



# Space Technology Mission Directorate Game Changing Development Program — In-Space Manufacturing (ISM)

Jennifer Edmunson and Curtis Hill | FY19 Annual Review Presentation | September 24, 2019

# ISM Technology Overview



## ➤ Technology Goal

- Develop multiple on-demand manufacturing technologies for infusion into independent, sustainable deep-space vehicle and habitat programs
- Portfolio includes multiple projects, SBIRs, and partnerships focused on materials and manufacturing process research and development for space

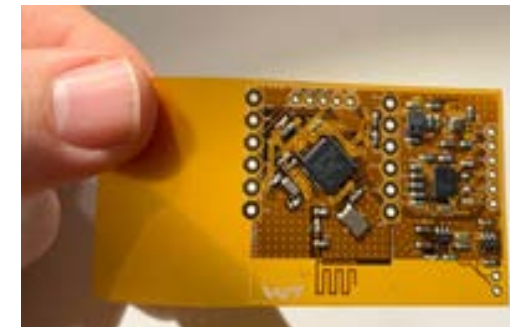
## ➤ Technical Capabilities

- Printing with polymers
- Recycling/reuse of polymers (e.g. packaging materials)
- Fabrication and inspection of metallic materials and components (image at top right)
- Printing and application of printable electronic sensor platforms and energy & power systems (image at bottom right)
- Development of new materials/feedstocks, including in-situ regolith materials, to support on-demand in-space and lunar/planetary surface manufacturing

## ➤ Exploration & Science Impact

- Enables sustainable, affordable Exploration Mission operations
- Addresses significant logistics challenges for long-duration missions
- Enables fabrication of components via utilization of lunar/planetary resources
- Addresses energy storage and power generation needs for exploration demands

FabLab print volume prototype in an EXPRESS rack mockup (Techshot, Inc.)



Flexible Wearable Crew Health Sensor Device



# ISM Mission Infusion & Partnerships

- SBIRs (38 since 2013 with 3 ISS Demonstrations)
- Future Engineers SAA with ASME ( 6 national STEM Challenges since 2014)
- National Space Grant Foundation (6 X-Hab Challenges since 2014)
- NASA Tournament Labs (GrabCAD, Yet2, Freelancer Crowdsourcing)
- NextSTEP BAA (FabLab & Hab UTAS Collaboration)
- IDIQ (MIS ISS AMF Operations)
- STMD Tipping Point (MIS Archinaut)
- Multiple Cooperative Agreement Notices (CANs)
- Student Internships, Tech Fellows, and Visiting Professors
- NASA @ Work Challenges
- MSFC TIP/CIF Investments

# ISM Mission Infusion & Partnerships



ISM is collaborating with cross-cutting DoD sectors to initiate a virtual collaboration platform for government, industry, and academic stakeholders relative to technology development, digital design databases, materials, verification processes, etc. ISM team members are active in/with:

- Team Redstone Additive Manufacturing Integrated Product Team (AMRDEC, SMDC, NASA)
- DARPA: Technology development
- Oak Ridge National Labs: Collaboration with technology, process, and skill development
- Picatinny Arsenal: Printable electronics, materials, and processes
- Aviation and Missile Research, Development and Engineering Center (AMRDEC): Share capabilities and interests in advanced materials manufacturing
- Air Force Research Labs, Wright-Patterson Air Force Base: Dielectric inks and antennas
- NextFlex: Printable Electronics Consortium funded by the Office for the Secretary of Defense
- America Makes: ISM team member is on the Board with regular involvement in relative activities



# ISM Mission Infusion & Partnerships



## ➤ Contributing partners and/or stakeholders

- HEOMD AES
- HEOMD ISS
- SBIR Program



## ➤ Infusion/transition plan

- ISS technical demonstrations – completed and more are planned
- ISS repair and maintenance – potential
- Lunar Gateway – potential
- Lunar habitat – potential
- Mars habitat - potential



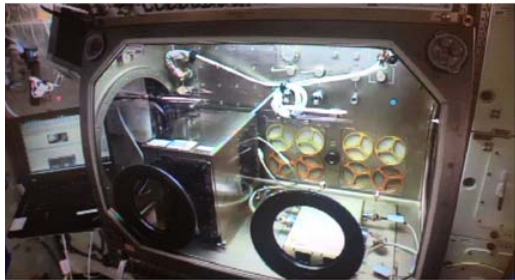
# ISM Technology Goals & Project Objectives



## Technology Goals

Goal #1	Manufacturing Technology & Material Development: Work with industry and academia to develop on-demand manufacturing and repair technologies.
Goal #2	Recycling & Reuse Technology/Material Development: Work with industry and academia to develop recycling & reuse capabilities to increase mission sustainability.
Goal #3	Multi-Material Fabrication Development: Utilization of NASA Engineering Resources in combination with NIST, academia, and industry to develop next-generation sensor technologies, and energy & power utilization for future missions.

### Goal #1



3D Printing In Zero-G (Made In Space) in MSG

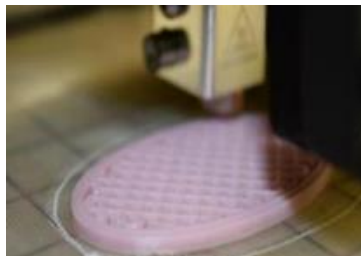


Student-Designed Tool (Future Engineers)

### Goal #2



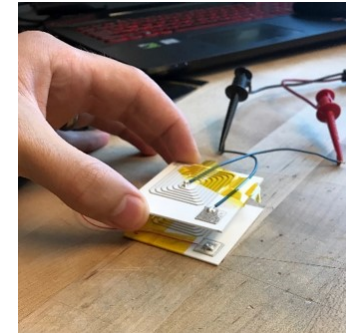
Refabricator (Tethers Unlimited)



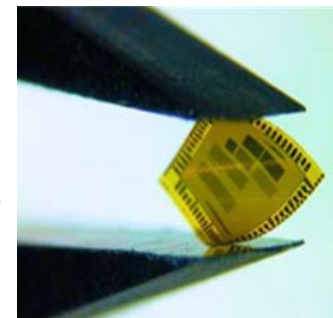
Recycled Anti-Static Bags  
Image courtesy of (Cornerstone Research Group)



### Goal #3



Printed Wireless Humidity Sensor (In-House Work)



Flexible Electronics  
Image courtesy of (American Semiconductor, Inc.)

# ISM Technology Goals & Project Objectives



## Project Objectives

<p>Objective #1 New Technology Goal</p>	<ul style="list-style-type: none"><li>• Develop the Multi-Material FabLab as the First-Generation Exploration System for on-demand manufacturing of metallic parts (and embedded electronics in future iterations)</li><li>• Support operations for the two polymer printers currently on the ISS (3DP Tech Demo &amp; AMF) and infuse lessons-learned into future design.</li><li>• Provide SME and management support for the STMD TDM Archinaut One Tipping Point for External ISM.</li></ul>
<p>Objective #2 Recycle/Reuse Goal</p>	<ul style="list-style-type: none"><li>• Refabricator (integrated 3D Printer/Recycler) Tech Demo currently on ISS.</li><li>• Food &amp; Medical Grade Polymer Recycling &amp; Fabrication – Incorporates lessons learned from the Refabricator to develop the 1<sup>st</sup> Generation Exploration System.</li><li>• Development of Recycling &amp; Common Use Materials for feedstock.</li></ul>
<p>Objective #3 Multi-Material Fabrication with Printed Electronics Goal</p>	<ul style="list-style-type: none"><li>• Develop a wearable, flexible sensor device for Astronaut Crew Health Monitoring, utilizing new printed environmental and biosensing technologies.</li><li>• Develop new energy storage &amp; power generation technologies for supercapacitors, power harvesting, and recycling of distributed energy systems inefficiencies.</li><li>• Develop new materials preparation techniques and laser sintering technology in support of FabLab to realize in-situ 3D printing of metals, electronics, and composite materials.</li></ul>

# ISM Technical Approach

## ➤ Manufacturing Technology & Material Development

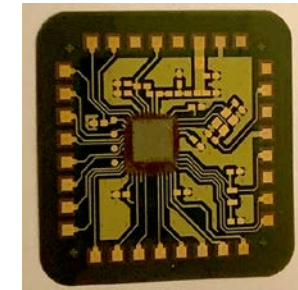
- Two polymer printers are currently on the ISS (3DP Tech Demo & AMF)
- Multi-Material FabLab – On-demand manufacturing of Metallic Parts (and Embedded Electronics in future enhancements)
- Supporting STMD TDM Archinaut One Tipping Point for External ISM

## ➤ Recycling & Reuse Technology/Material Development

- Refabricator (Integrated 3D Printer/Recycler) Tech Demo currently on ISS
- Food & Medical Grade Polymer Recycling & Fabrication – Incorporates lessons-learned from the Refabricator to develop the 1st Gen. Exploration System
- Recycling & Common Use Materials Development

## ➤ Multi-Material Fabrication with Printed Electronics

- Development of wide array of printable sensors for multiple applications, including Crew Health and Structural Health Monitoring
- Developing a next-generation wearable flexible multi-sensor AstroSense device for astronaut crew health monitoring - completed and tested version 1 flexible device in FY19
- Developing many projects in Energy Storage & Power Generations for ground-based applications, ISS, habitats, and future missions





# ISM Technical Status



## FY19 FabLab Phase A technical accomplishments/status/issues

### Techshot, Inc.

- Bound metal deposition (BMD) additive manufacturing
  - Post-processing furnace
  - Subtractive manufacturing subsystem
  - In-situ inspection system developed for verification
- Conducted successful PDR on 18-20 June 2019
- Delivered material test specimens, material characterization report, and design details on 16 August 2019
- Delivery of prototype furnace delayed, will result in delay of challenge build parts (5) delivery to NASA – no-cost extension likely



Prototype Techshot FabLab Printer, left (image courtesy of Techshot)

Photo of material test specimens, below.



# ISM Technical Status



## FY19 FabLab Phase A technical accomplishments/status/issues

### Tethers Unlimited, Inc. (TUI)

- Robotic arm with inspection system
- Conducted PDR on 14-15 August 2019 – less than successful
  - Details in design/analysis lacking
- Delta-PDR requested prior to 27 October 2019
  - Projected date 10 October 2019

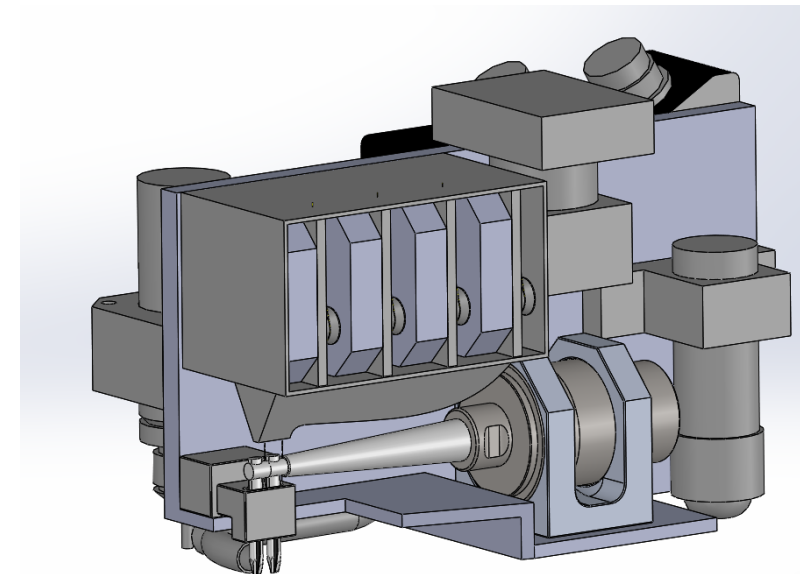


Model courtesy of TUI

## FY19 FabLab Phase A technical accomplishments/status/issues

### Interlog Corp.

- Ultrasonic bonding additive manufacturing
  - Subtractive manufacturing subsystem
- Bonding development proved unsuccessful for structural aluminum alloys
- Contractor and NASA agreed to descope
- Close-out review conducted 27 August 2019
- Contract ends 30 September 2019



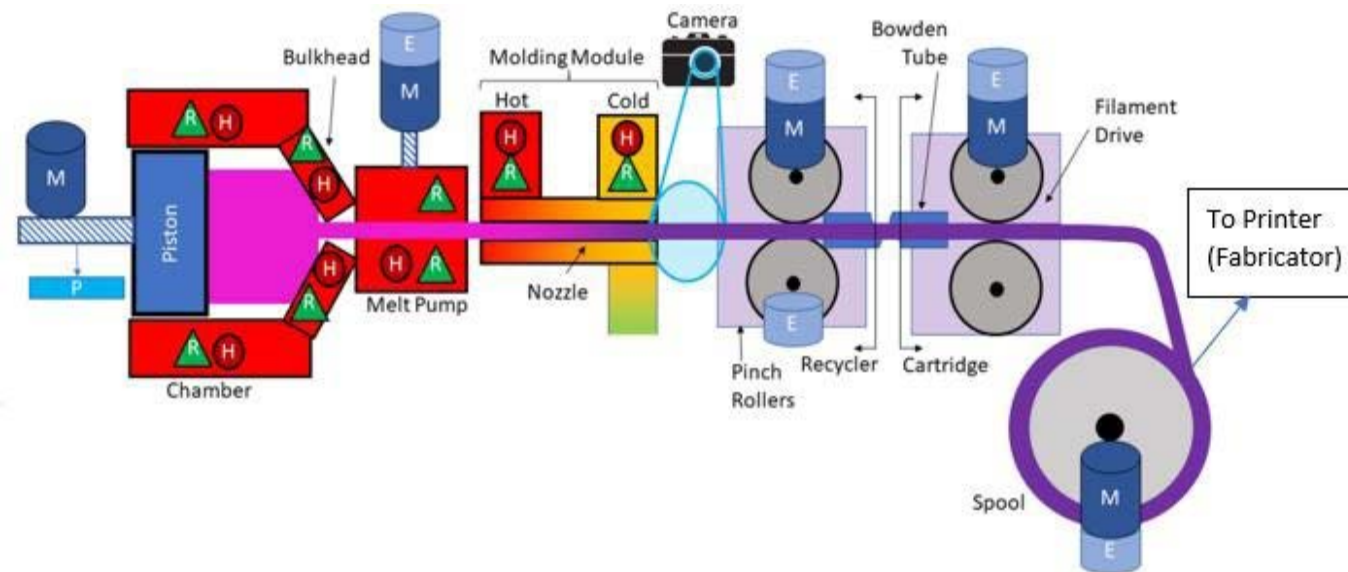
Model courtesy of Interlog

# ISM Technical Status



## FY19 Refabricator technical accomplishments/status/issues

- Anomalous operation, likely filament break previously reported at Mid-Year Review
- Attempt to recover recycler operations was unsuccessful
- Refabricator repurposed for in-space printing using filament that was recycled on ground before launch
- Upon return, system will be evaluated, repaired, and prepared for re-flight



Block diagram of Refabricator courtesy of Tethers Unlimited, Inc.

# ISM Technical Status

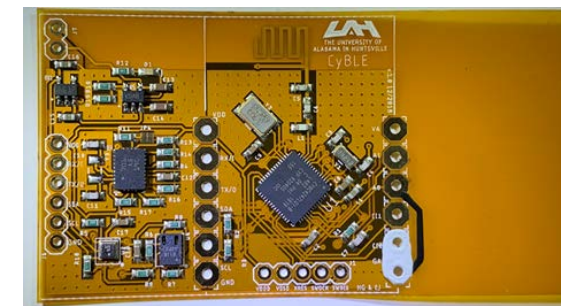


## FY19 MMF-PE technical accomplishments/status/issues

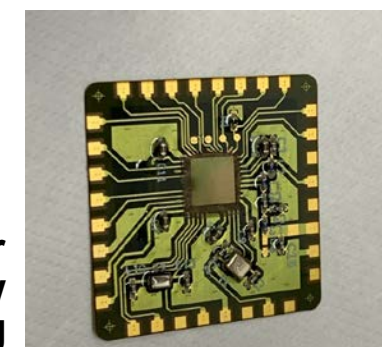
- Delivered the ECLSS/United Technologies Corporation Aerospace Systems (UTAS) Air Revitalization System (ARS) Wired Pressure/Temperature Sensor to UTAS
- Completed development, fabrication, and extensive functional testing of Cypress BLE-based flexible wireless boards for Crew Health Monitoring
- Completed development of a directly-mounted Nordic BLE “interposer” board for wireless sensing for Crew Health
- Presentations and discussions with Flight Surgeons and Medical Avionics groups at JSC for input into new sensor types and functionality for next-generation AstroSense wearable device



**ECLSS Composite Temperature sensor**



**Cypress BLE Flexible Sensor Platform with Printed Temperature and Respiration Sensors**



**Chip-mounted Interposer wireless BLE board for Crew Health Monitoring**



**Printed cortisol sensor**

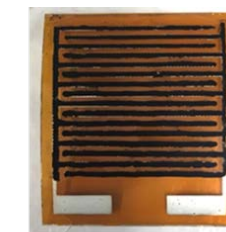
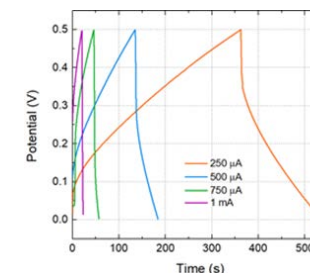
# ISM Technical Status



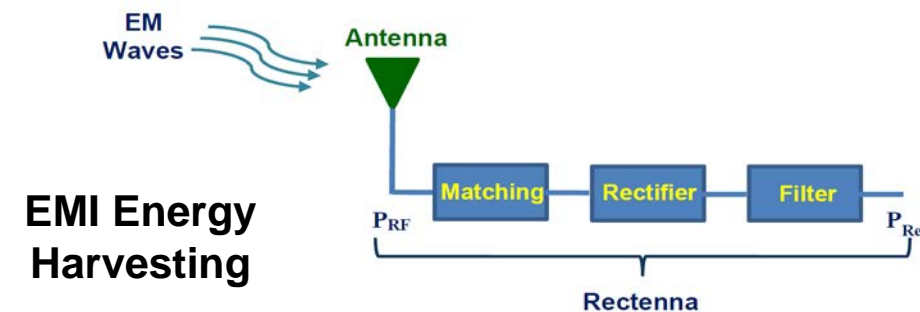
## FY19 MMF-PE technical accomplishments/status/issues

- Completed two Cooperative Agreement Notice (CAN) projects on Energy Storage with UAH & Auburn on development of high-performance supercapacitors (several commercial companies have commercial evaluation licenses on these technologies)
- Developed a fully-printed supercapacitor at ARC with MSFC-developed inks. New printed supercapacitor technology development in process via CAN collaborations at Auburn Univ. and Georgia Tech.
- New projects started in Power Harvesting include:
  - Electromagnetic energy harvesting from flexible printed antenna array
  - Development of new ceramic material for habitat thermoelectric generator

SPS Supercapacitor



ARC Supercapacitor with MSFC inks



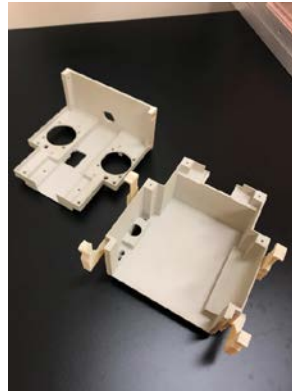
# ISM Technical Status



## FY19 MMF-PE technical accomplishments/status/issues

- Support accomplishments for JSC RFID-Enabled Autonomous Logistics Management (REALM)
  - Shipped five sets of flight RFID enclosure housings and parts to JSC REALM
  - Delivered flexible printed microstrips for resolution of EVA antenna connection issue
  - New RFID Q-wave antenna being 3D printed by ISM MMF
- ISM MMF is collaborating with REALM RFID to develop RFID wireless sensing for Crew Health and Environmental Monitoring on ISS. REALM group has delivered a wireless sensing develop kit to MSFC for 3D-printed sensor and software development.
- Delivered first set of ISM-developed composite pyroelectric sensor material samples for extended radiation exposure testing on the MISSE-11 test bed. A second set of composite sensor material samples will be tested on the MISSE-13. An array of commercial & ISM-developed conductive inks will be tested on METIS flight.

REALM housings



RFID wireless sensing development kit



Composite sensor & conductive materials for radiation testing

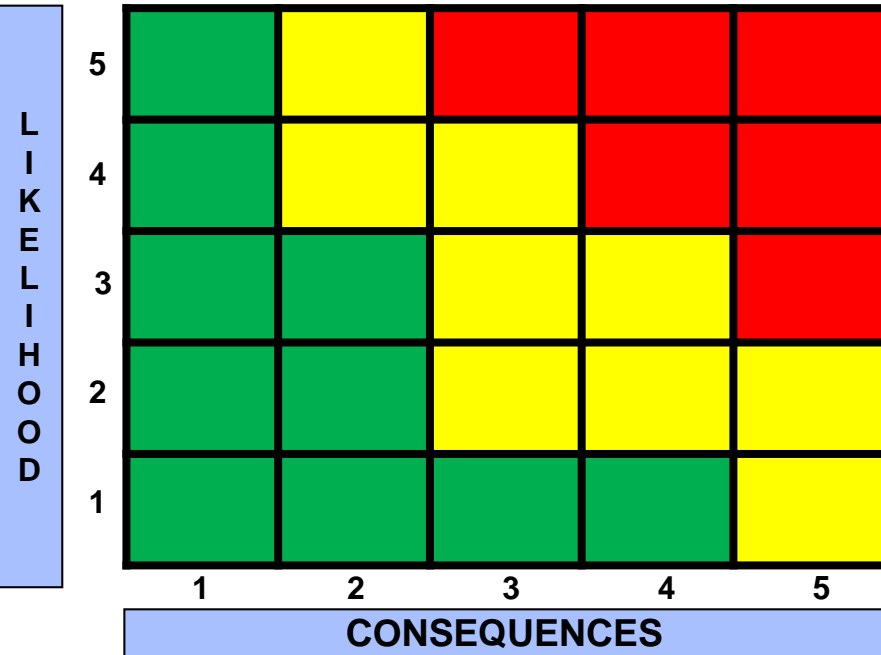
# ISM Technical Status



SBIR Company	Title	Award
Actuated Medical	AM of PEEK and Fiber-Reinforced PEEK for NASA Applications and Custom Medical Devices	Phase II
GeoComposites	Development of Fiber Reinforced Composite Feedstock for ISM of High Strength Parts	Phase II
Cornerstone Research Group	Automated In-Process Quality Control of Recycled Filament Production and FDM Printers	Phase II
Space Foundry	Plasma Jet Printing for ISM & ISRU	Phase II
UltraTech	ISS Multi-Material Fabrication Laboratory using Ultrasonic Additive Manufacturing (UAM) Technology	Phase II
Made In Space	Vulcan Advanced Hybrid Manufacturing System	Phase II
Tethers Unlimited	Metal Advanced Manufacturing Bot-Assisted Assembly (MAMBA)	Phase II
Techshot	Sintered Inductive Metal Printer with Laser Exposure (SIMPLE)	Phase II-E
Tethers Unlimited	ERASMUS Food Contact Safe Plastics Recycler and 3D Printer	Phase II
Tethers Unlimited	Customizable, Recyclable ISS Packaging (CRISSP)	Phase II-E
Cornerstone Research Group	Reversible Copolymer Materials for FDM 3D Printing of Non-Standard Plastics	Phase II-E
Tethers Unlimited	ISS Refabricator Technology Demonstration	Phase III
Made In Space	Additive Manufacturing Facility (AMF)	IDIQ



# ISM Technical Risk Summary



Risk ID	Description/Status	Trend
ID#		

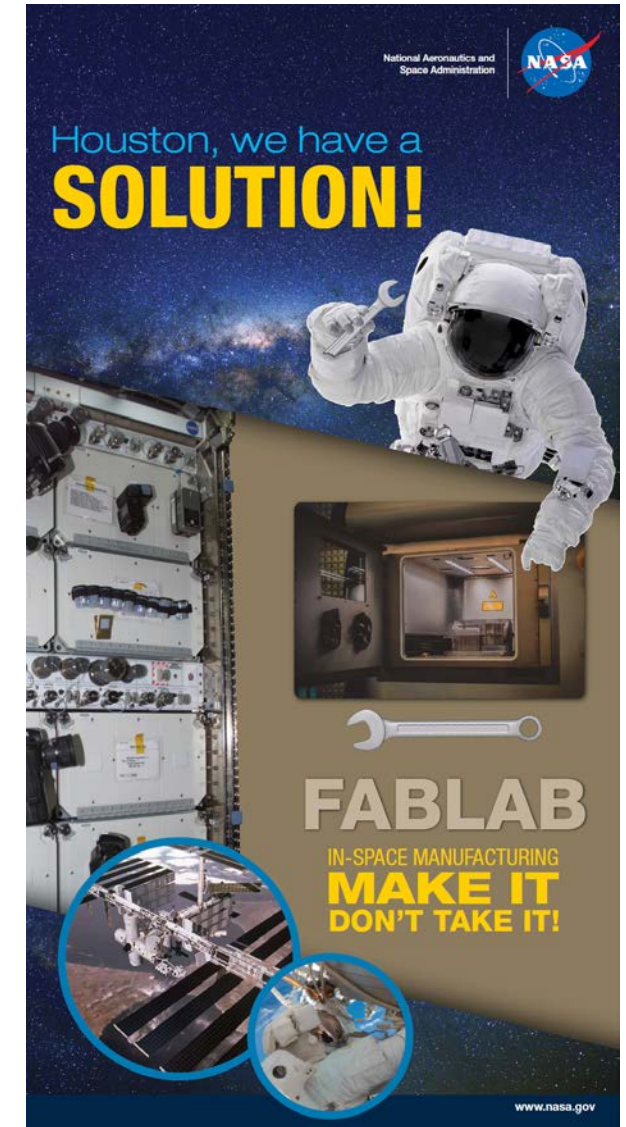
No Project-Level Risks

<b>Criticality</b>	<b>L x C Trend</b>	<b>Approach</b>
High	↓ Decreasing (Improving)	M - Mitigate
Med	↑ Increasing (Worsening)	W - Watch
Low	→ Unchanged	A - Accept
	□ New Since Last Period	R - Research

# ISM EPO Summary Chart



- Summary of Education and Public Outreach
  - Stats: 3 patents, 6 conference papers, 8 journal publications, and 28 presentations
  - 3 summer interns, 1 NASA Space Technology Research Fellow
  - Website <https://www.nasa.gov/oem>
- Significant Media Coverage
  - 25 Media Articles (Refabricator, X-Hab)
    - Sources: GeekWire, NASA.gov, YouTube, CNN, Washington Post, Spaceflight Now, Space.com, Quartz.com, 21<sup>st</sup> Century Tech, Raycom New Network, Marshall Star, The Boss Magazine, 3D Printing.com, Astronomy Magazine, 3D Printing Industry, SpaceDaily.com, 3D Printing Media Network, 3ders.org, Digital Trends, and Newswise



# ISM Annual Summary



- **FabLab**
  - Successful PDR 18-20 June 2019 and materials delivery 16 August 2019 for Techshot
  - Draft final report received from Interlog; closeout report due 30 September 2019
  - Delta PDR for Tethers Unlimited planned for 10 October 2019
- **Refabricator**
  - Unsuccessful recycling of filament on-orbit - repurposed to test pre-flight recycled filament printing and filament bonding technology and now awaiting crew time
- **Multi-Material Fabrication with Printed Electronics**
  - Successful completion of prototype flexible Crew Health wireless sensor board
  - Completed multiple collaboration projects with academia on Energy & Power development of supercapacitor technology
  - Delivered new design AES REALM RFID enclosures and microstrips to resolve technical issues. Collaborating on new RFID antenna design/fabrication and new RFID wireless communications development kit.
- **SBIR**
  - 12 in progress (8 continuing, 4 recent awards), 1 IDIQ, leverages ~\$7.4M of SBIR funds



# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
October 2018	<i>ACS Sensors, Vol. 3, Issue 9, pp. 1782-1788</i>	A Single Input Multiple Output (SIMO) Variation-Tolerant Nanosensor	Dr. Meyya Meyyapan and ISM ARC Printable Electronics Team
October 2018	AIAA Next Gen Technical Symposium, Huntsville, AL	ISM at NASA MSFC: A Portfolio of Fabrication and Recycling Technology Development for the ISS	Dr. Tracie Prater
Oct. 2018 through March 2019	FIRST LEGO League	Participated in videoconferences with teams from VA, KY, NY, and FL to answer students' questions regarding Refabricator ISS Technology Demonstration	Dr. Tracie Prater (ISM Technical Integration Mgr.); Diane Risdon (Refabricator Task Lead)
October 2018	World Space Week	Participated in a ISM Classroom chat (virtual) for middle and high school students	Dr. Tracie Prater
November 2018	N/A	Participated in a virtual panel discussion on careers at NASA with Georgia Institute of Technology's School of Engineering	Dr. Tracie Prater

# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
November 2018	TMS Annual Meeting in Phoenix, AZ	Co-authored presentation of Laser sintering of Al nanoparticles for Al-air battery	Curtis Hill and University of Tennessee/Oak Ridge National Labs
December 2018	WiSEE2018, Passive Wireless Sensor Technology Workshop (PWST), Huntsville, AL	Moderated the Aerospace & Remote Sensing Session; presented In-Space Manufacturing	Curtis Hill (ISM Materials SME)
December 2018	WiSEE2018, Passive Wireless Sensor Technology Workshop (PWST), Huntsville, AL	Presented Overview of In-Space Manufacturing	Dr. Tracie Prater
December 2018	WiSEE2018, Passive Wireless Sensor Technology Workshop (PWST), Huntsville, AL	Monitoring of Respiration by Means of an Additively Manufactured Barium Titanate-based Hygroscopic Sensor	Ian Small, Dr. Terry Rolin, and Dr. Emil Jovanov
February 2019	Heterogeneous Integration Roadmap Annual Symposium, Milpitas, CA	Invited talk on Emerging Research Devices	Dr. Meyya Meyyapan

# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
March 2019	“Human Library” Career Day at Randolph School, Huntsville, AL	Presented careers at NASA	Dr. Tracie Prater
March 2019	Alabama Public Television’s “Mission Control” Digital Shorts Campaign	<a href="#">Interview with a student reporter on In-Space Manufacturing, including 3D Printing and the Refabricator. Will be streamed live from the U.S. Space &amp; Rocket Center on SPACE DAY, 5/3/19 (Link: Facebook)</a>	Niki Werkheiser (ISM Project Manger)
March 2019	“STEM for Kids” event at the Nashville Public Library	Speaker at the event	Dr. Tracie Prater
March 2019	50 <sup>th</sup> Anniversary of the Apollo landing on the Moon, Huntsville Public Library	Panel moderator on future space exploration	Niki Werkheiser
March 2019	Tour of Multi-Material Fabrication with Printed Electronics labs at MSFC	Provided a tour for a professor from the University of Alabama, followed with a discussion of the potential uses for functional fabrics in sensor development.	Curtis Hill

# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
March 2019	Materials Development, Energy Storage and Sensor Research Seminar at Auburn University	Held a seminar on In Space Manufacturing Flexible Sensing Technology with the Material Science and Mechanical Engineering Departments	Curtis Hill
March 2019	Science, Technology, and Engineering Jamboree at MSFC	Presented posters featuring ISM, Multi-Material Fabrication with Printed Electronics, STMD TDM IRMA MIS Archinaut	ISM Team
April 2019	Printed Electronics: Equipment, Processing and Applications, Workshop, Seattle, WA	Keynote talk on FHE Applications for Aerospace	Dr. Meyya Meyyapan
April 2019	SPIE Defense + Commercial Sensing Expo, Baltimore, MD	Keynote talk on Nano-enabled Devices and Sensors for Space Exploration	Dr. Meyya Meyyapan
April 2019	2019 Wearables Technologies Workshop at JSC Technology Innovation Center	Presentation on In-Space Manufacturing Flexible Sensors Development	Curtis Hill



# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
May 2019	San Jose State University, Graduate Research & Senior Project Day, Department of Chemical and Material Engineering	Presentation on Printed and Flexible Device Technology	Dr. Meyya Meyyapan
May 2019	JSC Wearables, Medical/Flight Surgeons, and Avionics Groups	Presentation on An Overview of In-Space Manufacturing Sensor Platform Development	Curtis Hill
May 2019	The Center for Nanophase Materials Sciences (CNMS) at Oak Ridge National Laboratory Workshop	Co-authored poster on Printed flexible silver sensors with electro-deposited TiO <sub>2</sub> nanowires for room temperature CO <sub>2</sub> gas sensing	Curtis Hill and University of Tennessee/Oak Ridge National Labs
June 2019	Sensors Expo 2019, San Jose, CA	Keynote talk on Printed Electronics: Equipment, Processing and Application Development	Dr. Meyya Meyyapan
June 2019	Washington State University, Pullman, WA	Carbon nanomaterials for biosensing applications	Dr. Jessica Koehne

# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
June 2019	IEEE Santa Clara Valley-San Francisco Chapter of Electron Device Society, Santa Clara, CA	Presentation on Printed Electronics for In-Space Manufacturing	Dr. Jinwoo Han
June 2019	University of California, San Diego, Department of Electrical Engineering	Introduction of NASA In-Space Manufacturing Program	Dr. Jinwoo Han
June 2019	National Space and Missile Material Symposium (NSMMS) in Las Vegas, NV	Presentation on 3D printing and laser curing of Al/ $\alpha$ -Fe <sub>2</sub> O <sub>3</sub> nanothermites for gas and strain sensing	Curtis Hill
June 2019	National Space and Missile Material Symposium (NSMMS) in Las Vegas, NV	Poster presentation on Using defects to create ceramics with giant permittivity as ultracapacitors	Curtis Hill and Auburn University Dr. ZY Cheng
June 2019	Team Redstone IPT Meeting, Huntsville, AL	MSFC Strategic Goals for Printed Electronics	Ian Small & Furman Thompson

# ISM EPO Summary Chart



## ➤ FY19 Conferences & Presentations cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
June 2019	National Space and Missile Material Symposium (NSMMS) in Las Vegas, NV	Poster presentation on Printed flexible silver sensors with electro-deposited TiO <sub>2</sub> nanowires for room temperature CO <sub>2</sub> gas sensing	Curtis Hill and University of Tennessee Dr. Anming Hu
June 2019	Meeting with ISM ARC Research Team	Presented an Overview of In-Space Manufacturing Sensor Platform Development	Curtis Hill
July 2019	JSC Wearables, Flight Surgeons, and Soft Goods (EVA Suit) Groups	Presentation on ISM Flexible Sensor Development and Biosensor Development	Curtis Hill and Dr. Jessica Koehne
August 2019	Redstone IPT	Overview of In-Space Manufacturing	Dr. Tracie Prater
September 2019	OSAM Industry Day	Overview of In-Space Manufacturing	Larry Huebner

# ISM EPO Summary Chart



## ➤ FY19 Publications

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
October 2018	<i>ACS Sensors, Vol. 3, Issue 9, pp. 1782-1788</i>	A Single Input Multiple Output (SIMO) Variation-Tolerant Nanosensor	Dr. Meyya Meyyapan and ISM ARC Printable Electronics Team
October 2018	Engineered Science 2018, 4, p52-64	Electrophoretic deposition and thermo-chemical properties of Al/Fe <sub>2</sub> O <sub>3</sub> nanothermite thick films	Curtis Hill & University of Tennessee researchers
November 2018	Journal of The Electrochemical Society. 2018;165(3):A584-A92.	Laser sintering of printed anodes for Aluminum-air batteries	Curtis Hill & University of Tennessee and Oak Ridge National Lab researchers
November 2018	Materials, 1, 46-51	High permittivity behavior and microstructure in a two-phase barium-silicon titanate	Curtis Hill, Dennis Tucker, and Auburn University researchers
January 2019	Journal of Laser Applications, 30(3), p.032605.	Laser sintering of printed anodes for Aluminum-air batteries	Curtis Hill & University of Tennessee and Oak Ridge National Lab researchers

# ISM EPO Summary Chart



## ➤ FY19 Publications cont.

Date	Technical Forum/Publication	Paper/Abstract Title	Presenter(s)/Author(s)
February 2019	Manufacturing Science and Engineering Conference Proceeding	Fabrication and Performance of NiCuCoFeMn High Entropy Alloy Nanopastes for Brazing Inconel 718,	Curtis Hill & University of Tennessee researchers
May 2019	Chemosphere, 230, pp.527-535.	Additively Manufactured Barium Titanate-based Hygroscopic Sensor	Curtis Hill & University of Tennessee and Oak Ridge National Lab researchers
March 2019	IET Nanodielectrics, 2(1), 41-47	Microstructure and enhanced dielectric properties of BaTiO <sub>3</sub> -SiO <sub>2</sub> nanocomposites using hydrogen treated nanoparticles	Curtis Hill and Auburn University researchers
July 2019	AZO Materials, 7/19	Using Micromilling to Develop Optimized Ceramic Nanoparticulate Materials	Curtis Hill & Lee Allen
Pending September 2019	Sensors and Actuators A	Printed flexible sensors functionalized with TiO <sub>2</sub> nanowires for room temperature CO <sub>2</sub> gas sensing	Curtis Hill & University of Tennessee researchers



# ISM EPO Summary Chart

## Media

Date	Project	Description	Outlet	Link
11/5/2018	Refabricator	Article: "Tethers Unlimited's 3-D printer and recycler is ready for delivery to space station"	GeekWire	<a href="https://www.geekwire.com/2018/tethers-unlimiteds-3-d-printer-recycler-set-delivery-space-station/">https://www.geekwire.com/2018/tethers-unlimiteds-3-d-printer-recycler-set-delivery-space-station/</a>
Nov-18	Refabricator	NASA Refabricator ScienceCast	NASA.gov	<a href="https://science.nasa.gov/science-news/sciencecasts/the-in-space-refabricator">https://science.nasa.gov/science-news/sciencecasts/the-in-space-refabricator</a>
Nov-18	Refabricator	NASA Official Refabricator Image Release	NASA.gov	<a href="https://www.nasa.gov/content/official-refabricator-image-release">https://www.nasa.gov/content/official-refabricator-image-release</a>
11/13/2018	Refabricator	NG-10 Press Briefing (Refabricator starts ~10:45 mins)	YouTube	<a href="https://youtu.be/teX_RKvbHyI">https://youtu.be/teX_RKvbHyI</a>
11/17/2018	Refabricator	Article: "A 3D printer with a recycling device is headed to the International Space Station"	CNN	<a href="https://www.cnn.com/2018/11/17/us/nasa-3d-printer-northrop-grumman-international-space-station/index.html">https://www.cnn.com/2018/11/17/us/nasa-3d-printer-northrop-grumman-international-space-station/index.html</a>
11/17/2018	Refabricator	Article	Washington Post	
11/17/2018	Refabricator	Article	Spaceflight Now	<a href="https://www.spaceflightnow.com/2018/11/17/nasa-3d-printer-northrop-grumman-international-space-station/">Spaceflight Now</a>
11/17/2018	Refabricator	Article	Space.com	<a href="https://www.space.com/41111-nasa-3d-printer-northrop-grumman-international-space-station/">SPACE</a>
11/17/2018	Refabricator	Article	Quartz.com	<a href="https://qz.com/1467735/international-space-station-gets-3d-printer/">https://qz.com/1467735/international-space-station-gets-3d-printer/</a>
Nov-18	Refabricator	Montevallo Elementary FIRST Lego Robotics Refabricator Skit	YouTube	<a href="https://youtu.be/u5vnx1nvkU">https://youtu.be/u5vnx1nvkU</a>
11/18/2018	Refabricator	Article	21st Century Tech	<a href="https://www.21stcentech.com/nasa-refabricator-star-trek-replicator-pretty-amazing/">https://www.21stcentech.com/nasa-refabricator-star-trek-replicator-pretty-amazing/</a>
11/19/2018	Refabricator	Article	Raycom New Network (Circulated on various news networks)	<a href="https://www.wsfa.com/2018/11/19/nasa-recycles-space-meet-refabricator/">https://www.wsfa.com/2018/11/19/nasa-recycles-space-meet-refabricator/</a>
11/21/2018	Refabricator	Article	Marshall Star	<a href="https://www.marshallstar.com/2018/11/21/nasa-3d-printer-northrop-grumman-international-space-station/">Marshall Star</a>
11/21/2018	Refabricator	Article	The Boss Magazine	<a href="https://thebossmagazine.com/the-refabricator-converts-plastic-waste-into-valuable-tools-on-the-iss/">https://thebossmagazine.com/the-refabricator-converts-plastic-waste-into-valuable-tools-on-the-iss/</a>
11/21/2018	Refabricator	Article	3D Printing.com	<a href="https://3dprinting.com/news/refabricator-3d-printer-launched-en-route-to-space-station/">https://3dprinting.com/news/refabricator-3d-printer-launched-en-route-to-space-station/</a>
12/3/2018	Refabricator	Refabricator highlighted by Marshall Center Director Jody Singer as one of the Center's major accomplishments in 2018.	Marshall Star	<a href="https://www.nasa.gov/centers/marshall/about/star/star181206.html">https://www.nasa.gov/centers/marshall/about/star/star181206.html</a>
1/30/2019	Refabricator	Refabricator featured in the Marshall Star Year-in-Review.	2018 Marshall Star Year-in-Review	<a href="https://www.nasa.gov/sites/default/files/atoms/files/2018_marshall_star_year_in_review_final.pdf">https://www.nasa.gov/sites/default/files/atoms/files/2018_marshall_star_year_in_review_final.pdf</a>
2/8/2019	Refabricator Installation	Article featuring the installation of the Refabricator on ISS.	GeekWire	<a href="https://finance.yahoo.com/news/astronauts-install-tethers-unlimited-3-180523944.html">https://finance.yahoo.com/news/astronauts-install-tethers-unlimited-3-180523944.html</a>
2/11/2019	Refabricator Installation	Article featuring the installation of the Refabricator on ISS.	Astronomy Magazine	<a href="http://www.astronomy.com/news/2019/02/the-international-space-stations-new-3-d-printer-recycles-old-plastic-into-custom-tools">http://www.astronomy.com/news/2019/02/the-international-space-stations-new-3-d-printer-recycles-old-plastic-into-custom-tools</a>
2/11/2019	Refabricator Installation	Article featuring the installation of the Refabricator on ISS.	3D Printing Industry	<a href="https://3dprintingindustry.com/news/nasa-installs-tether-refabricator-aboard-iss-for-in-space-3d-printing-148728/">https://3dprintingindustry.com/news/nasa-installs-tether-refabricator-aboard-iss-for-in-space-3d-printing-148728/</a>
2/11/2019	Refabricator Installation	Article featuring the installation of the Refabricator on ISS.	SpaceDaily.com	<a href="http://www.spacedaily.com/reports/Refabricator_to_recycle_reuse_plastic_installed_on_Space_Station_999.html">http://www.spacedaily.com/reports/Refabricator_to_recycle_reuse_plastic_installed_on_Space_Station_999.html</a>
2/12/2019	Refabricator Installation	Article featuring the installation of the Refabricator on ISS.	3D Printing Media Network	<a href="https://www.3dprintingmedia.network/nasa-refabricator-3d-printer-iss/">https://www.3dprintingmedia.network/nasa-refabricator-3d-printer-iss/</a>
2/12/2019	Refabricator Installation	Article featuring the installation of the Refabricator on ISS.	3ders.org	<a href="https://www.3ders.org/articles/20190212-nasa-installs-tethers-unlimited-refabricator-on-the-iss-that-recycles-plastic-for-3d-prints.html">https://www.3ders.org/articles/20190212-nasa-installs-tethers-unlimited-refabricator-on-the-iss-that-recycles-plastic-for-3d-prints.html</a>
2/14/2019	Refabricator Activation	Article	Digital Trends	<a href="https://www.digitaltrends.com/cool-tech/refabricator-3d-printing-recycling-iss/amp">https://www.digitaltrends.com/cool-tech/refabricator-3d-printing-recycling-iss/amp</a>
2/21/2019	2019 X-Hab	An article featuring the ISM 2019 X-Hab project with the University of South Dakota appeared in Newswise	Newswise	<a href="https://www.newswise.com/articles/senior-design-students-develop-materials-for-space-station?fbclid=IwAR1K1QAHCao-0p4fBaYt2N20mBDsDEMgb1tsRnU7HV6JLQrfwOYjkDK30BE">https://www.newswise.com/articles/senior-design-students-develop-materials-for-space-station?fbclid=IwAR1K1QAHCao-0p4fBaYt2N20mBDsDEMgb1tsRnU7HV6JLQrfwOYjkDK30BE</a>

# ISM EPO Summary Chart



## ➤ FY19 United States Patent Awards

Inventors	Technology
Curtis Hill, Terry Rolin	Dielectric Particle Processing for Ultracapacitance
Curtis Hill, Terry Rolin	Solid State Ultracapacitor
Curtis Hill, Terry Rolin, Ian Small	Energy Storage System Using Rare Earth and Hydroxyl Co-doped Ceramic in Humid Environment

# ISM Backup Photos



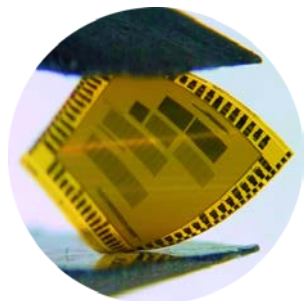
Caption: Astronaut David Saint-Jacques holding a block of Ultem 9085 plastic to be recycled using the Refabricator



Caption: Future Engineers student-designed part (first student-designed part printed in space!) in front of the commercial Additive Manufacturing Facility



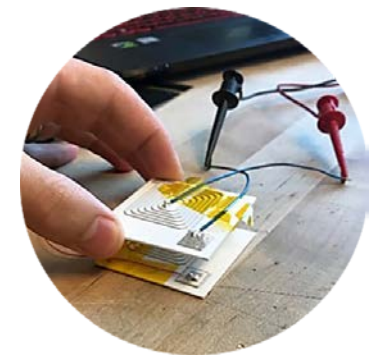
Caption: Astronaut Butch Wilmore holding a socket wrench printed using the 3D Printing In Zero-G payload (first 3D printer in space)



Caption: American Semiconductor, Inc.'s Flex-IC printed flexible complementary metal-oxide-semiconductor



Caption: Future Engineers student-designed part on the International Space Station



Caption: Wireless humidity sensor developed through the In-Space Manufacturing project