National Aeronautics and Space Administration

Overview of the In-Space Manufacturing Technology Portfolio

Redstone Integrated Product Team

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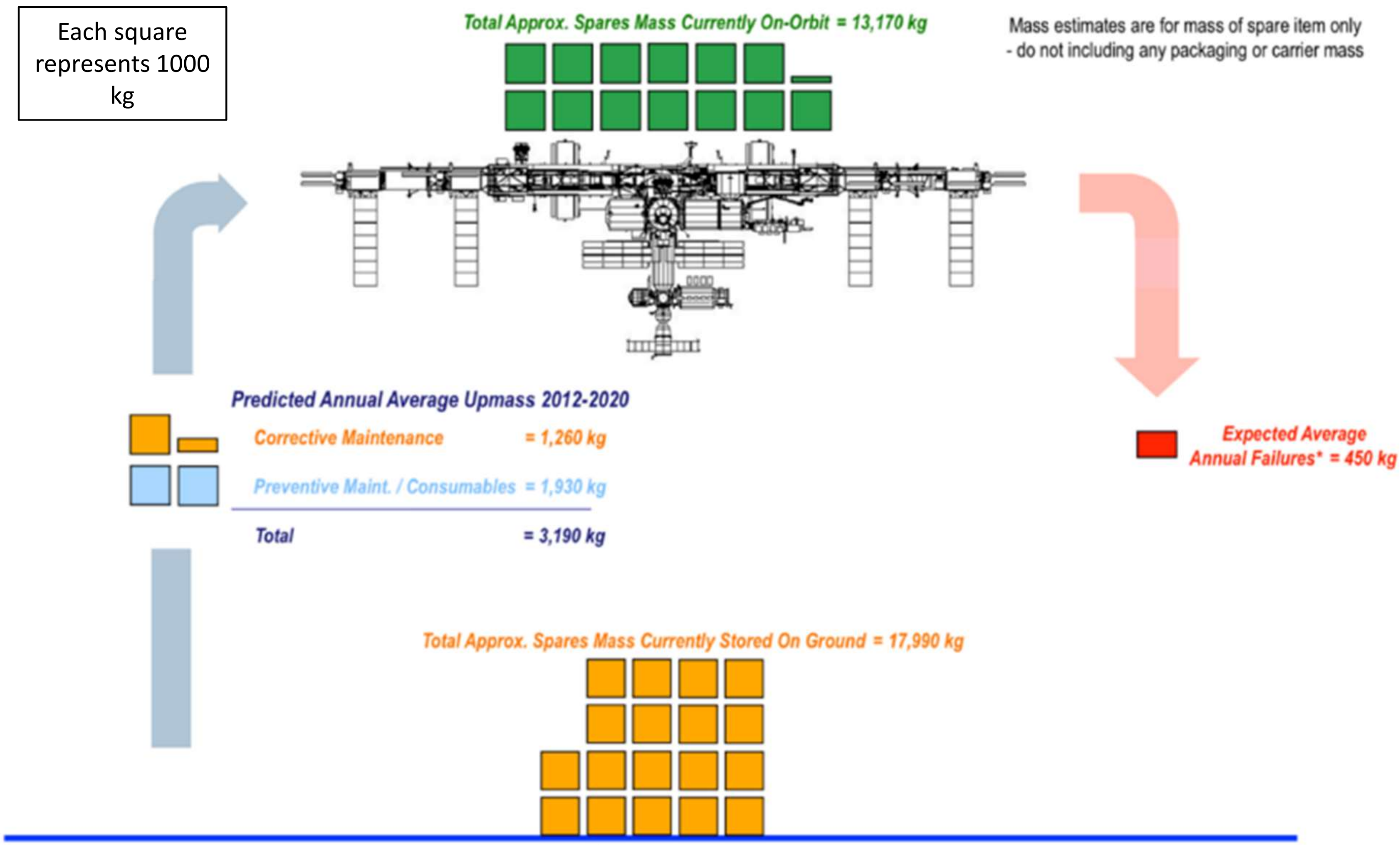
MARSHALL SPACE FLIGHT CENTER

Why manufacture in space: The logistics quandary of long endurance spaceflight



- Based on historical data, 95% of spares will never be used
- Impossible to know which spares will be needed
- Unanticipated system issues always appear, even after years of testing and operations

* - Based on predicted MTBFs

Image credit: Bill Cirillo (LaRC) and Andrew Owens (MIT)

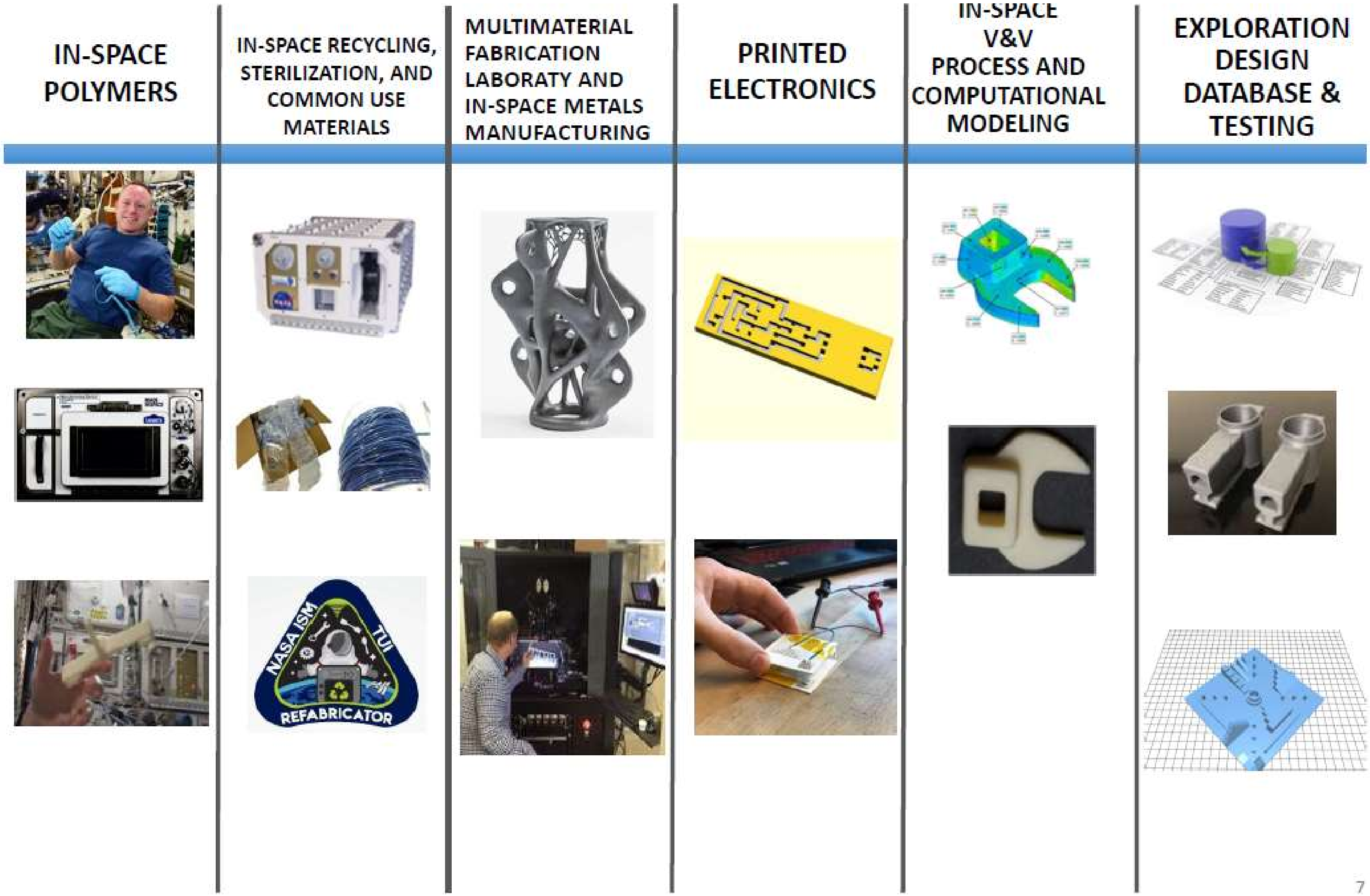
In-space manufacturing removes constraints

Constraint[1]	Constraint removed by ISM?
Structures must be designed for launch loads.	ISM enables structures which are optimized for operation in space, not for launch loads.
Structures must fit within launch vehicle payload fairings.	ISM enables structures whose size is limited only by the fabrication volume of the ISM capability.
Materials must be disposed of at the end of their lifecycle.	Materials can be recycled and used for further manufacturing.
All the spare parts and equipment needed for on-orbit servicing or repair and replacement activities must be prepositioned.	Spare parts can be made on-demand. ISM capabilities can enable on-orbit servicing and repair of equipment.
Component reliability and redundancy (R&R) largely driven by mission life/duration.	Redundancy is augmented by ISM capability to make components on demand. R&R requirements may be reduced in some instances when an ISM capability is present.

Paradigm shift

1. Table adapted from Moraguez, Matthew. "Technology Development Targets for In-Space Manufacturing." Master's thesis. MIT, 2018

In-Space Manufacturing Project Portfolio



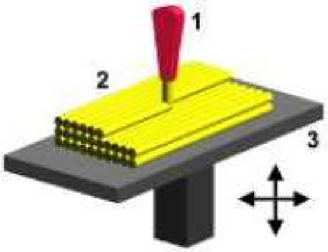
In-space manufacturing of polymers

- **ISM has been investigating use of fused filament fabrication (FFF) in microgravity since 2014.**

- **3D Printing in Zero G Technology Demonstration Mission (first printer on ISS) manufactured 55 parts of Acrylonitrile Butadiene Styrene on-orbit.**

- **ISM is a user of the Additive Manufacturing Facility, a commercial facility from Made in Space, Inc. capable of printing with multiple thermoplastics: ABS, ULTEM 9085 (PEI/PC), and High Density Polyethylene (HDPE).**
  - ISM is currently using AMF to conduct materials characterization studies of ABS using a composite testing methodology.

- **ISM also supports ground-based work on development of higher strength polymer feedstocks.**
  - To date, various high strength, high temperature fiber reinforcements have been incorporated into matrix materials of PEEK, ABS, and nylon (Onyx).



Fused filament fabrication:
1) nozzle ejecting molten plastic,
2) deposited material (modeled part),
3) controlled movable table

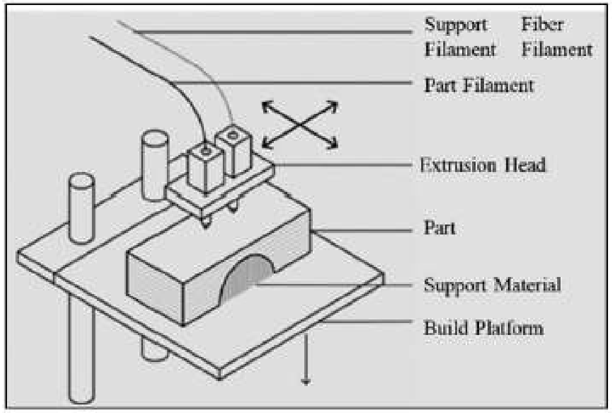
Illustration of the FFF process

3D Printing in Zero G Tech Demo payload in the microgravity science glovebox.

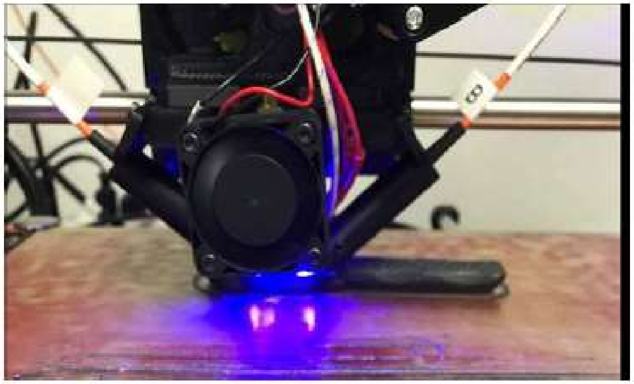
In-space manufacturing of polymers

SPHERES Tow Hitch: SPHERES consists of 3 free-flying satellites on-board ISS. Tow hitch joins two of the SPHERES satellites together during flight. Printed 2/21/17.

The Made in Space Additive Manufacturing Facility (AMF)



Dual nozzle FDM concept for combination of matrix and continuous fiber reinforcement material. Image credit: Geocomposites.



Retrofitted FFF head with laser printing PEEK wrench. Image credit: Actuated Medical, Inc.

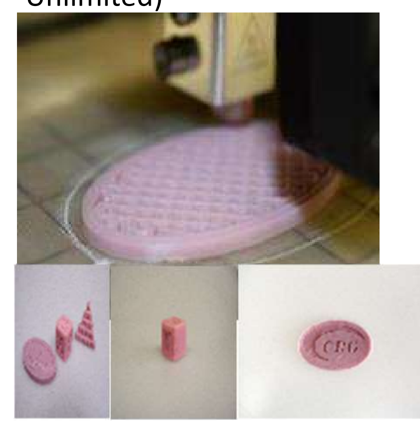
In-Space Recycling

- **Recycling is a critical piece of the puzzle to enable long duration, long endurance missions.**
- **Installed on ISS in 2019, the ReFabricator is an integrated 3D printer and recycler built by Tethers Unlimited (TUI) under a small business contract.**
    - ReFabricator extrudes blocks of ULTEM 9085 (PEI/PC) as filament feedstock for additive manufacturing through a process known as Positrusion.

Common Use Materials

- **Logistics reduction activities under ISM include the development of common use materials.**
  - Common use materials are materials for use as launch packaging that are intended to be reused and recycled.
- **Cornerstone Reseach Group (CRG) developed a thermally-reversible polymer material compatible with fused filament fabrication (FFF) systems.**
  - These materials are designed to be recycled, blended, and extruded. The RVT material can be in film or foam form.
  - Additives can also be combined with existing waste packaging, enabling reclamation of filament for additive manufacturing from packaging materials.
- **Under an SBIR phase II, TUI is working to expand recycling capabilities for ReFabricator to include PET-G, PC, ABS, RVT (material developed by Cornerstone Research Group), and ULTEM 1010 (PEI).**
  - These materials can be 3D printed as foam packaging.
  - TUI has also performed vibration testing of various foam configurations and materials under this effort.

3D printed foam packaging (image from Tethers Unlimited)



FFF prints using reclaimed anti-static bagging film with reversible cross-linking additive (image from Cornerstone Research Group)

In-Space Sterilization

- **ERASMUS from Tethers Unlimited (NASA SBIR Phase II) is a Medical-Grade and Food-Safe Plastic Recycling and Sanitization System**
- **ERASMUS will enable use of recycled materials for medical grade and food-safe applications on ISS**
  - bacteria and viruses are more virulent in space and crew immune systems tend to be compromised
  - ERASMUS provides a dry heat sterilization process and UV sanitization routine which can be integrated with 3D printing and recycling systems

Examples of biomedical components and food utensils manufactured with ERASMUS. Image courtesy of TUI.

In-Space Manufacturing of Metals

- **Several projects focus on developing metal manufacturing capabilities for in-space manufacturing and accompanying subtractive processes needed to provide a finished part**.

- **Vulcan (SBIR phase II) is a hybrid additive (wire + arc) and subtractive (5-axis CNC) system intended for use on ISS.**
  - Materials demonstrated to date include Titanium and Aluminum ER4043.
  - Has ability to print both plastic and metal as well as remove the part from the substrate (build plate).

Rendering of Vulcan as a double locker ISS payload (image credit: Made in Space).

Part produced with Vulcan prototype systems (image credit: Made in Space).

In-Space Manufacturing of Metals

- **Phase II SBIR with Ultratech Machinery**
  - Ultrasonic additive manufacturing process integrated with CNC in ground-based prototype system
  - solid-state process that occurs at room temperature uses sound waves to remove the oxide layer between adjacent layers of metal foil, creating a metallurgical bond
  - Early tests of the prototype system produced quality material in 6016 T6 and 7075 T6 and enabled material production at significantly lower power and forces
- **Phase II SBIR MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly)**
  - Consists of three technologies integrated into a double locker
    - a press that processes virgin or scrap material into a metal ingot
    - a CNC mill designed to operate in microgravity
    - a robotic assistant to facilitate automated processing of material/parts through the subsystems

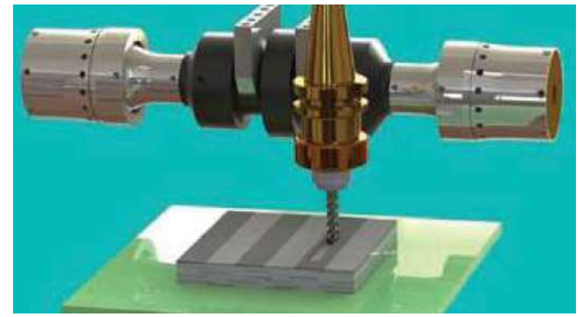
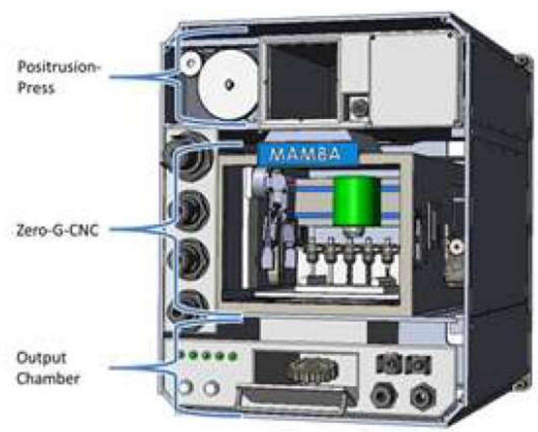


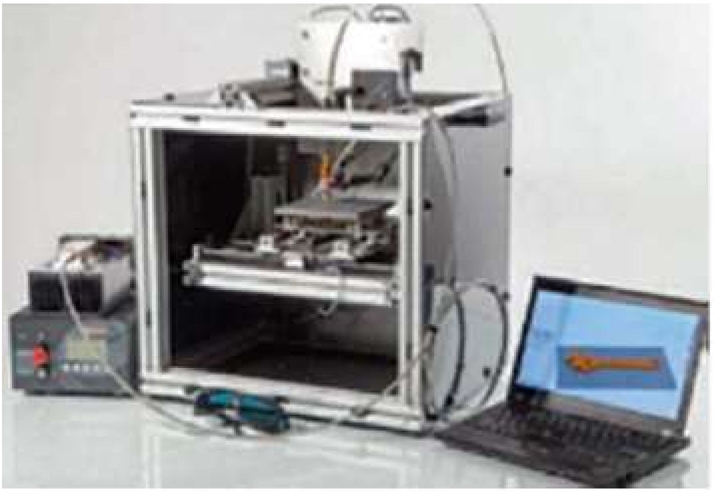
Illustration of UAM process. Image courtesy of UltraTech



Schematic of MAMBA system. Image courtesy of TUI

In-Space Manufacturing of Metals

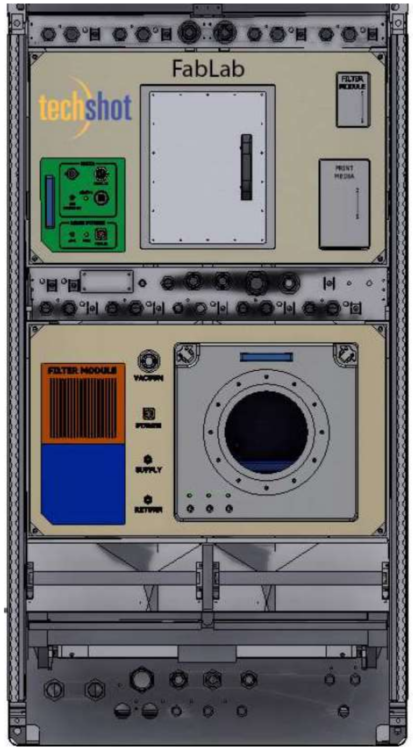
- **Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) from Techshot**
  - 3D metal printer in which a ferromagnetic wire metal filament is heated to its Curie temperature through induction
  - Metal deposited on a build platform where a low power laser completes the melt



Sintered Inductive Metal Printer with Laser Exposure (SIMPLE).
Image courtesy of Techshot.

In-Space Manufacturing of Metals

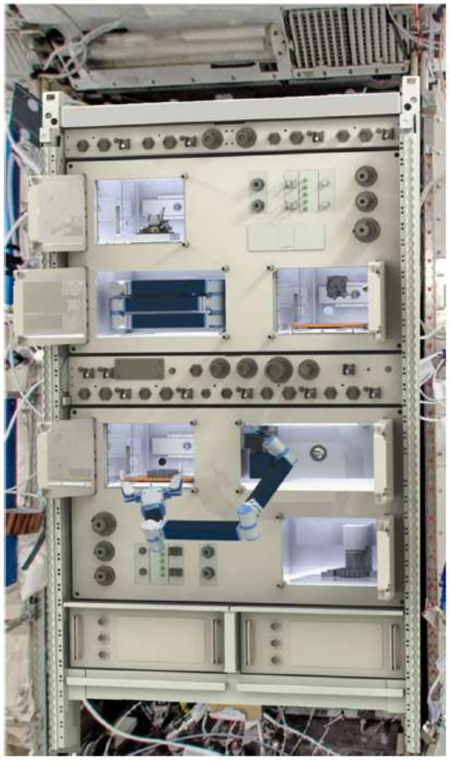
- **Ultimately, an integrated "FabLab" facility with the capability to manufacture multi-material components (including metals and electronics), as well as automation of part inspection and removal will be necessary for sustainable exploration opportunities.**
- **Phase A of the Fabrication Laboratory effort focuses on demonstration of a metal manufacturing capability that is compatible with ISS constraints**
  - 2000 W maximum power draw, 576 lb weight limit for system, 16 cubic feet of volume
  - System must fit in an EXPRESS rack and also include an inspection capability
  - Crew time requirements for part handling and processing should be minimized.
- Techshot, Inc. and Interlog, Inc. are funded under separate 18-month activities to develop a ground-based prototype integrated system for manufacturing and part inspection under phase A.
- Priority metal materials for phase A demonstration were identified by NASA as Ti-64 and AA 7075.



Techshot, Inc. Fabrication Laboratory. Image courtesy of Techshot.

Verification and Validation: Empyrean Fabrication Laboratory

- Tethers Unlimited, Inc. (TUI) Empyrean FabLab seeks to increase astronaut efficiency by providing autonomous processing and verification and validation services in a system designed for microgravity operation.
  - focus on a suite of support technologies for microgravity-enabled multi-material manufacturing, including robotic handling, quality control, autonomy, and teleoperation capabilities.



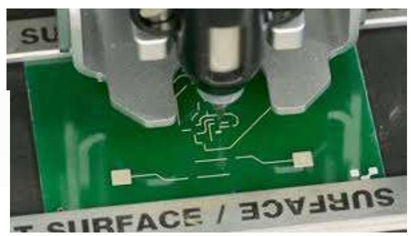
TUI Empyrean Fab Lab (image courtesy of TUI). Partners include IERUS technologies and Olis Robotics.

Printable Electronics

Evaluating technologies to enable multi-material, on-demand digital manufacturing of components for sustainable exploration missions

Material processing

nScrypt 3D Multi-Material Printer



Voltera electronics printer

nScrypt 3D multi material printer

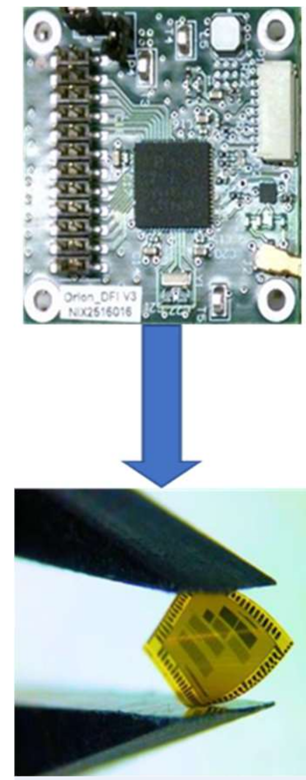
- 4-head capability:
  - SmartPump for inks
  - 2 nFD heads for filament polymers
  - Pick & place head for discrete electronic components.
  - nMill for polishing, drilling, subtractive processing
- High precision 3D deposition in a 300x300x150mm volume. Developing materials and processes leading to a multi material FabLab for International Space Station.
- Recent addition of a laser sintering capability.

Voltera Electronics Printer

- Added in 2018 for quick-turnaround prototyping of sensors and testing of inks.
- Printing resolution is good for prototyping and general electrical circuits, but not fine pitch devices or tight line spacing.

Printable Electronics

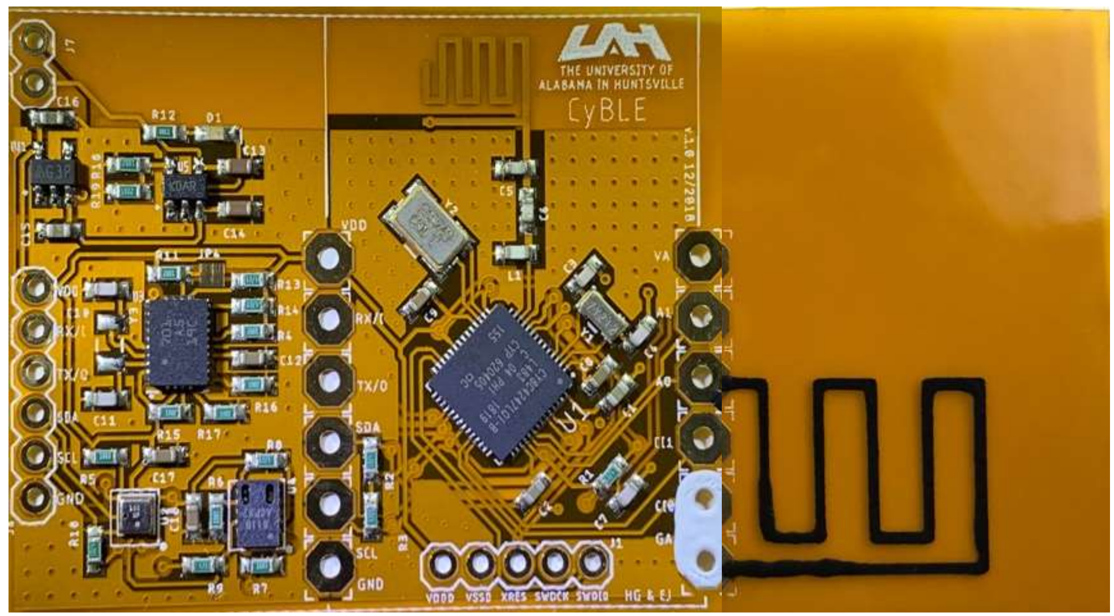
- **Development of Flexible Sensing Technology:**
  - Development of next-generation flexible sensor platforms and printed sensors for Crew Health Monitoring on International Space Station.
  - Development of materials and processes for printed sensors.
  - Evaluation and incorporation of new component technologies (flexible components, wireless communications, etc.)
- **Energy Storage Technology Development:**
  - Develop triboelectric power in order to build a self-contained sensor system.
  - Further maturation of an all-printed supercapacitor.
  - Developing very high energy density supercapacitors for battery replacement with several commercial companies.
  - Developed an Al-air battery with University of Tennessee & ORNL for scalable battery replacement applications.



Flexible Electronics Sensors

Printable Electronics

First Generation Personal CO_2 Monitor

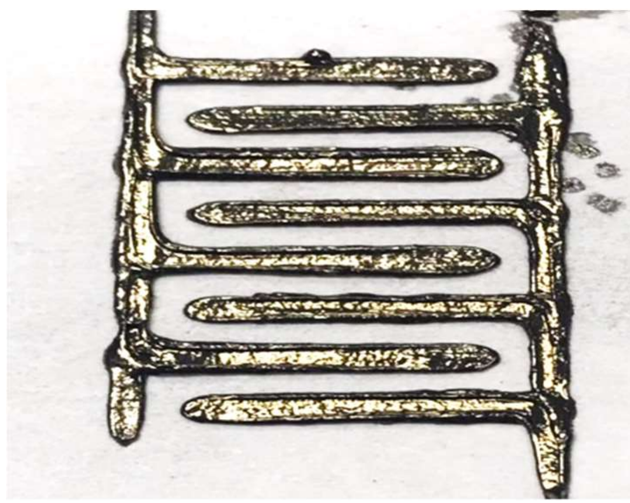


Flexible Sensor Platform with High Speed BLE Communications with printed thermistor & respiration sensors

Printable Electronics

First Generation Personal CO_2 Monitors

3D-Printed Al-Fe_3O_2 Nanothermite Sintered CO_2 Sensor



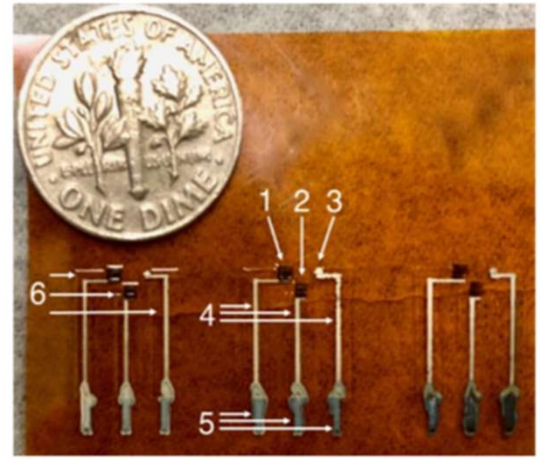
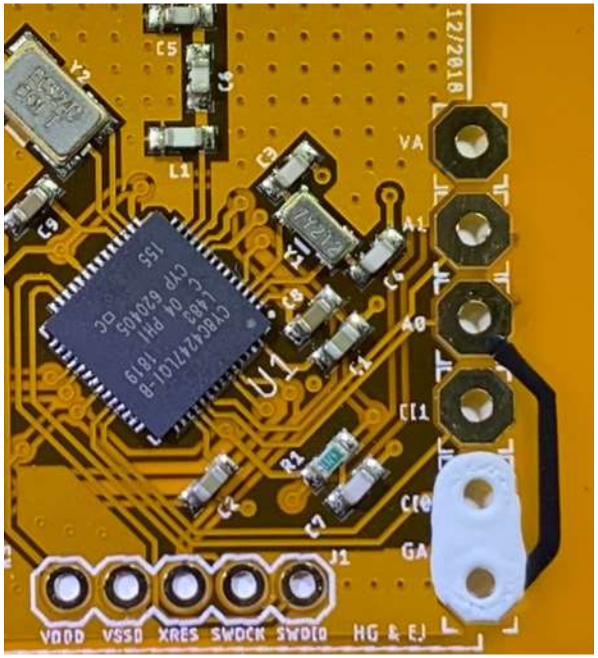
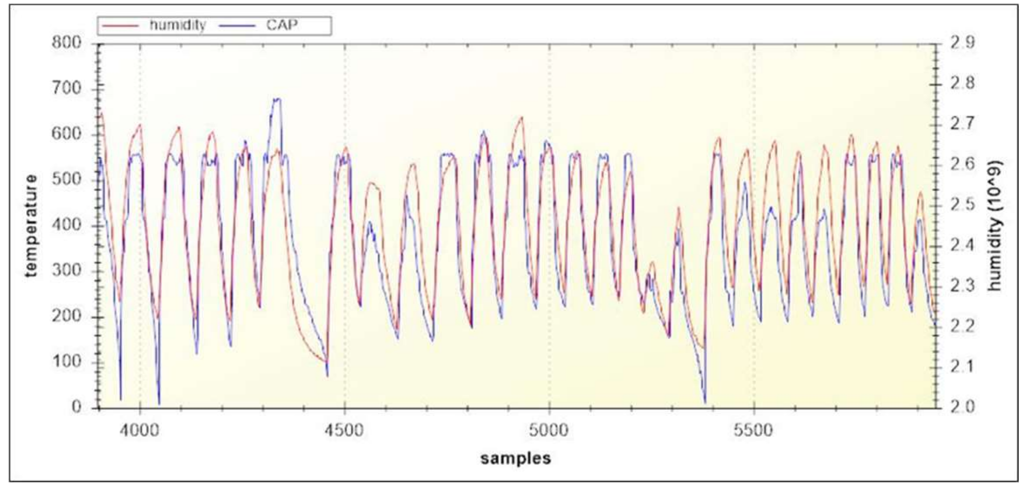


Figure 1. Printed electrochemical biosensor in polyimide substrate. 1) Counter electrode; 2) Working electrode; 3) reference electrode; 4) SU-8 layer; 5) Silver connection lead; 6) Connection pads.

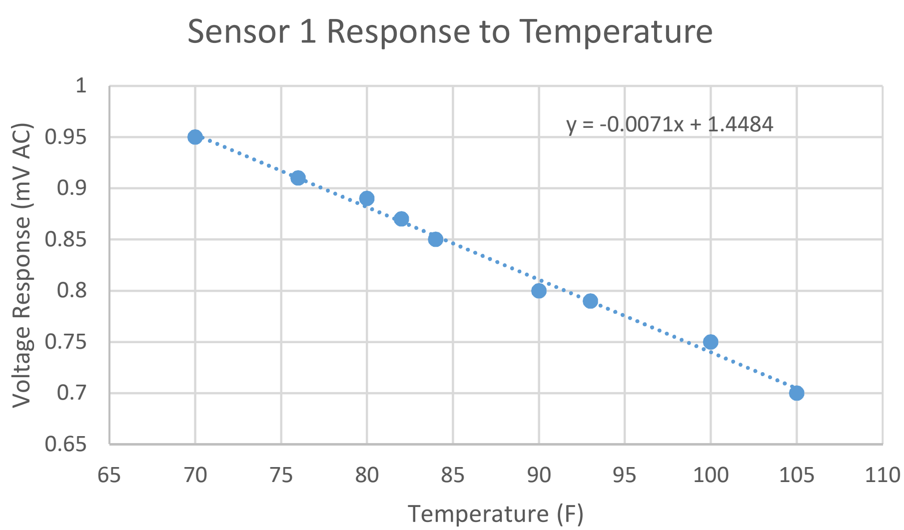
3D-Printed Cortisol Biosensor

Printable Electronics



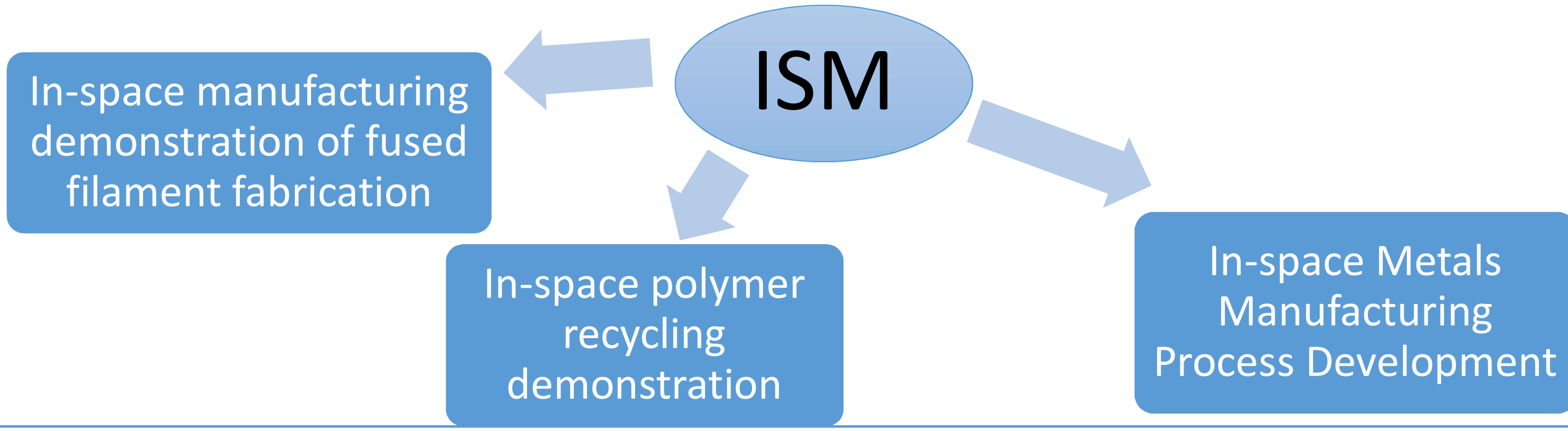


Humidity/Respiration Sensor



Composite Temperature & Pressure Sensor

Computational Modeling



NASA Ames Research Center (ARC) physics group provides analysis and modeling support of in-space manufacturing. The ARC team has significant experience in modeling physics phenomena and materials in microgravity.

- Development and validation of computational models to support understanding of processes in zero-G environments
- Reveal specific features of materials manufactured in micro-gravity that are distinct from earth-processed specimens
- Enable physics based analysis of the ISM payloads before launch.
- Reveal possible gaps in experimental performance.
- **Support verification and validation of parts manufactured in-space**

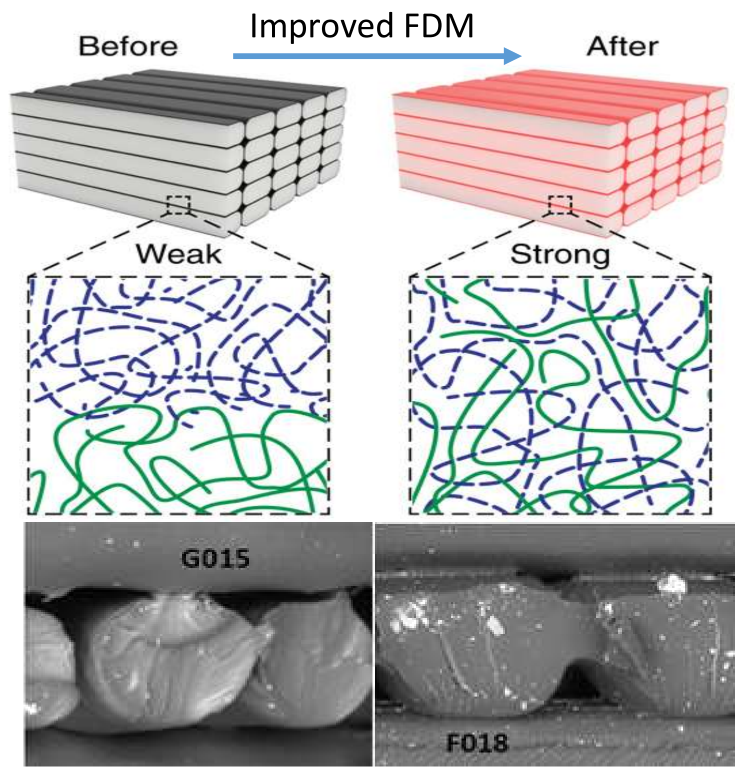
Computational Modeling of FFF

Strength of the manufactured parts (elastic moduli, fracture strength and toughness, anisotropy, plasticity etc.) is determined by the properties of material and filament interfaces.

The interfacial properties are controlled by welding.

In turn, welding process is controlled by entanglement and diffusion of polymers which strongly depend on

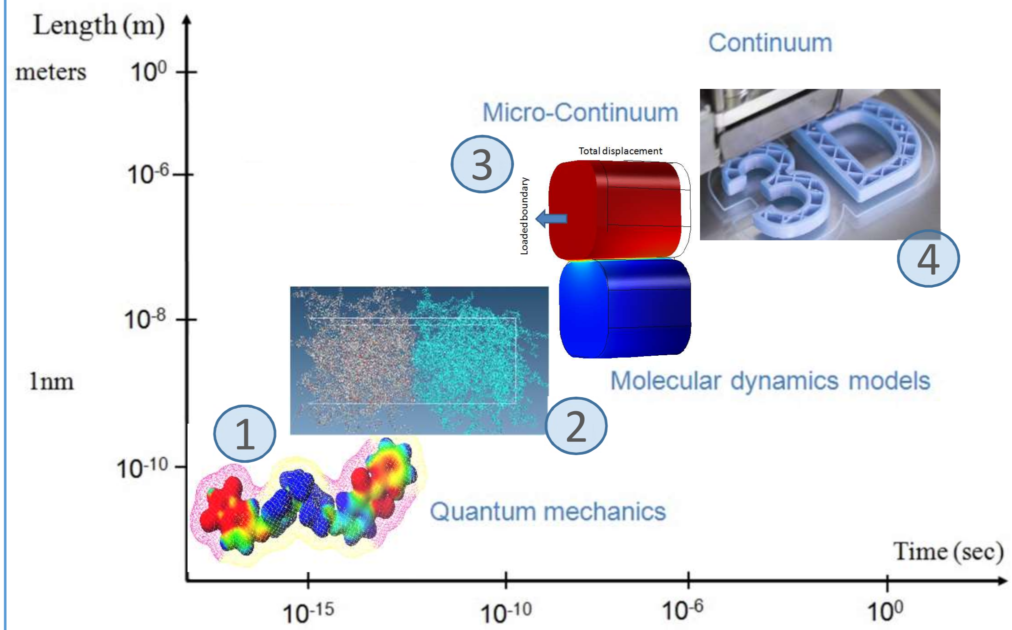
- Molecular conformation
- Temperature - glass transition temperature
- Molecular orientation in deposition flow
- Polymer alignment
- Rheology of entangled polymers: Non-Newtonian and non-linear properties



In this work we analyzed amorphous thermoplastics: Ultem (polyetherimide / polycarbonate) and ABS (Acrylonitrile-butadienestyrene)

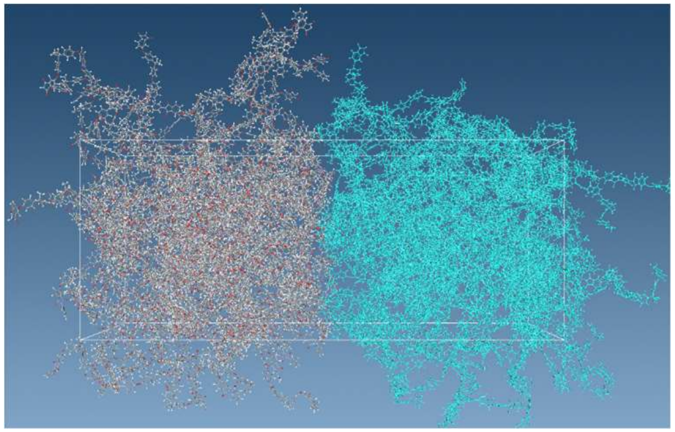
Computational Modeling: Multiscale approach

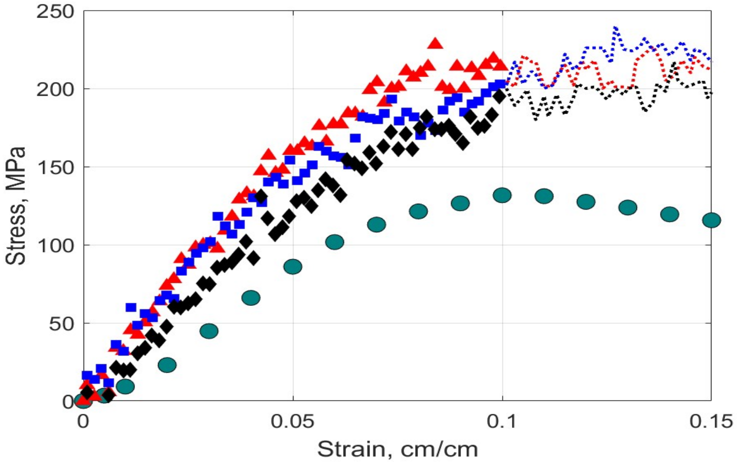
- ARC developed a novel multiscale approach to support additive manufacturing of polymers in space.
- The models in the multiscale approach extend from (1) quantum mechanical models of the monomers (bottom left), (2) fully atomistic model of the interface, (3) microscopic continuous model of the filament interface, and (4) model of the bulk manufactured parts.
- The proposed approach was applied to analyze polymer 3D printing
- Currently we are extending the approach to encompass analysis of a metal manufacturing process



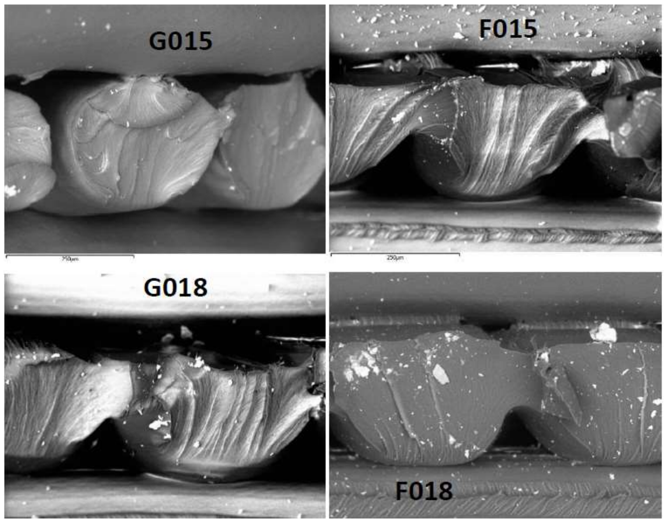
Computational Modeling: Molecular Dynamics modeling for ULTEM 9085

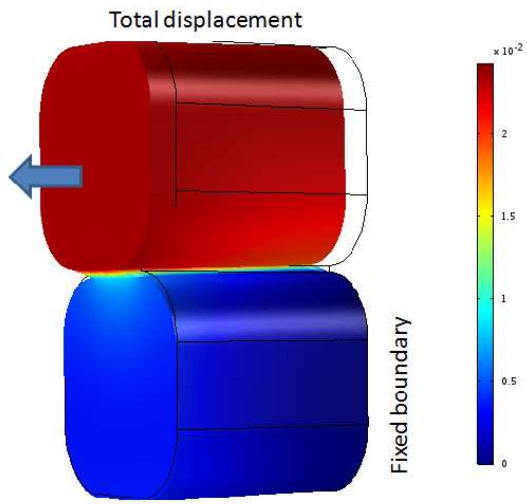
- ARC developed a fully atomistic model of the interface in polyetherimide/polycarbonate blends (Ultem 9085)
- The model was validated by comparison of the MD-predicted (i) glass transition temperature, (ii) bulk modulus, (iii) coefficient of thermal expansion, (iv) IR spectra, and (v) heat capacity with experimental data
- The model (top figure) was used to estimate (i) interdiffusion rate, (ii) strain-stress curves (bottom figure), (iii) shear viscosity and their dependence on the welding time.

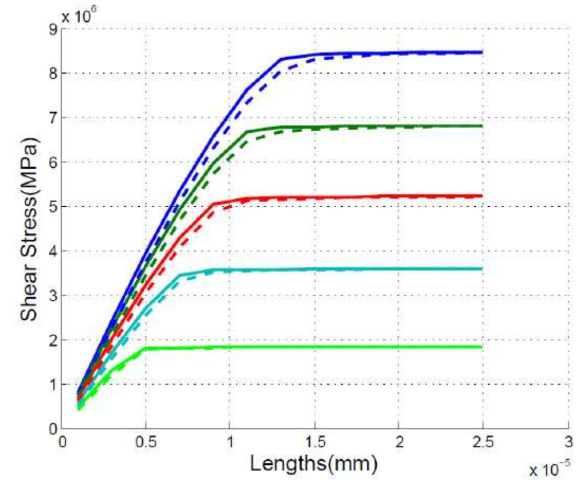




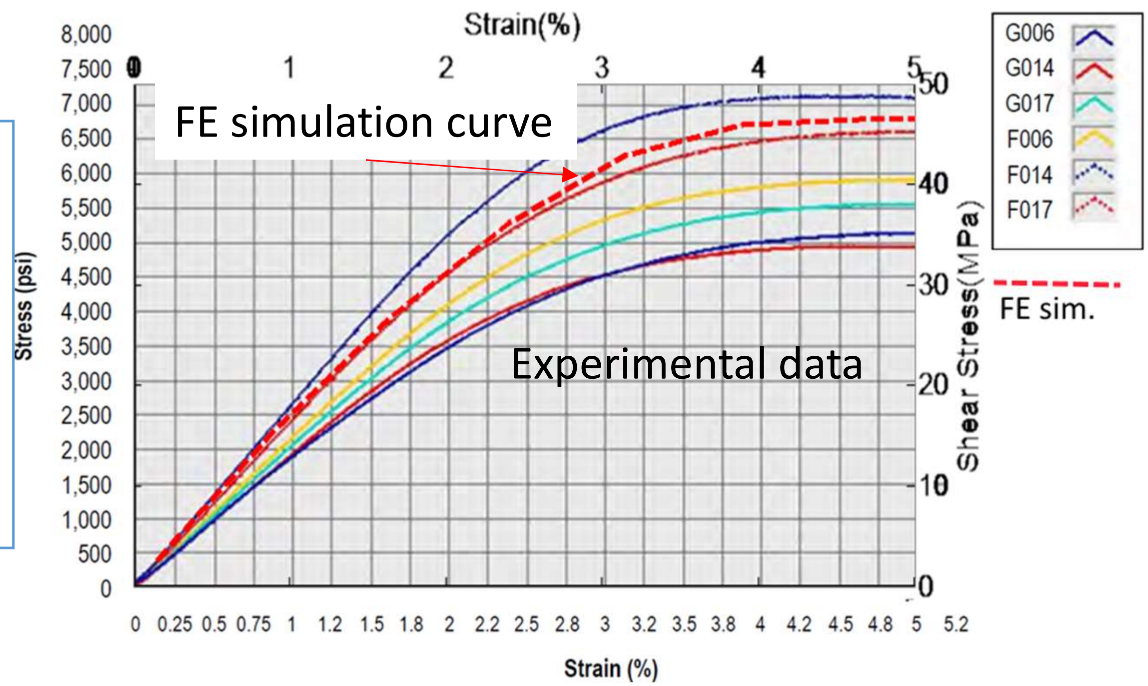
Computational Modeling: Anchoring data







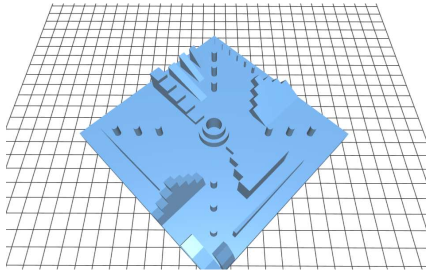
Stress-strain curves for ground and flight flexure specimens plotted on the same axis with embedded theoretical curve (red dashed line obtained using finite element simulation for a specific void volume fraction).



Design Database: "What We Make"

- The in-space manufacturing design database curates parts that represent candidates for just-in-time manufacturing in real mission scenarios.

- Currently the database includes:
  - -parts that have been manufactured on ISS to date
  - -Components from ISS systems that require frequent replacement or have incidences of failure
  - -Items from the medical tool kit



- A NASA Space Technology Research Fellowship (NSTRF) activity seeks to use the design database and ISS part databases to develop a method to evaluate the utility of various manufacturing technologies to meet sparing and resupply needs on space missions. This activity may also help to define requirements for future ISM systems, including production rates and reliability.

- Fabrication Laboratory work includes the production and testing of five "challenge parts" that represent use cases for in-space manufacturing on long duration space missions.

Overview of ISS Databases

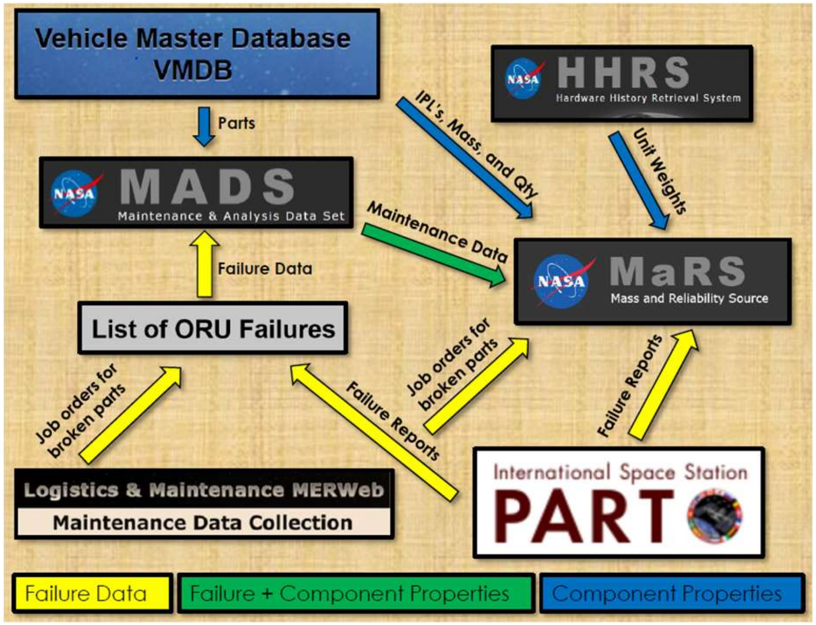
Maintenance and Analysis Data Set (MADS)

Maintenance Data Collection (MDC)

ISS Problem Analysis Reporting Tool (PART)

Vehicle Master Database (VMDB)

Design Database (ISM)



[Ogilvie and Rothe (2017)]

In-space manufacturing key takeaways

In-space manufacturing represents a suite of manufacturing technologies available to crew on long duration missions to reduce logistics and provide a capability for on-demand repair and replacement.

ISM requires integration with space systems designers early in the development process. To make use of ISM, systems must be designed for accessibility and maintainability.

The ISM design database activity will be used in part to define the "what we make" of ISM and will be a key driver for requirements of ISM platforms going forward.