectives, continued

5. Flight Demo Technologies Development

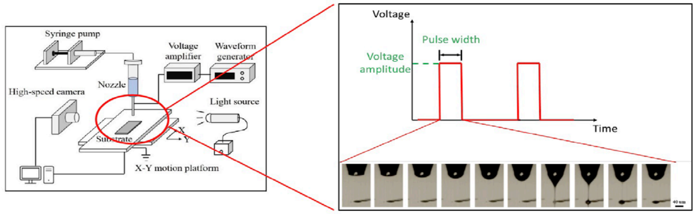
- **External collaborations:**
  1. **Auburn (Dean)** – moisture sensor
  2. **Auburn (Cheng) –** flexible supercapacitor
  3. **Auburn (Lall)** – multilayer flexible electronics & validation testing
  4. **Boise State (Verghese) –** printed thermo-electric device
  5. **Boise State (Subbaraman) –** evaluation of multiple on-demand deposition processes
  6. **CalTech (Gao)** – molecularly-imprinted polymer cortisol sensor
  7. **Florida A&M University (FAMU) (Ramakrishnan) –** on-demand printed structural health monitoring sensors
  8. **Georgia Tech (Ready)** – carbon nanotube optimized supercapacitor
  9. **Georgia Tech (Yeo)** – flexible multi-layer crew health sensor
  10. **Georgia Tech (Tentzeris)** – printed CO_2 sensor for crew health monitoring
  11. **Georgia Tech (First)** – printed radiation sensor (in collaboration with MMPACT)
  12. **Georgia Tech (Shen) –** printed semi-conductor device
  13. **Iowa State (Qin) –** electrohydrodynamic inkjet deposition for microgravity
  14. **West Virginia University (Sierros)** – on-demand printed actuators with embedded sensors
  15. **Youngstown State (Cortes) –** printed ceramic temperature sensors
  16. **University of Alabama in Huntsville (UAH) (Pour) –** on-demand printed antennas for RF power harvesting
  17. **University of Texas El Paso (UTEP) (McDonald) –** on-demand printed batteries
  18. **University of Louisville (Atre) –** laser sintering of Copper for printed electronics
  19. **University of Wyoming (Johnson)** – machine learning on electronics and gas sensors

ODME Accomplishments

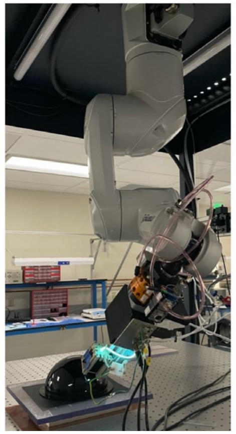
On-demand printed electronics capability development:

- **Flight Testing Verification -**
    - **Parabolic flights of Thin Film Deposition development November 2021**
        - **Space Foundry Inc. –** demonstration of Plasma Jet Deposition – funded by SBIR Phase III ($225k) and Flight Opportunities ($225k), total $450k
        - **Iowa State University –** demonstration of Electrohydrodynamic Inkjet Deposition – funded by Flight Opportunities ($332k)
    - **Sounding Rocket flight test** of printed electronics and printed sensors planned in late FY 2022. Collaborative project with GSFC and Wallops with GSFC ODME team as lead. Prototypes completed and vibration testing started at GSFC.
- **Materials International Space Station Experiment (MISEE**) - Testing of ODME materials on ISS for radiation and atomic oxygen

MISEE flight samples of ODME materials



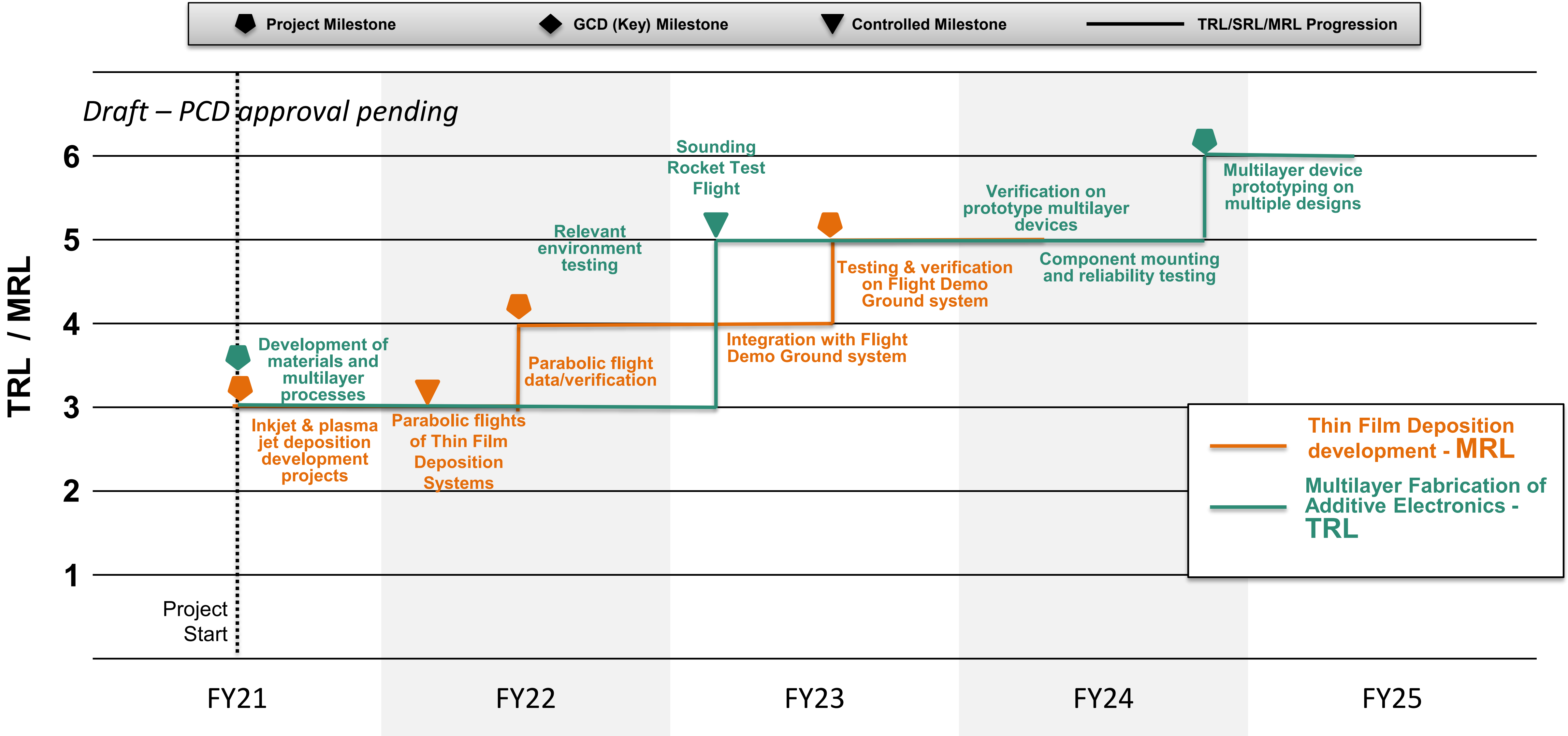
Iowa State Electrohydrodynamic Inkjet



Space Foundry Plasma Jet

Sounding Rocket Flight Test

TRL/MRL Progression
ODME



Technical Assessment

Technical Elements	TRL				AD²	
	Entry	Current[1]	Exit	Verification	Entry	Current
Multilayer Fabrication of Electronics in Microgravity	**3**	**3**	**6**	Milestone ID#7815	**7**	**7**

Technical Elements	MRL				AD²	
	Entry	Current[1]	Exit	Verification	Entry	Current
Thin Film Deposition Technology	**3**	**3**	**5**	Milestone ID#7816	**7**	**7**

Draft – PCD approval pending

Date of last Technical Assessment was XYZ

ODME Key Performance Parameter (KPP) Status

Key Performance Parameters								
Parameter Name	**Unit**	**State of the Art**	**Threshold Value**	**Project Goal**	**Current Value to Date**	**TBoE for the Provided Current Value**	**Expected Exit Value**	**TBoE for the Provided Exit Value**
Fabricate functional multi-layer devices in microgravity	N/A	(1) Multi-layer (ground-based)	(2) Single-layer printed boards	(3) Multi-layered boards	Multilayer fabrication ground-based	Substantiated	Multilayer fabrication in microgravity	Verified
Printed feature resolution of single-layer electronic devices	microns	30	300	100	300µm	Estimated	100µm	Verified
Printed feature resolution of multi-layer electronic devices	microns	30	300	100	200µm	Substantiated	100µm	Verified

Draft – PCD approval pending

ODME Existing Risk Chart

Risk ID #01

Trend

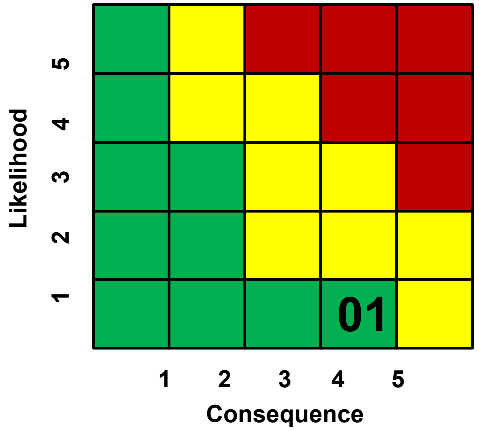
Criticality

LOW

Planned Closure
12/31/2022

Open Date
05/01/2020

Risk 01: ODME Resource Availability	**1 x 4**
Risk Statement: Given that the On Demand Printed Electronics Project is heavily dependent on EM and ES in house technology development, there is a possibility that critical key personnel could be unavailable. This risk has been mitigated over the past year as MSFC engineering groups have added FTE and WYE resources to support ODME. The risk has been kept as a "watch" status as the project moves towards flight demonstrations and resources remain critical.	**Risk Type:** Technical, Schedule and Performance **Assigned to:** **Strategy:** Watch



Steps	**Watch Plans**
1	Define tasks and resources needed to achieve
2	Communicate with management resource needs

ODME Existing Risk Chart

Risk ID #02

Trend

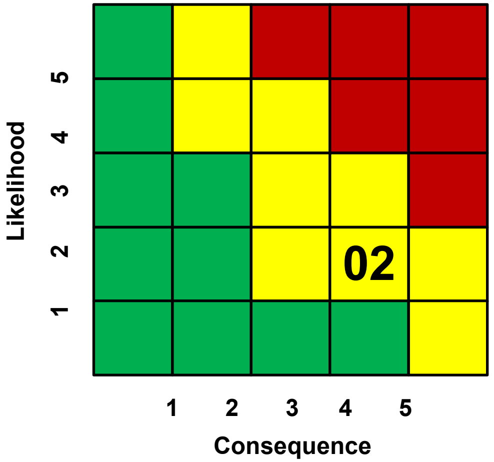
Criticality

HIGH

Planned Closure
12/31/2022

Open Date
05/01/2020

Risk 02: ODME ISS Demonstration	2 x 4
Risk Statement: With the objective of ODME is to develop manufacturing capabilities for on-demand printed electronics and sensors, a plan forward for the demonstration of ODME on ISS is required. The ODME project involves in house development of materials and processes for printing electronics. A plan has been developed for the dual approach for the ODME flight demo. However, we do not have the resources for the hardware and integration of a standalone system separate from the current FabLab limited ODME demo.	**Risk Type:** Technical, Schedule, Cost, Performance **Assigned to:** **Strategy:** Mitigate



Action	Due Date	Mitigation Actions	L x C
-	May 2020	Date Submitted	3 x 4
1	May 2021	Feasibility study for ISS Flight Demo approach for ODME project. Develop FabLab ODME demo.	2 x 4
2	Dec 2021	Develop specifications for ODME standalone ground development system and procure system	2 x 4
3	Mar 2022	Acquire resources as necessary, obtain stakeholder buy in for development and integration	1 x 4
4	Dec 2022	Develop system for demonstration of printed electronics on ISS	Eliminate (Retire)

ODME Mission Infusion & Partnerships

NASA Centers

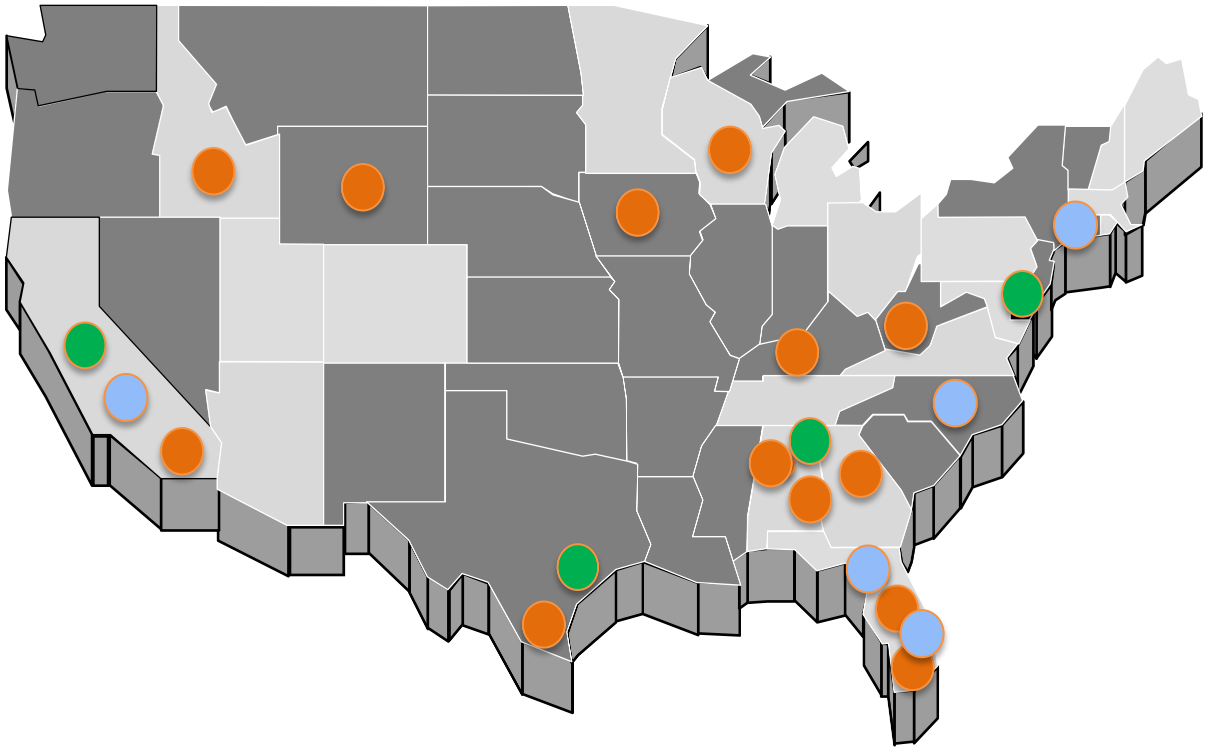
- GSFC
- MSFC
- ARC
- JSC

University Collaborations

- University of Alabama Huntsville (UAH)
- Auburn University
- Boise State
- Georgia Tech
- CalTech
- Iowa State University (ISU)
- University of Miami
- Florida A&M University
- West Virginia University
- Youngstown University
- University of Texas El Paso (UTEP)
- University of Louisville
- University of Wyoming

Private Companies

- NextFlex
- nScrypt
- Multi3D
- LambdaVision
- Redwire/Made in Space



Collaborative multidisciplinary partnerships to leverage fiscal resources, ideas, knowledge & expertise.

On-Demand Manufacturing of Electronic (ODME) Components Goals & Project Objectives

Technology Goals	
Project Goal	Develop and demonstrate the feasibility of a low-gravity, on-demand manufacturing system for flexible hybrid electronic devices on the International Space Station.

Project Objectives	
Objective #1	Conduct feasibility study for print systems, including an integrated ODME system with ODMM/metals, and a completely-independent standalone ODME system.
Objective #2	Down-select ODME system from feasibility study.
Objective #3	Build and test selected on-demand manufacturing system for flexible hybrid electronics (EDU).
Objective #4	Deliver to ISS a flight-ready, on-demand manufacturing system for flexible hybrid electronics devices.
Objective #5	Demonstrate the manufacture and verification of flexible hybrid electronics devices in a low-gravity environment on ISS.
Objective #6	Evaluate flexible hybrid electronics devices manufactured and verified on ISS against ground-manufactured devices.

Draft – PCD approval pending

ODME Flight System Demos

ODME Demo as part of TechShot FabLab

Included in the SOW for TechShot IDIQ Task for FY21:

- **Specifics of the demo are being finalized by a team including NASA ODME, TechShot, and nScrypt engineers**
- **The demo will utilize most of the capability of the FabLab:**
  - SmartPump extrusion paste printing
  - nFD polymer extrusion printing
  - Will not use FabLab furnace – no thermal post processing
  - Component pick & placement
  - nMill milling capability
  - Print inspection
  - Two planned devices:
    - Printed CO_2 sensor
    - Arduino accelerometer

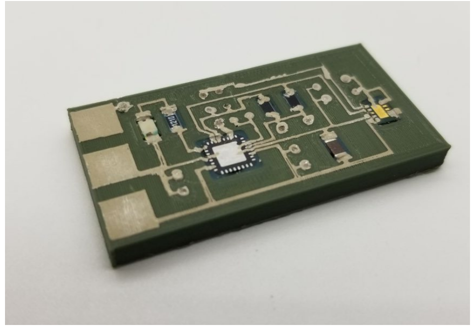


Figure 1. ODME demonstration of an additively-printed multilayer CO_2 sensor

ODME Standalone System

Feasibility study by ODME:

- New system to be single Quad Locker size, with significant less mass and volume from FabLab
- Planned separate Flight Demo for FY25
  - Next-generation nScrypt heads (50% smaller)
  - Next-generation chip placement (much wider range of component placement and capability)
  - Complete inspection and repair of individual layers
  - In-situ laser sintering (no thermal post processing)
  - Utilizes full 6" x 6" x 6" 3D envelope originally planned for FabLab

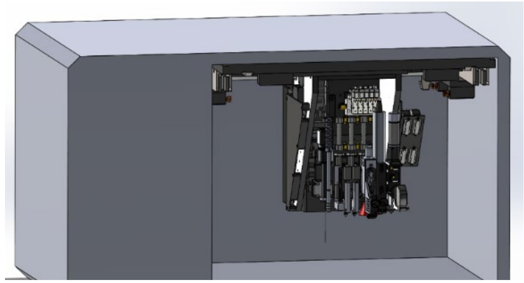


Figure 2. Prototype enclosure to mimic and follow the requirements of a Quad locker on the ISS.

Figure 3. Next-generation tool heads for printing and processing of a wide range of printed electronics and sensors.

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					• Cost is within budget and anticipated to remain within budget. A CR was submitted for a potential parabolic flight opportunity with Space Foundry for relevant verification of thin film deposition in microgravity. • Schedule has returned to GREEN due to Restart Plan 2 approved on 12/03, which has allowed MSFC to return to labs through May 2021 • Technical remains GREEN as tasks and project tasks to support technical development are in place and all are proceeding on schedule. • Programmatic remains GREEN. Project PCD and Project Plan are in final reviews with PEM. PCD should be submitted soon for Chief Engineer approval.
Annual					• Cost is within budget and anticipated to remain within budget. NASA Flight Opportunities is going to fund a parabolic flight opportunity in November 2021 with Space Foundry for relevant verification of thin film deposition in microgravity. • Schedule remains GREEN due to ODME Restart Plan 3 approved on May 26, which has allowed MSFC to return to labs through August 2021. This latest restart plan includes onsite work by Pathways Interns and a visit by a NSTGRO Fellowship Researcher. NextFlex sensor development contract is being awarded but the delay has the potential for impacting the crew health sensing schedule milestone. • Technical remains GREEN as tasks and project tasks to support technical development are in place and all are proceeding on schedule. • Programmatic remains GREEN. Project PCD and Project Plan are in final reviews with PEM. PCD is uploaded to GCD SharePoint and is in queue for Chief Engineer approval.

ODME Education/Public Outreach

FY21 Activities to Date

- NSMMS (virtual) Curtis Hill presented on June 25 (Additive Manufacturing Session): *Development of Flexible Energy Storage Devices for Wearable Electronics Using Polymer-based Composites*
- IEEE iTherm Conference (virtual) Curtis Hill co-authored on two presentations:
  - *Process Development for Printing Copper Conductible Ink on Flexible Substrates Using Aerosol Jet Technology*
  - *Process Recipes for Additively Printed Copper Ink Flexible Circuits using Direct Write Methods*
- Jessica Koehne was a panelist the Young Professional Network Event on 6/2 at the 18th International Meeting on Chemical Sensors (IMCS). This event was run concurrently with the 239th Electrochemical Society Meeting. The event was virtual.
- Jessica Koehne was an organizer and moderator of the "Microfluidic Devices and Sensors" on 5/31. The symposium was virtual.
- Jessica Koehne was an invited speaker at the 4DMS+SoRo International Summer School, co-sponsored by the Electrochemical Society on 6/21. This is a virtual event.
- Curtis Hill presented at the 2021 NSMMS Conference on 6/25 as part of the Additive Manufacturing session. His paper was "Development of Flexible Energy Storage Device for Wearable Electronics Using Polymer-based Composites."
- Curtis Hill presented an overview of the ODME project to the Florida A&M-Florida State Materials Science department on 7/1.

Interns:

Brennan Wessels - University of Tennessee
Jennifer Wolfe - Georgia Tech
Austin Fox - University of Alabama in Huntsville (Austin converted from Pathways Intern to FTE earlier in 2021)
Dylan Radcliff - University of California at Davis

NSTGRO Graduate Fellowships:

Mark Ciappesoni - University of Miami *"Ink-jet printable infrared detectors for in-space deployment"*
Alexandra Marnot - Georgia Tech *"3D Printing of Dense Regolith Suspensions for Construction and Weatherability at Ultra-low Temperature"*

ODME Education/Public Outreach

6 Month Look-Ahead

8/9-18/21: ISS Research & Development Conference (virtual) Curtis Hill co-authored on presentation:

- *Multiprinter Additive Manufacturing of Flexible and Lightweight Thermoelectric Energy Harvesters Using Colloidal Nanoparticles*

9/20: Curtis Hill will present at the Boston University Institute of Electrical and Electronics Engineers (IEEE)

10/26-28/21:

- InterPACK International Technical Conference and Exhibition on Packaging and Integration of Electronic and Photonic Microsystems (virtual) Curtis Hill co-authored on two presentations:
    - *Print Consistency and Process Interaction for Inkjet-Printed Copper on Flexible Substrates*
    - *Additively Printed Flexible Temperature Sensor for Wearable Applications*

Plans Forward and Infusion Plan

- **Infusion/transition plan**
  - On-Demand Manufacturing of Electronics is a critical need for future habitats and missions. The technology infusion plan involves flight tests (MISEE, Sounding Rocket, Parabolic Flights) and a FY24 planned ISS demonstration of the flight system. Elements of the technology are being developed FY21-23.

- **Exploration & Science Applicability**
  - Applicable to current ISS operations
  - Applicable to Artemis II, Lunar Surface Habitat
  - Applicable to MTM and future missions

Summary

- **University Project Collaborations started in FY21**
  - Started 19 new projects with 12 different universities
- **NASA@work funded projects**
  - Started 2 new research projects at 2 NASA Centers
- **Interns**
  - OMDE mentored a total of 6 interns this year
  - ODME served as Research Collaborator for 2 new NSTGRO Graduate Fellowship Researchers, from two different universities.
- **Publications and EPO**
  - Published 11 new research papers in collaboration with four different universities
  - Presented ODME project research at 3 different conferences
  - Presented to 4 student groups from elementary age to university graduate students

➢ **Summarize the TechMat Capability End State for the Scope of the Project**

The ODME project is developing technologies for the hardware required to on-demand electronics and sensors in a microgravity environment. To develop these technologies, ODME has engaged multiple research universities and private companies to collaborate in the development of the hardware, materials, and processes required for the microgravity demonstration on the ISS. The parallel development of sensor devices for a wide range of mission requirements as well and the power generation and energy storage devices to allow these sensors and printed electronics devices to be able to operate without batteries or external power.

The MRL for the thin film deposition and sensor printing will be developed from MRL3 to MRL5. The TRL for multilayer fabrication of these devices will be developed from TRL3 to TRL6.

BACKUP

<Technology Name>

Risk Title (Short risk title)- Risk Owners Name

Risk ID #
No. unique to this risk- stays with risk even when closed/retired.

Trend

Criticality

Current L/C
5x5

Affinity Group
Technical, Cost, Schedule, Performance

Planned Closure
mm/dd/yyyy

Open Date
mm/dd/yyyy

Risk Statement :

Approach: (choose one) Mitigate, Watch, Accept, Research

Risk Statement in the format "Given that (state the fact)…there is a possibility (state the concern)…resulting in (state the consequence..)"

Context

Info and background NOT in the Risk Statement. Captures the what, when, where, why, and how of the risk, specifically: What do we need to know to fully understand the risk? What are the relevant and related circumstances, contributing factors, and related issues?

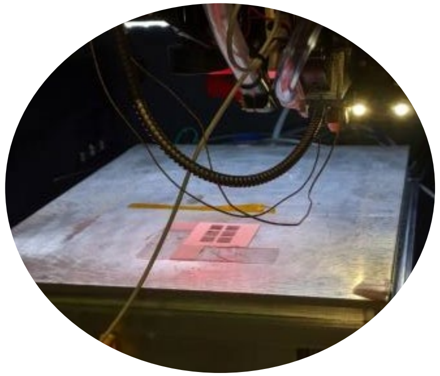
Status

mm/yyyy of update. Information regarding current status. Update semi-annually. **Current status on top**. OK to eliminate status updates more than two years old to keep this page from getting too large.

Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C

(Note: The Schedule UID is the unique id no of the mitigation step in your schedule if appropriate.
Dollars to implement are not extra approved $ from the Program Office but $ set aside as part of project budget to mitigate.)

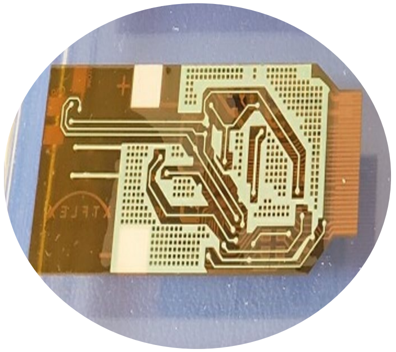
Cover Slide Annotate Images



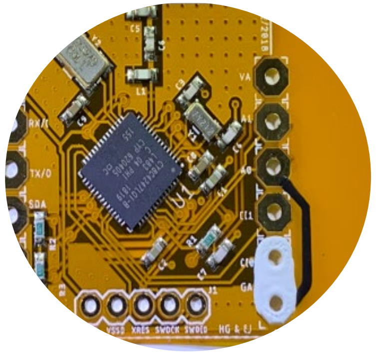
Laser Sintering

Fabrication Laboratory (FabLab)

Titanium (Ti-64) molecule



Multilayer flexible electronic device



Multilayer flexible electronic device

AstroSense wireless wearable sensor

GCD Project Performance Evaluation Criteria

	Technical/Performance
Green	Project is demonstrably making progress on the Learning Trajectory (e.g. milestones met, knowledge advanced) or advancing TRL. Project is on track to meet L1 requirements.
Yellow	Project is making progress on the Learning Trajectory or advancing TRL with issues. Project is on track to meet L1 requirements but issues exist that may threaten achievement.
Red	Project has ceased to make progress on the Learning Trajectory or advance TRL. Project is unable to meet one or more L1 requirements.

	Cost
Green	Project can meet its commitments with its planned/allocated budget.
Yellow	Project cannot meet its commitments within its planned/allocated budget but will not be requesting additional budget from Program. Mitigation plans have been developed.
Red	Project cannot meet its commitments within its planned/allocated budget and will be requesting additional budget from Program.

	Schedule
Green	Project can meet its commitments within its planned/allocated schedule baseline for critical milestones.
Yellow	Project cannot meet its commitments within its planned/allocated schedule baseline but mitigation plans have been developed to pull it back in.
Red	Project cannot meet its commitments within its planned/allocated schedule baseline.

	Programmatic (Institutional, Internal/External Dependencies **)
Green	Relevance of technology to stakeholders and/or technology infusion path is maintained. Mission sponsor still actively interested. No issues exist with workforce, test facilities, etc.
Yellow	Relevance of technology to stakeholders and/or technology infusion path are threatened. Mission sponsor backing off. Issues exist with workforce, test facilities, etc. but plans to mitigate are available.
Red	Relevance of technology to stakeholders and/or technology infusion path are not projected to be met, or has lost relevance to stakeholders. Mission sponsor cancelled interest. Issues pertaining to workforce, test facilities, etc. are preventing progress along the Learning Trajectory.

Source: BPR Assessment Criteria for NASA R&T Projects, OCE/S. Hirshorn, 09/17/2015

National Aeronautics and Space Administration

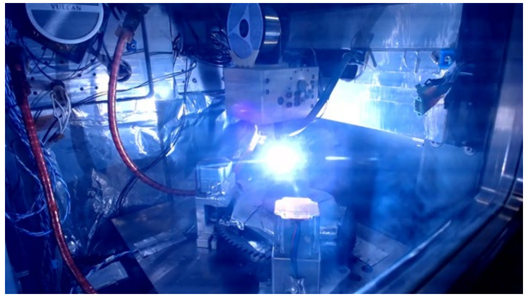
Annual Program Review
Game Changing Development Program

Chris Roberts | FY21 On-Demand Manufacturing of Metals (ODMM) | 09.15.21

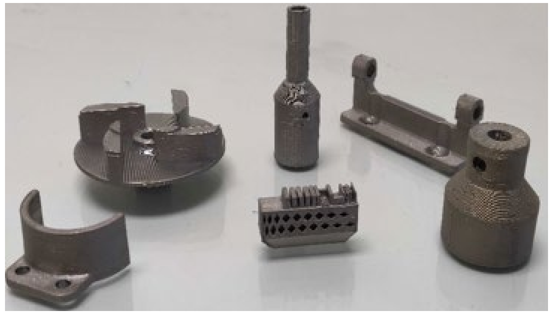
On-Demand Manufacturing of Metals (ODMM) Overview

- **Technology Product Capability**
  - Pursue development of two hybrid (additive + subtractive) manufacturing systems for demonstration of on-demand metal manufacturing on ISS
    - Bound metal additive manufacturing (Fabrication Laboratory from Techshot, Inc.)
    - Wire+arc additive manufacturing (Vulcan from Redwire, formerly Made in Space, Inc.)
    - Systems will be demonstrated on ISS, producing specimens and parts which are returned to earth for testing and comparison with ground-manufactured specimens
- **Technical Capabilities**
  - Develop systems which meet ISS operational constraints (mass, power, volume, safety, limited crew interaction)
  - Develop systems capable of manufacturing parts in commonly used aerospace alloys, such as Titanium and Aluminum
- **Exploration & Science Applicability**
  - Current approach to logistics, which relies on pre-positioned spares, is not sustainable for long duration missions where cargo resupply opportunities are limited
  - Once tested on ISS, capabilities developed under ODMM can provide a means to manufacture parts at the point of use on future space missions, reducing the amount of upmass and enhancing crew safety

Part produced with Vulcan subsystems. Image from Made in Space.



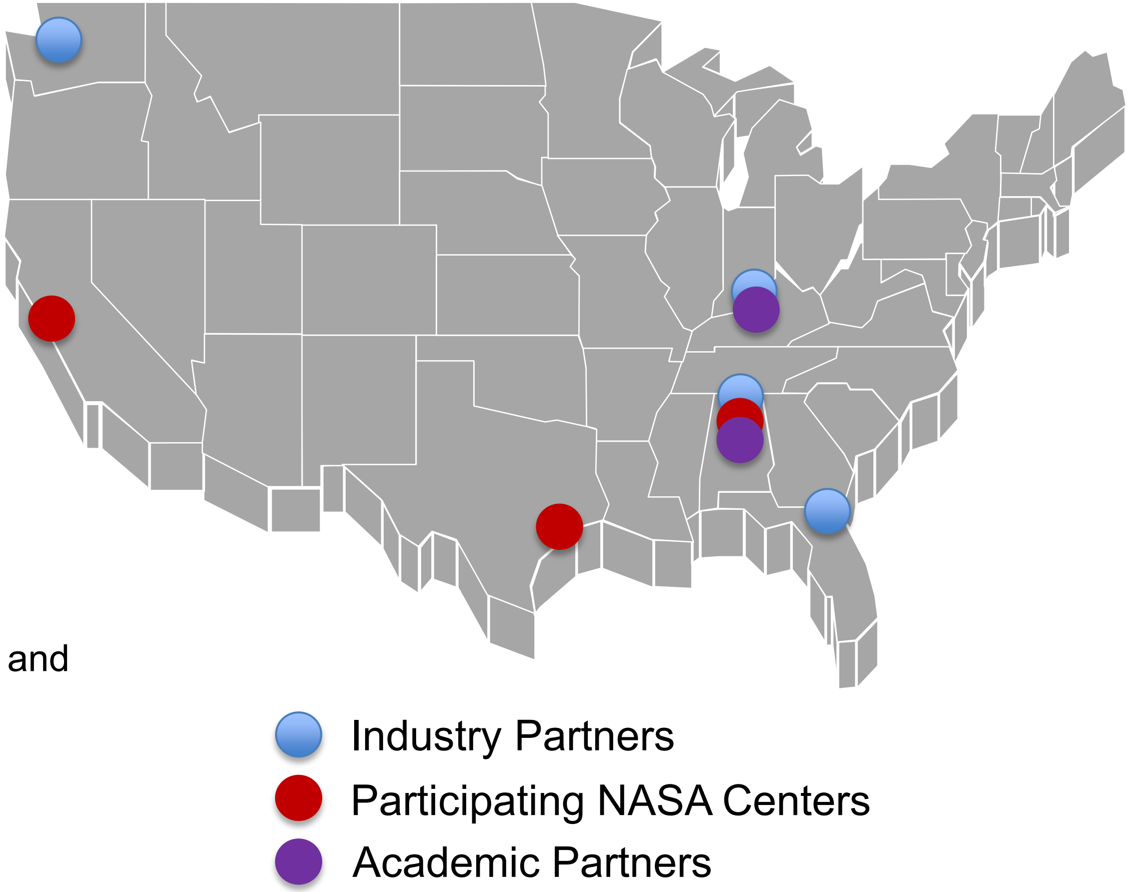
Vulcan system in operation. Image from Made in Space.



Parte manufactured with FabLab prototype system. Image from Techshot.

Mission Infusion & Partnerships

- Contributing partners and/or stakeholders
  - Geocomposites LLC
  - Techshot, Inc.
  - Redwire Space, Inc.
  - Tethers Unlimited, Inc.
- Contributing Centers
  - Marshall Space Flight Center
  - Ames Research Center
  - Johnson Space Center
- Academic Partners
  - University of Louisville
  - University of Alabama Birmingham



- Infusion/transition plan
  - Technologies will be proven and demonstrating using the ISS as a testbed and then infused into future NASA missions such as Gateway and Lunar Surface Habitats.
  - ISS Demonstrations – some complete and more to come
  - Lunar Habitat– potential
  - Gateway – potential
  - Mars Habitat - potential

ODMM
Technology Goals & Project Objectives

Technology Goals	
Goal #1	Develop and demonstrate the feasibility of a low-gravity, on-demand manufacturing system for metal parts on the International Space Station.

Project Objectives	
Objective #1	Design, build, and demonstrate an on-demand manufacturing approach in low gravity for metal parts.
Objective #2	Deliver to ISS a flight-certified, on-demand manufacturing system or systems.
Objective #3	Demonstrate the manufacture of metal parts in a low-gravity environment on ISS.
Objective #4	Evaluate parts made on ISS against parts produced on the ground.
Objective #5	Develop physics-based models to predict processing parameters and material outcomes under low-gravity conditions for metals.

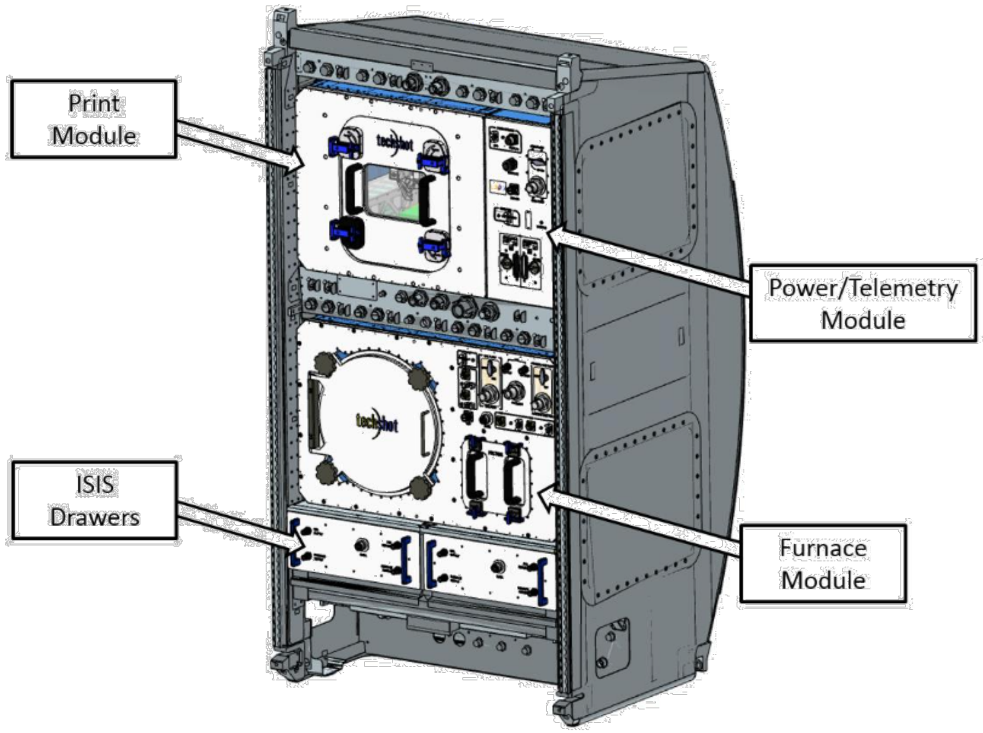
ODMM Accomplishments: Techshot FabLab

Techshot Fabrication Laboratory (FabLab):

Goal: The Techshot FabLab aims at maturing a bound metal deposition system capable of producing Ti64 components in space providing a pioneering approach to enable sustainable and affordable exploration operations and logistics.

Background:

- Bound metal deposition technology
  - A paste or filament is used to print a “green” part
  - Astronaut transfers “green” part to furnace chamber. Furnace combines a low temp thermal debind to remove binder and a high temperature sinter procedure to consolidate material
  - Finishing milling completes high precision features
- Started under AES with a NextSTEP BAA (completed 6/29/2020)
  - Result: ground-based prototype manufacturing facility that printed, debound, and sintered Ti64 parts from a paste feedstock.

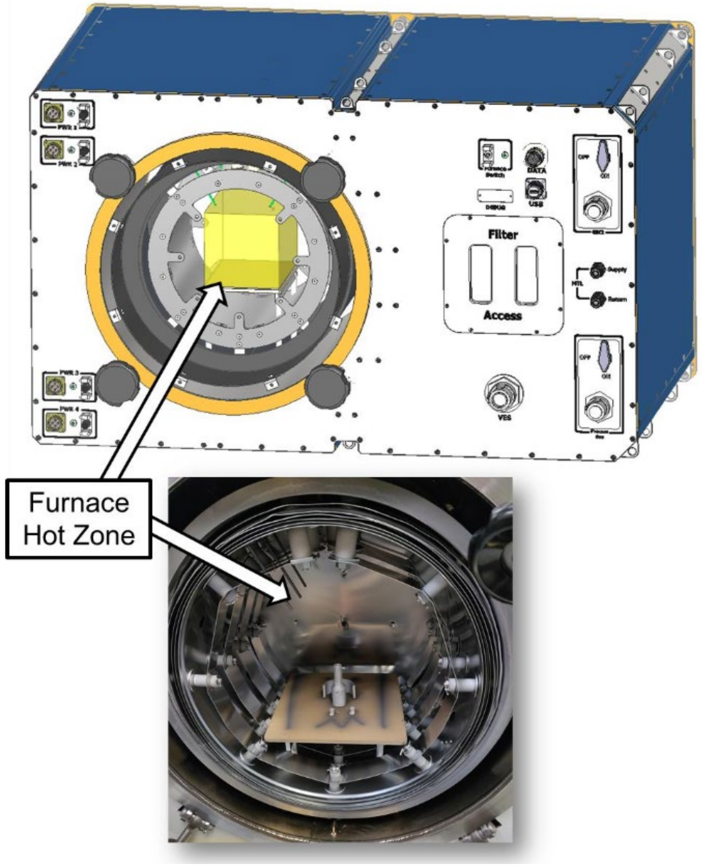


FabLab Bound Metal Deposition System
Image Credit: Techshot

ODMM Accomplishments: Techshot FabLab

- Techshot placed on a Task Order administered by JSC 01/31/2021
  - Revise Furnace Module to meet ISS Power Requirements
  - Identify High Risk Safety and Interface Requirements
  - Develop Furnace Module Control Software
  - Evaluate the inclusion of ODME capabilities within the FabLab System

- Mature the design to meet EXPRESS Rack Requirements
  - The print unit occupies one quad locker, the vacuum furnace unit occupies a quad locker, and the process gas system fits an ISIS drawer.
  - Preliminary Analysis completed by vacuum furnace manufacturer TMI indicates that the revised furnace design will be capable of meeting the 2kW ceiling (testing to be completed by 12/31/2021



Furnace Module
Image Credit: Techshot

ODMM Accomplishments: Techshot FabLab

- Materials Development
  - Lower sintering temperatures explored decreasing furnace power
    - Maximum processing temperature 1250 C to 1150 C
  - University of Louisville continuing to develop bound metal filaments

- Identification of High-Risk Safety and Integration Items
  - Safety Review Panel (SRP) Phase 0 TIM completed 07/08/2021
    - Working Groups scheduled for areas of concern
    - Contract Modification to address SRP concerns provided to the CO 08/11/2021
      - Develop a preliminary fracture control plan
      - Identify a weldment inspection protocol for the furnace module
      - Develop a risk mitigation/reduction approach for coolant compatibility

- CCRPP awarded to Techshot (contract still in negotiation):
  - Develop printer and furnace subsystems to optimize the process environment
  - Design systems for the containment and transfer of parts into the furnace chamber
  - Perform feedstock optimization analysis
  - Develop ODME hardware configurations for systems level integration and testing

Challenge build parts from Techshot Phase A FabLab
Image Credit: Techshot

ODMM Accomplishments: Redwire Vulcan

Vulcan from Redwire (formerly Made in Space):

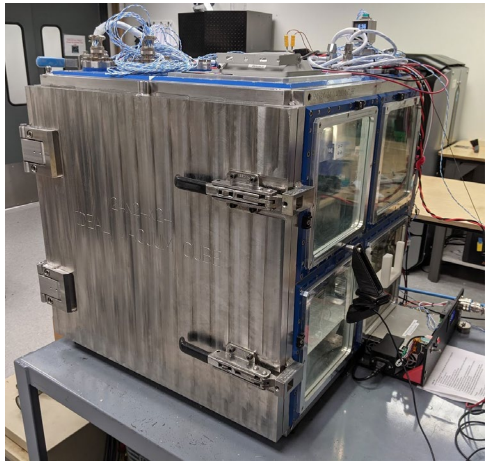
Goal: The Vulcan System aims at maturing a Wire+Arc Additive Manufacturing (WAAM) system capable of producing aluminum components in space providing a pioneering approach to enable sustainable and affordable exploration operations and logistics.

Vulcan prototype system. Image credit: Redwire

Background:

- WAAM Technology
  - Creates near-net-shape part using a MIG type process
  - Final geometry machined from the blank.
  - Reduced argon flow minimizes consumables

- Started under the SBIR project and completed a Phase I, II, and II-E.
  - Result: ground-based prototype of critical systems and demonstration of manufacturing using Al4043 welding wire.



EDU Vacuum Chamber. Image credit: Redwire

ODMM Accomplishments: Redwire Vulcan

- Redwire Phase III Flight Vulcan Kickoff held 12/18/2020
    - Design, develop, and test a manufacturing system for multi-material additive manufacturing (polymer and metal) in microgravity
        - Demonstrate dry machining and FOD management
        - Incorporate remote commanding
        - Demonstrate Fixturing of a part using a robotic gripper

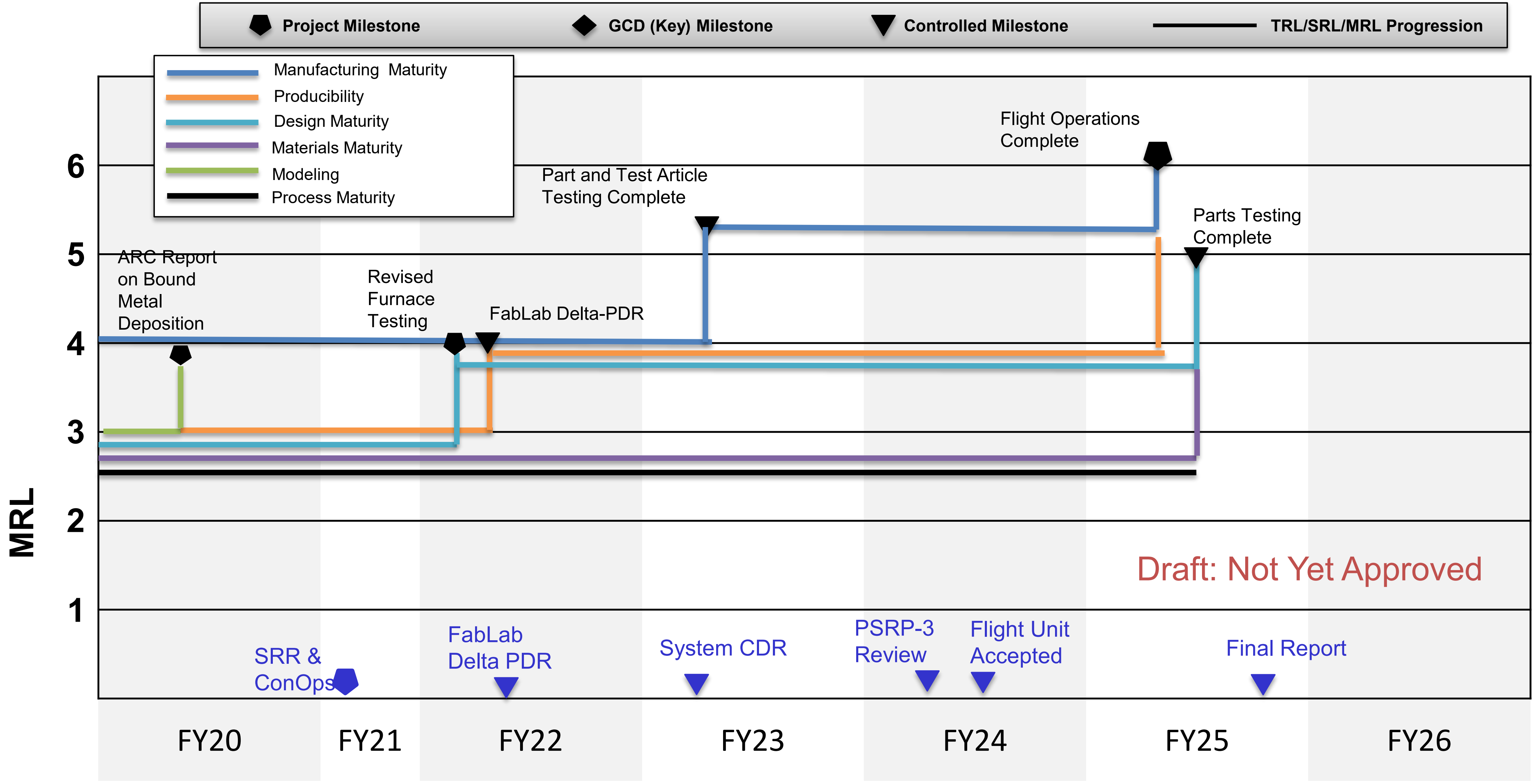
    Fabricate representative parts and other test specimens for characterization by NASA

- System Requirements Document Delivered 03/15/2021
- The Redwire team completed their phase 0 safety TIM 07/10/2021
- Flight Design and EDU continue to mature towards a CDR

- ODMM engages a modeling team at Ames Research Center (ARC) to generate a model to predict microgravity effects

Image credit: Redwire

ODMM
FabLab MRL

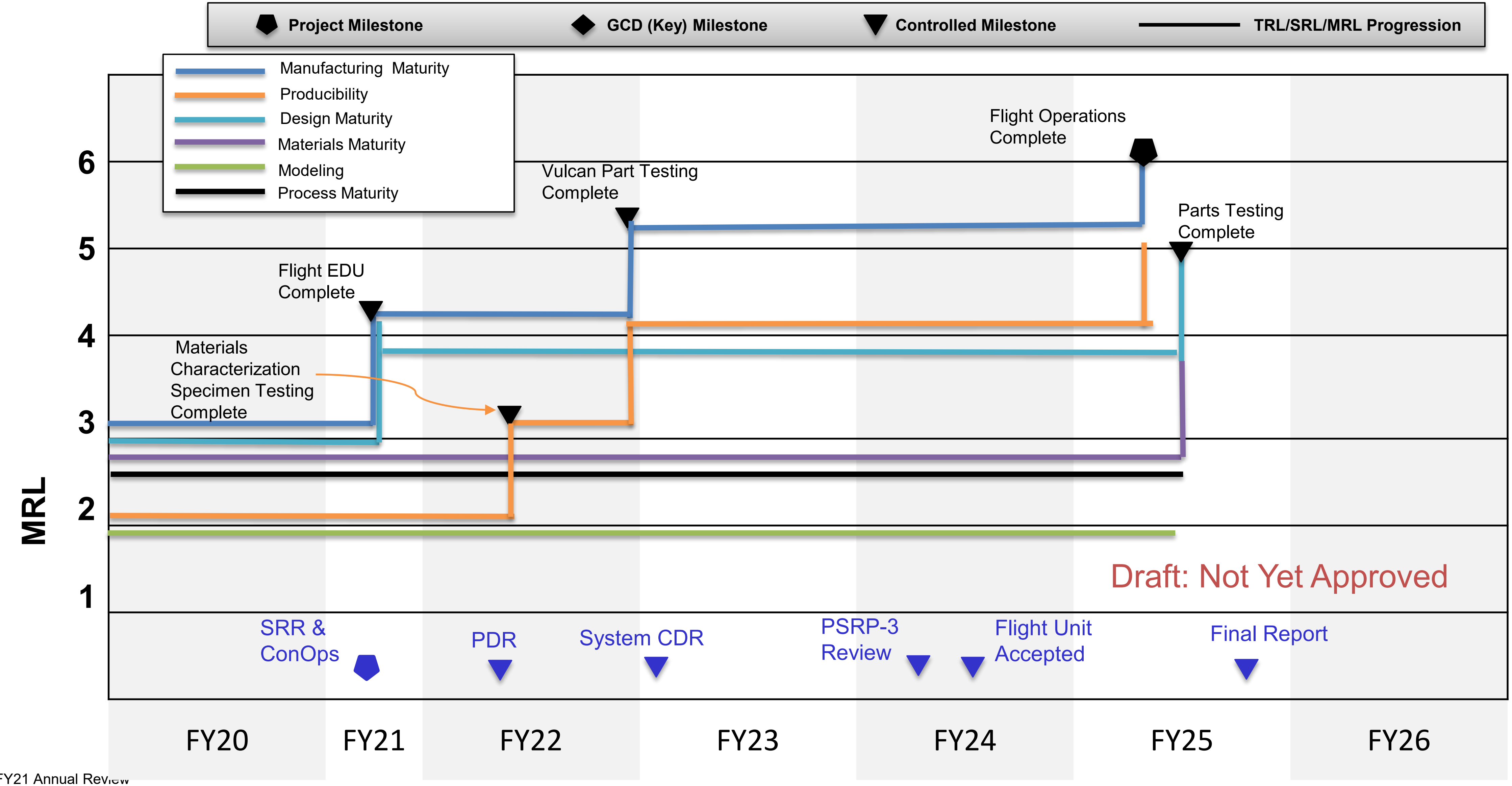


FabLab Technical Assessment

Technical Elements	MRL				AD[2]	
	Entry	Current[1]	Exit	Verification	Entry	Current
Manufacturing Maturity	4	4	6	T-K04 Flight Operations Complete	7	7
Producibility	3	3	5	T-K04 Flight Operations Complete		
Design Maturity	3	3	5	T-C13 Part Testing Complete		
Materials Maturity	3	3	4	T-C13 Part Testing Complete		
Modeling and Simulation	3	4	4	ARC Bound Metal Deposition Report		
Manufacturing Process Maturity	3	3	3			

Date of last Technical Assessment was XYZ

ODMM
Vulcan MRL



Vulcan Technical Assessment

Technical Elements	MRL				AD[2]	
	Entry	Current[1]	Exit	Verification	Entry	Current
Manufacturing Maturity	3	4	6	M-K04 Flight Operations Complete	7	7
Producibility	2	2	5	M-K04 Flight Operations Complete		
Design Maturity	3	4	5	M-C16 Part Testing Complete		
Materials Maturity	3	3	4	M-C16 Part Testing Complete		
Modeling and Simulation	2	2	2			
Manufacturing Process Maturity	3	3	3			

Date of last Technical Assessment was XYZ

ODMM FabLab Key Performance Parameter (KPP) Status

Key Performance Parameters								
Parameter Name	**Unit**	**State of the Art**	**Threshold Value**	**Project Goal**	**Current Value to Date**	**TBoE for the Provided Current Value**	**Expected Exit Value**	**TBoE for the Provided Exit Value**
Bulk Density	%	100	95	97	96	Estimated[1]	97	Verified
Ultimate Tensile strength (UTS)	MPa	950	900	950	949	Estimated[1]	950	Verified
Linear Elongation	%	18	5	10	15	Estimated[1]	12	Verified
Accuracy of printed parts	% of deviations from part model within +/- 0.5 mm	N/A	95	98	N/A		95	Verified

Technical Basis of Estimate (TBoE)

(1) Values provided by contractor testing report. Samples were processed in an analogous environment while testing sintering protocols. Furnace Testing to be completed in December will provide greater confidence in the results. KPPs will not close until specimens are manufactured on orbit.

KPPs are not yet in an approved state.

ODMM Vulcan Key Performance Parameter (KPP) Status

Key Performance Parameters4								
Parameter Name	**Unit**	**State of the Art**	**Threshold Value**	**Project Goal**	**Current Value to Date**	**TBoE for the Provided Current Value**	**Expected Exit Value**	**TBoE for the Provided Exit Value**
Bulk Density	%	100	96	99	96.6	Estimated[(1)]	98	Verified
Ultimate Tensile strength (UTS)	MPa	950	120	150	172	Estimated[(1)]	172	Verified
Linear Elongation	%	18	10	13	17	Estimated[(2)]	13	Verified
Accuracy of printed parts	% of deviations from part model within +/- 0.5 mm	N/A	95	98	N/A		95	Verified

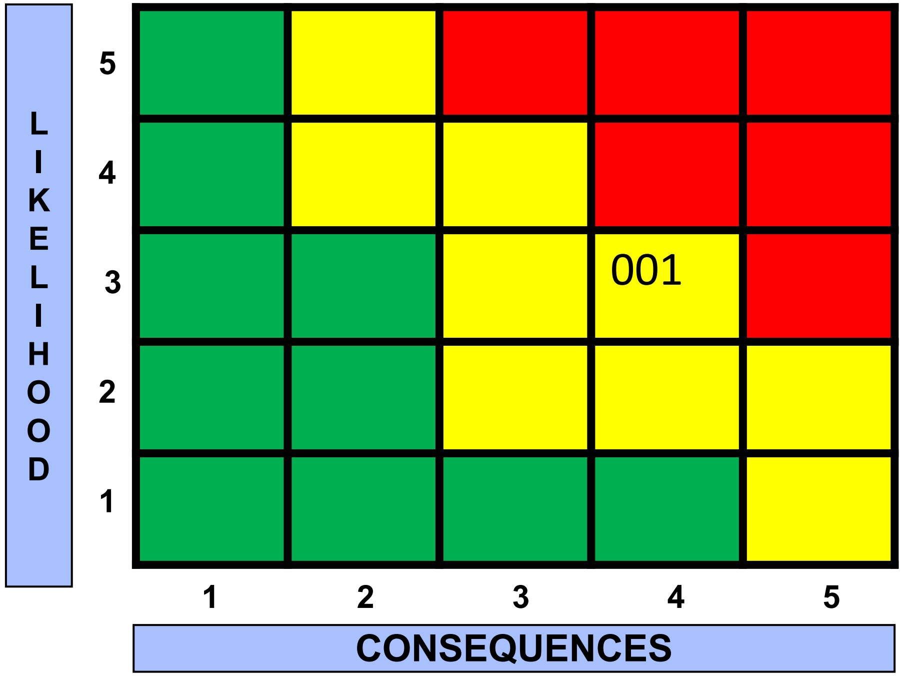
Technical Basis of Estimate (TBoE)

(1) Values from R4043 Vulcan Tensile Specimens Work Order #2021-0106, Sequence 1 which tested 4 samples

(2) Values from Southern Research Center "Material Testing in Support of Material Characterization for the Vulcan In-Space Manufacturing System" final report which tested 2 samples.

KPPs are not yet in an approved state.

Technology Maturation – GCD PPBE23 Risk Updates



Criticality
- High
- Med
- Low

L x C Trend
- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: T-Technical C-Cost Sc-Schedule Sa-Safety

Risk ID	Affinity	Description/Status	Proposed Mitigation	Trend	Approach
001	T	Given that the ISS has limited power allocation of only 2KW and currently Techshot Fablab's first generation micro-furnace design (phase-A prototype) is above the EXPRESS Rack power constraint, there is a possibility that the second generation microfurnace may not be able to meet the power allocation.	1.Test furnace with original equipment manufacturer (OEM) controls and electronics to obtain ground-based power requirements for sintering. 2. AC to DC power conversion to realize greater efficiency 3. Hot zone insulation pack design optimization 4. Hot zone volumetric design optimization (reduce size of hot zone in furnace)	⇩	M

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year	GREEN	YELLOW	YELLOW	GREEN	• GREEN on cost since both follow-on activities for development of hybrid metal additive manufacturing systems for ISS are within budget for FY21. Both efforts are now on contract. • YELLOW for schedule due to a longer than anticipated time to get the follow-on work on contract with Techshot. • YELLOW for technical since the current FabLab furnace design from Techshot is not within ISS power requirements. • GREEN for programmatic since ODMM is largely on track to demonstrate on-orbit metal manufacturing by the end of FY24.
Annual	GREEN	GREEN	YELLOW	GREEN	• GREEN on financial status since both follow-on activities for development of hybrid metal additive manufacturing systems for ISS are within budget for FY21. Both efforts are on contract. • YELLOW for technical status since the Techshot FabLab furnace exceeds ISS power allowance. Preliminary analysis of the furnace module by the contractor indicate that power targets will be meet with the redesigned EDU; thus, technical status is trending towards GREEN. • GREEN on schedule as no delays are imminent or anticipated. • GREEN for programmatic. PCD approved by GCD

EPO Update

- 3/2 – Tracie Prater spoke at the University of Tennessee Honors Program
- 3/18 Tracie Prater spoke at the Intrepid Museum Virtual Astronomy Live
- 3/18 – Tracie Prater spoke at the Women in Space Exploration (WiSE)
- 4/19-4/23 American Society of Civil Engineers (ASCE) Earth & Space Conference
- 5/24-27 Society of Advancement of Material and Process Engineering (SAMPE) annual meeting

Plans Forward and Infusion Plan

- **Infusion/transition plan**
  - Currently ISS (and future crewed missions beyond ISS) lack the capability to repurpose materials and/or fabricate spare parts, replacement units, and specialty tools in situ. Through FY24 and potentially beyond, ISS serves as the testbed to evaluate technologies to meet these future mission needs.
  - Once systems have been initially demonstrated on ISS and material coupons and parts from the system have been downmassed to earth and evaluated, results will inform further maturation of the systems to meet mission needs for sparing and repair. Continued operation of systems on ISS will be used to develop characteristic properties for specimens and parts produced in microgravity.
  - Inspection technologies must also be developed in parallel with the manufacturing systems. Inspection capabilities are needed to produce parts for use beyond the exempt category (the “exempt” designation corresponds to parts with no consequences of failure).
  - Beyond the initial metal manufacturing demonstrations, ISS will continue to be used to mature these technologies and explore their subsequent infusion into future orbital platforms, lunar surface manufacturing, and transit habitats.
- **Exploration & Science Applicability**
  - Current approach to logistics, which relies on pre-positioned spares, is not sustainable for long duration missions where cargo resupply opportunities are limited
  - Once tested on ISS, capabilities developed under ODMM can provide a means to manufacture parts at the point of use on future space missions, reducing the amount of upmass and enhancing crew safety

Summary

Goal Demonstrate metals additive manufacturing in microgravity and characterize the impact of microgravity on manufacturing technologies.

Why? The current logistics model is unsustainable for long duration space missions. On demand manufacturing of spares and new components not only enables sustainability goal, but it also increases reliability and safety.

Progress:

– The Techshot FabLab contract was put in place to address major technical challenges identified during Phase A. Through this effort, administered under an IDIQ with JSC, the Techshot FabLab is on track to meet resource requirements of the ISS. Future testing will verify a preliminary analysis showing a significant reduction in the power resources required.

– The Redwire VULCAN Manufacturing System continued into a Phase III SBIR with the aim of maturing into a flight system. The contractor successfully completed a safety TIM, designed an EDU, and provided materials characterization samples to MSFC.

BACKUP

<Technology Name>

Risk Title (Short risk title)- Risk Owners Name

Risk ID #
No. unique to this risk-stays with risk even when closed/retired.

Trend

Criticality

Current L/C
5x5

Affinity Group
Technical, Cost, Schedule, Performance

Planned Closure
mm/dd/yyyy

Open Date
mm/dd/yyyy

Risk Statement :

Approach: (choose one) Mitigate, Watch, Accept, Research

Risk Statement in the format "Given that (state the fact)…there is a possibility (state the concern)…resulting in (state the consequence..)"

Context

Info and background NOT in the Risk Statement. Captures the what, when, where, why, and how of the risk, specifically: What do we need to know to fully understand the risk? What are the relevant and related circumstances, contributing factors, and related issues?

Status

mm/yyyy of update. Information regarding current status. Update semi-annually. **Current status on top**. OK to eliminate status updates more than two years old to keep this page from getting too large.

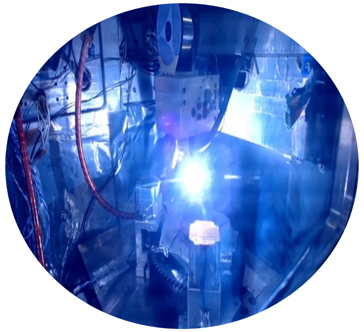
Mitigation Steps	Dollars to implement	Trigger/ Start date	Schedule UID	Completion Date	Resulting L/C

(Note: The Schedule UID is the unique id no of the mitigation step in your schedule if appropriate.
Dollars to implement are not extra approved $ from the Program Office but $ set aside as part of project budget to mitigate.)

Cover Slide Annotate Images

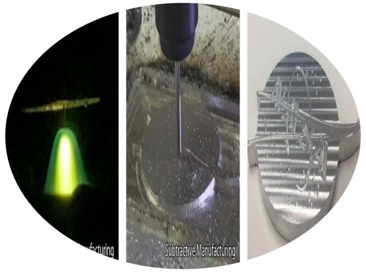
Part produced with Vulcan subsystems. Image from Made in Space.

Techshot Fabrication Laboratory (FabLab). Image from Techshot.

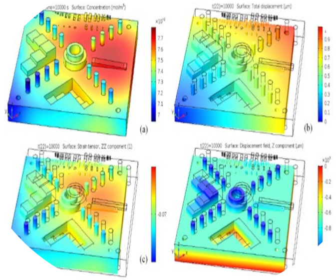


Vulcan EDU in operation. Image from Made in Space.

Parts manufactured with FabLab prototype system. Image from Techshot.



Steps in Vulcan manufacturing process (hybrid wire+arc additive manufacturing). Image from Made in Space.



Prediction of part shrinkage in bound metal additive manufacturing (Techshot FabLab process). Image from NASA Ames Research Center.

GCD Project Performance Evaluation Criteria

	Technical/Performance
Green	Project is demonstrably making progress on the Learning Trajectory (e.g. milestones met, knowledge advanced) or advancing TRL. Project is on track to meet L1 requirements.
Yellow	Project is making progress on the Learning Trajectory or advancing TRL with issues. Project is on track to meet L1 requirements but issues exist that may threaten achievement.
Red	Project has ceased to make progress on the Learning Trajectory or advance TRL. Project is unable to meet one or more L1 requirements.

	Cost
Green	Project can meet its commitments with its planned/allocated budget.
Yellow	Project cannot meet its commitments within its planned/allocated budget but will not be requesting additional budget from Program. Mitigation plans have been developed.
Red	Project cannot meet its commitments within its planned/allocated budget and will be requesting additional budget from Program.

	Schedule
Green	Project can meet its commitments within its planned/allocated schedule baseline for critical milestones.
Yellow	Project cannot meet its commitments within its planned/allocated schedule baseline but mitigation plans have been developed to pull it back in.
Red	Project cannot meet its commitments within its planned/allocated schedule baseline.

	Programmatic (Institutional, Internal/External Dependencies **)
Green	Relevance of technology to stakeholders and/or technology infusion path is maintained. Mission sponsor still actively interested. No issues exist with workforce, test facilities, etc.
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Source: BPR Assessment Criteria for NASA R&T Projects, OCE/S. Hirshorn, 09/17/2015

National Aeronautics and
Space Administration

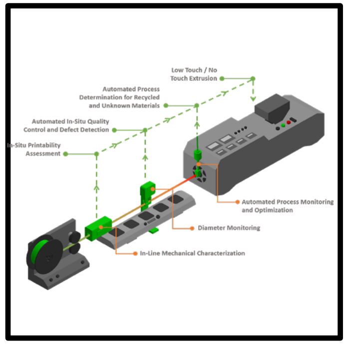
Annual Program Review
Game Changing Development Program

Alex Blanchard | FY21 Recycle and Reuse | 09.15.21

Recycle and Reuse (RnR) Overview

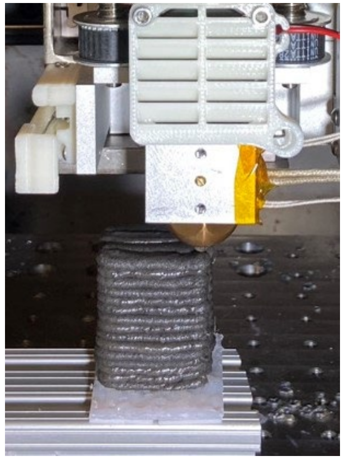
- Technology Product Capability
  - The In-Space Manufacturing (ISM) Recycling and Reuse project is responsible for developing and demonstrating recycling and in-situ resource manufacturing technologies for NASA Exploration Missions. This includes testing & advancing the desired technologies, as well as establishing the required skills & processes for the processes that will enable the technologies to become institutionalized.

Recyclable Packaging Materials Image Courtesy of Cornerstone Research Group



In Process Monitoring Suite Image Courtesy of Cornerstone Research Group

- Technical Capabilities
  - Development of Recyclable Packaging Materials and Processes
  - Development of In-Process Monitoring technologies for filament feedstock production
  - Demonstration of regolith/polymer blend printing on orbit (AES funded)
  - Demonstration of a closed-loop recycling ecosystem of flexible thermoplastic polyurethane material



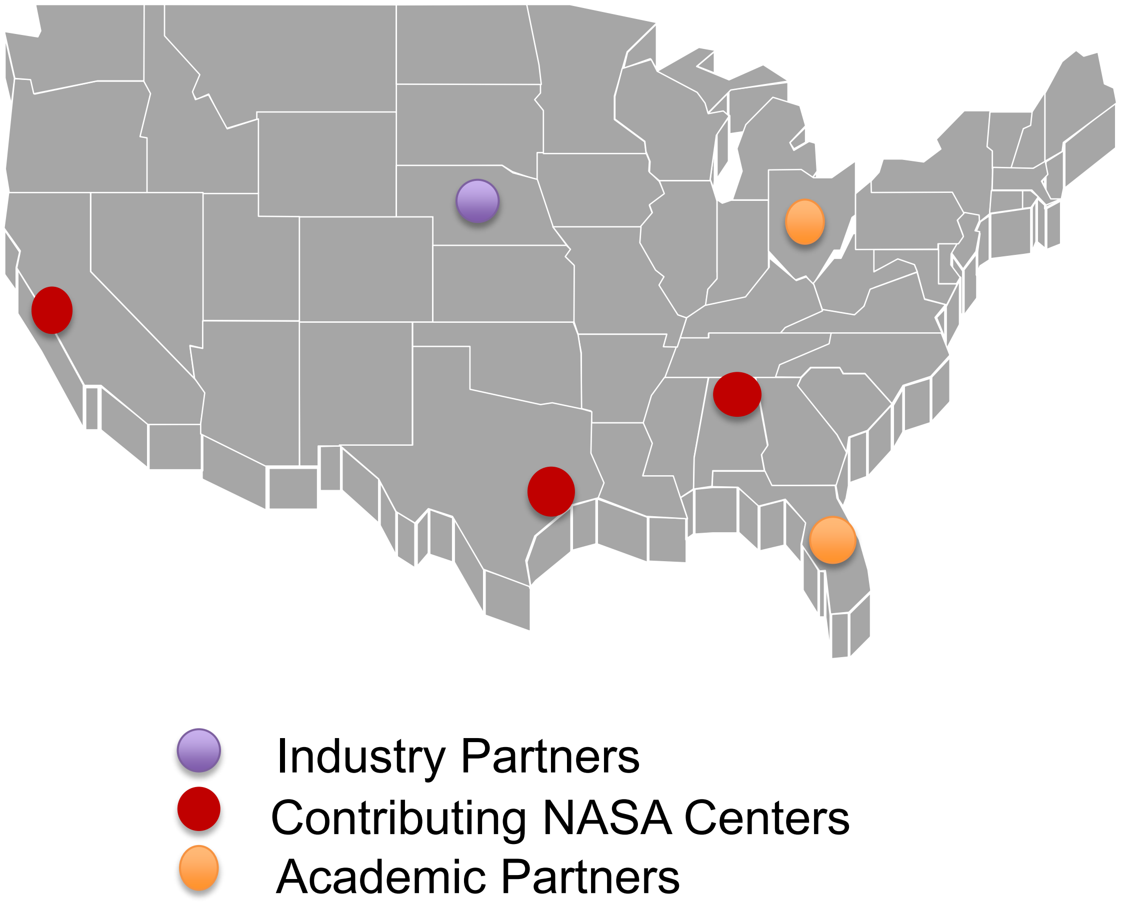
Regolith Polymer Printing Image Courtesy of Redwire

- Exploration & Science Applicability
  - Logistics reduction for long duration exploration missions
  - Sparing and Lunar Surface Manufacturing
  - Gateway logistics reduction

Mission Infusion & Partnerships

- Industry Partners
  - Cornerstone Research Group
  - Redwire Space, Inc.
- Contributing Centers
  - Marshall Space Flight Center
  - Johnson Space Center
  - Ames Research Center
- Academic Partners
  - University of Nebraska

- Infusion/transition plan
  - Technologies will be proven and demonstrating using the ISS as a testbed and then infused into future NASA missions such as Gateway and Lunar Surface Habitats.
  - ISS Demonstrations – potential
  - Lunar Habitat– potential
  - Gateway – potential
  - Mars Habitat - potential



Recycle and Reuse (RnR) Technology Goals & Project Objectives

Technology Goals

Goal #1	Develop in-process monitoring technology to ensure recycled polymer filament production quality.
Goal #2	Develop and assess launch packaging materials for recyclability.
Goal #3	Demonstrate and evaluate the recycling of launch packaging materials on-orbit.

Project Objectives

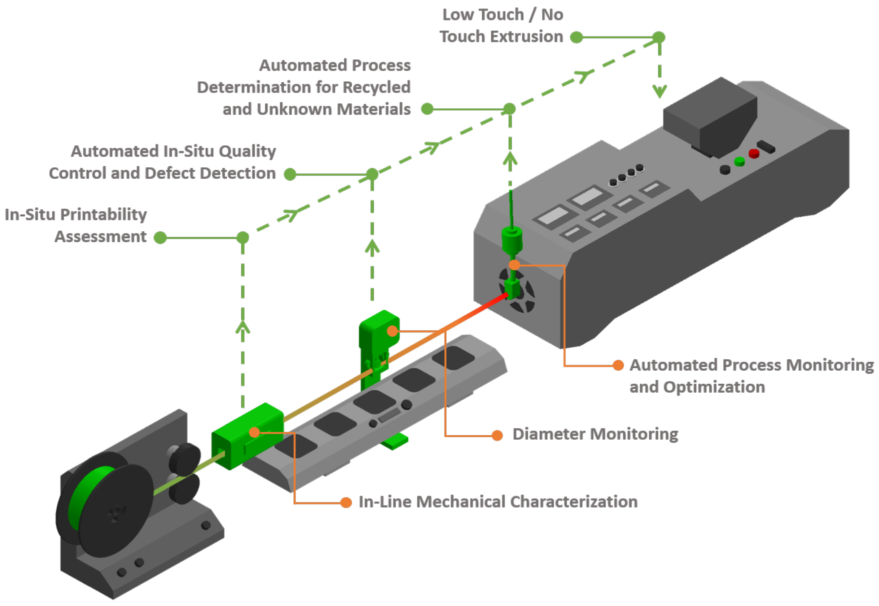
Objective #1	Identification of flame-retardant material chemistries and optimal loading percentage to meet ISS outgassing and flammability requirements.
Objective #2	Optimize the elastic modulus and tensile strength of the recyclable material through the inclusion of strengthening fillers.
Objective #3	Characterize the impact of the recycling process on mechanical and chemical properties the recyclable material.
Objective #4	Develop cleaning and pre-processing methodologies to ensure consistent feedstock production.
Objective #5	Certify the material for use aboard the ISS both in a virgin and recycled state.
Objective #6	Deliver to ISS a flight-certified purpose-built packaging material.
Objective #7	Demonstrate the complete lifecycle of the recyclable material from initial use through a printed component.
Objective #8	Demonstrate a complete recycling loop of flexible thermoplastic polyurethane (TPU) material starting from bulk TPU.
Objective #9	Characterize changes to mechanical and rheological properties of thermoplastic polyurethane material through each recycling iteration

Accomplishments

Cornerstone Research Group (CRG):

In Process Monitoring

- Winding down a two-year effort to develop an in-process monitoring system for polymer filament production. (Completed August 2021)
- Demonstrated successful closed loop feedback control of the polymer extrusion process.
  - Maintained an average diameter of 1.75mm with a standard deviation of 0.018mm
- Integrated diameter measurement capabilities with extrusion controller.
- Accurate and precise measurements of filament over extended periods were achieved.
  - The firm demonstrated the production of 2.5 lbs. of RVT (reversible thermosetting polymer) and 0.8 lbs. of polycarbonate with precise diameter control.



In Process Monitoring Suite Image Courtesy of Cornerstone Research Group

Accomplishments

Cornerstone Research Group (CRG):

Reversible Thermosetting Packaging Material

- A reversible thermosetting packaging material was developed under an SBIR Phase I, II and II-E
- The ISM team has set up a follow-on SBIR Phase III to continue maturation of this material towards flight.
- Base Period Objectives:

  To develop a foam packaging material that can be recycled aboard ISS by existing recycling system payloads.

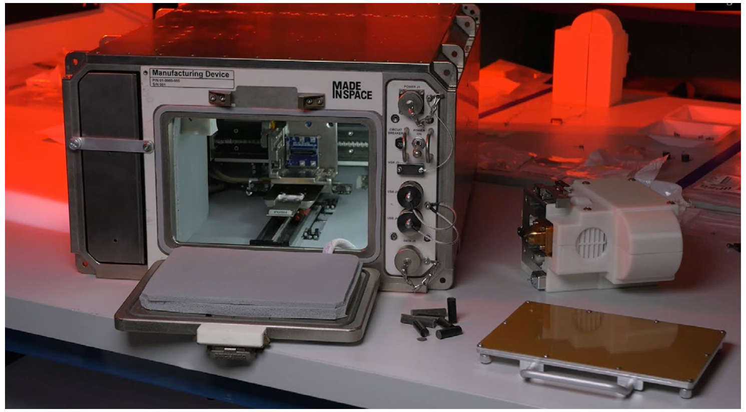
  1. Identification of flame retardant chemistry and percent loading to meet outgassing and flammability requirements
  2. Modification of the RVT chemistry and flame retardant percent loading to ensure printability of flame retardant copolymer
  3. Identification and implementation of fillers which improve stiffness and strength of the RVT baseline filament
  4. Define the useful life of the material
  5. Minimize the use of consumables such as water and additives.

Recyclable Packaging Materials
Image Courtesy of Cornerstone Research Group

Accomplishments

Redwire Regolith Print (RRP):

- Winding down a 16-month activity with Redwire (Previously Made in Space) to demonstrate on-orbit 3D printing using a regolith simulant/polymer feedstock.
- Developed concept of operations, systems requirements, specimen matrix for flight and ground-based printing for technology demonstration mission, assembly of new print heads and print beds for the additive manufacturing facility (AMF), and development of linear low-density polyethylene/regolith simulant blend.
- Flight hardware (print heads and print beds) handover successfully occurred on 5/18/21
- Launched 8/10/2021



The Redwire Regolith Print facility suite, consisting of Redwire's Additive Manufacturing Facility, and the print heads, plates and lunar regolith simulant feedstock that will be launching to the International Space Station.
Image Credit: Redwire Space, Inc

Strength	Standard	Specimen Shape	Minimum Number of Samples Per Standard	Sample Yield of RRP Printed Slabs
Tensile	ASTM D638-14	Dogbone	5	10
Compressive	ASTM D695-15	Prism	5	6
Flexural	ASTM D790-17	Simple Beam	5	5

Table 1. Anticipated mechanical specimens to be machined from regolith simulant/polymer blend slabs produced on Station.

3D Printing of regolith-based feedstock material.
Image credit: Made in Space.

Accomplishments

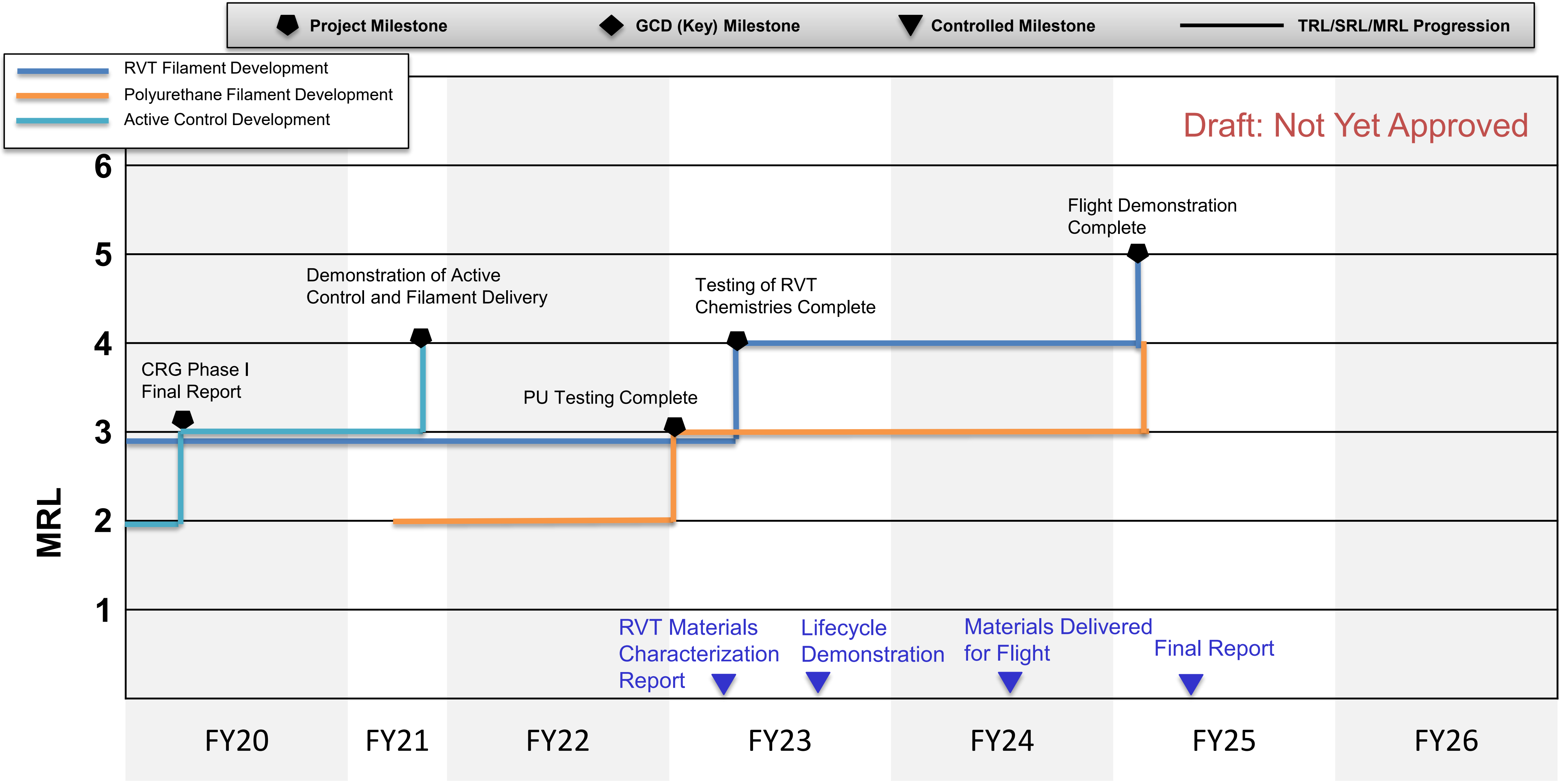
Refabricator ISS Technology Demonstration:

- The Refabricator payload was decommissioned on 19 November 2021.
- Indefinite delays to the downmassing of refabricator has prevented the commencement of an anomaly investigation to determine the root cause of failure. (Original Date: April 7, 2020)

University of Nebraska CAN:

- A Cooperative Agreement Notification (CAN) proposal from the University of Nebraska was awarded
  - Development and Testing of Recyclable and Antimicrobial Materials for Additive Manufacturing
  - Produce two chemistries of copper infused filaments
  - Characterize mechanical, chemical, and biological effects of recycling on the polymer

Recycling and Reuse



Technical Assessment

Technical Elements	MRL				AD[2]	
	Entry	Current[1]	Exit	Verification	Entry	Current
RVT Filament Delivery	3	3	5	Flight Demonstration Complete	7	7
Polyurethane Filament Delivery	2	2	4	Flight Demonstration Complete	7	7
Active Control Development	2	4	4	Final Report on Active Filament Control	6	6

Date of last Technical Assessment was XYZ

RnR Key Performance Parameter (KPP) Status

Key Performance Parameters								
Parameter	Units	State of the Art (SOA)	Threshold Value	Project Goal	Current Value To Date	TBoE for the provided Current Value	Expected Exit Value	TBoE for the provided Expected Exit Value
Spool Length of Packaging Materials	m	-	3	60	N/A	N/A[(1)]	60	Verified based on flight data
Tensile Strength of Compression Molded Specimen	MPa	-	9	9	N/A	N/A[(1)]	10	Verified

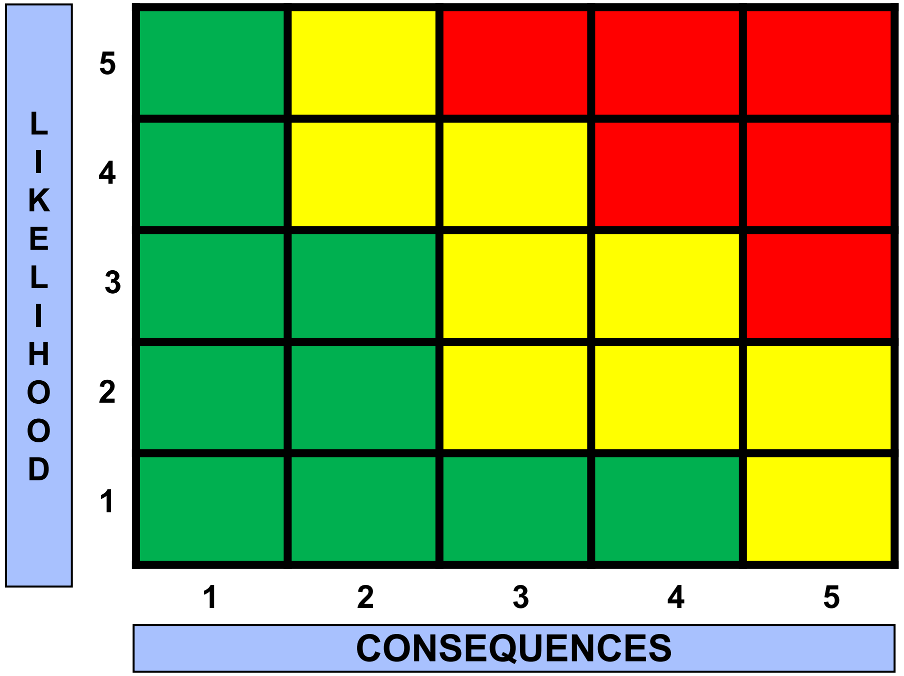
Notes:

Technical Basis of Estimate (TBoE)

[(1)] Filament chemistries are currently under development. The current effort is aimed at introducing strengtheners and fire retardants which will significantly impact mechanical properties. Thus, the current value is unknown.

KPPs are not yet approved.

Risk Summary



Risk ID	Affinity	Description/Status	Proposed Mitigation	Trend
ID#				

*No risks for RnR at this time.

Criticality
- High
- Med
- Low

L x C Trend
- Decreasing (Improving)
- Increasing (Worsening)
- Unchanged
- New Since Last Period

Approach
- M - Mitigate
- W - Watch
- A - Accept
- R - Research

Affinity: **T**-Technical **C**-Cost **Sc**-Schedule **Sa**-Safety

Project Assessment Summary

Project Name	Performance				Comments
	C	S	T	P	
Mid Year					• Cost is currently GREEN. Budget allocation was received from GCD which will allow the project to push forward with getting CRG on contract for a Phase III SBIR for recyclable packaging material development. • Technical remains GREEN as project tasks to support technical development are in place and all are proceeding on schedule. • Repeated delays to downmassing of Refabricator has resulted in a YELLOW status for schedule. These delays have impacted the start date of the payload anomaly investigation. • Programmatic remains GREEN. Project PCD and Project Plan are in final reviews with PEM. PCD should be submitted soon for Chief Engineer approval.
Annual					• Financial status is currently GREEN. Budget allocation was received from GCD which will allow the project to push forward with getting CRG on contract for a Phase III SBIR for recyclable packaging material development. • Following the indefinite delay of the Refabricator return, the ISM project is no longer tracking the failure investigation task. This has resulted in the schedule again being shown as GREEN. • Technical status remains GREEN as all technical tasks are proceeding on schedule. • Project status remains GREEN as the PCD is being updated and will be submitted for approval from GCD.

Plans Forward and Infusion Plan

- **Infusion/transition plan**
  - The International Space Station (ISS) is currently reliant on continual resupply missions from Earth for repair and maintenance. This logistical model is untenable for long-duration missions due to prohibitive costs and the additional time requirement for a resupply vessel to reach its outpost.
  - An ecosystem capable of recycling waste materials (i.e., packaging) into useable parts through an on-demand manufacturing system will reduce risk and enable Earth independent flight.
  - Currently ISS serves as a proving ground where new recycling and additive manufacturing technologies are tested prior to utilization in missions beyond low-Earth Orbit.
  - Apart from demonstrating additive manufacturing capability, advancement of novel packaging material(s) that are easily converted into filament for 3D printing will reduce waste packaging material and save on cost by eliminating the need to ship extraneous parts.
- **Exploration & Science Applicability**
  - For long duration exploration missions beyond low-earth orbit, cargo resupply missions will not be as frequent and logistics requirements can be reduced through on-demand manufacturing and recycling.
  - On-demand manufacturing will provide logistics reduction for sparing, lunar surface manufacturing, and Gateway.

Summary

Goal: Develop and demonstrate recyclable packaging materials and recycling technology in a microgravity environment.

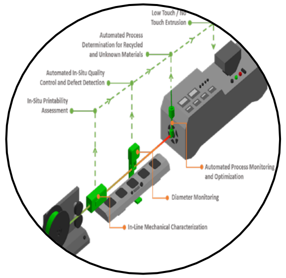
Why? The current logistics model is unsustainable for long duration space missions. Recycling and reuse has the potential to reduce mass, increase mission flexibility, provide a path towards sustainable on demand manufacturing.

Progress:

- Redwire Regolith Print (previously RegISS) was put on contract for a technology demonstration to demonstrate the feasibility of 3D printing regolith/polymer blends in low gravity environments. They successfully demonstrated this technology terrestrially and the new print hardware (print heads and beds) and filament was launched on August 10, 2021. Future mechanical testing will be performed at MSFC (Marshall Space Flight Center) on both ground and microgravity samples per ASTM standards.
- Cornerstone Research Group (CRG) successfully demonstrated a new in-line DMA (dynamic mechanical analysis) system based on a dual cantilever/3 point bend which provides real-time data on the filament flexural modulus and feeds that information back to the extruder. Moreover, by identifying real-time mechanical properties of the extruded filament the firm was able to automate the extrusion process. They also produced 2.5 lb. of extruded reversible thermoset (RVT) filament and 0.8 lb. of polycarbonate (PC) filament with high accuracy and precision over extended periods.
- During the next fiscal year the project anticipates starting three new tasks: 1) SBIR Phase III Maturation of the RVT filament material 2) University of Nebraska CAN for antimicrobial filament 3) Adidas SAA for recycling of apparel.

BACKUP

Cover Slide Annotate Images



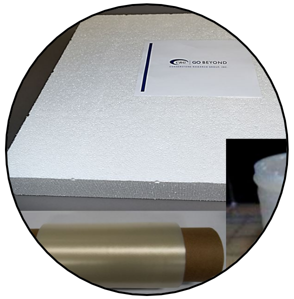
Recyclable Packaging Materials Image Courtesy of Cornerstone Research Group

In Process Monitoring Suite Image Courtesy of Cornerstone Research Group

Electric Power System onboard ISS

International Space Station

Shuttle Launch



Regolith Polymer Printing Image Courtesy of Redwire

GCD Project Performance Evaluation Criteria

	Technical/Performance
Green	Project is demonstrably making progress on the Learning Trajectory (e.g. milestones met, knowledge advanced) or advancing TRL. Project is on track to meet L1 requirements.
Yellow	Project is making progress on the Learning Trajectory or advancing TRL with issues. Project is on track to meet L1 requirements but issues exist that may threaten achievement.
Red	Project has ceased to make progress on the Learning Trajectory or advance TRL. Project is unable to meet one or more L1 requirements.

	Cost
Green	Project can meet its commitments with its planned/allocated budget.
Yellow	Project cannot meet its commitments within its planned/allocated budget but will not be requesting additional budget from Program. Mitigation plans have been developed.
Red	Project cannot meet its commitments within its planned/allocated budget and will be requesting additional budget from Program.

	Schedule
Green	Project can meet its commitments within its planned/allocated schedule baseline for critical milestones.
Yellow	Project cannot meet its commitments within its planned/allocated schedule baseline but mitigation plans have been developed to pull it back in.
Red	Project cannot meet its commitments within its planned/allocated schedule baseline.

	Programmatic (Institutional, Internal/External Dependencies **)
Green	Relevance of technology to stakeholders and/or technology infusion path is maintained. Mission sponsor still actively interested. No issues exist with workforce, test facilities, etc.
Yellow	Relevance of technology to stakeholders and/or technology infusion path are threatened. Mission sponsor backing off. Issues exist with workforce, test facilities, etc. but plans to mitigate are available.
Red	Relevance of technology to stakeholders and/or technology infusion path are not projected to be met, or has lost relevance to stakeholders. Mission sponsor cancelled interest. Issues pertaining to workforce, test facilities, etc. are preventing progress along the Learning Trajectory.

Source: BPR Assessment Criteria for NASA R&T Projects, OCE/S. Hirshorn, 09/17/2015