National Aeronautics and Space Administration

Overview of the In-Space Manufacturing Technology Portfolio

CUBES Seminar
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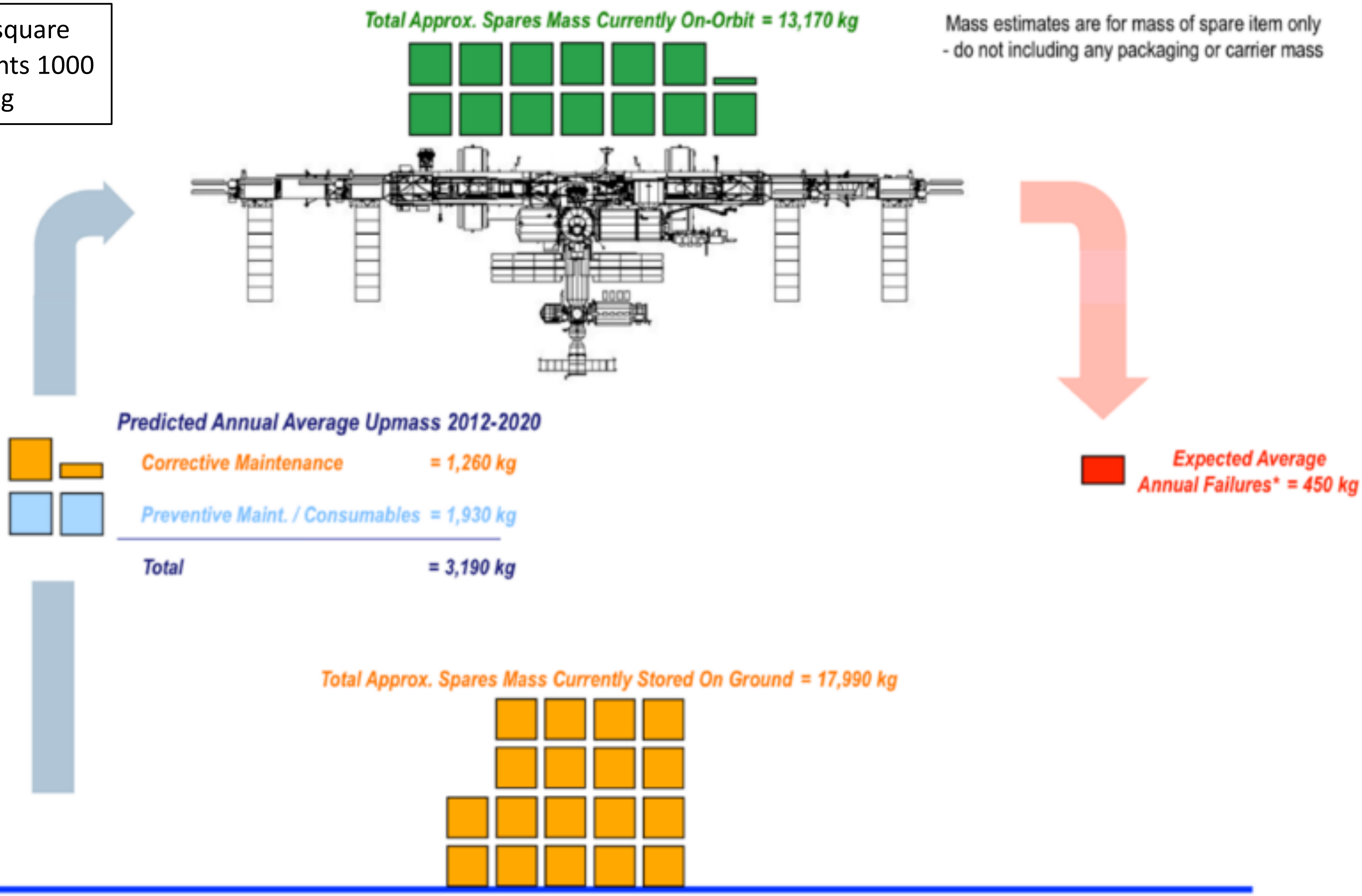
Tracie Prater, Ph.D.
Jennifer Edmunson, Ph.D.
Frank Ledbetter, Ph.D.
Kevin Wheeler, Ph.D.
Vasyl Hafiychuk, Ph.D.
Christopher Roberts, Ph.D. (presenter)
Mike Fiske
Leigh Elrod

MARSHALL
SPACE FLIGHT CENTER

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

Each square represents 1000 kg



- 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	Structure can be optimized for operation in space
Must fit within launch vehicle payload fairings	Size is limited only by the fabrication volume of the ISM capability
Materials are disposed at end of life	Materials are recycled
All the spare parts and equipment needed for on-orbit servicing or repair and replacement activities must be prepositioned.	Spares can be manufactured on-demand enabling on-orbit servicing and repair of equipment.
Component reliability and redundancy (R&R) largely driven by mission life/duration.	Redundancy is augmented. R&R requirements may be reduced.

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 POLYMERS

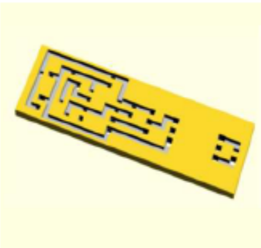
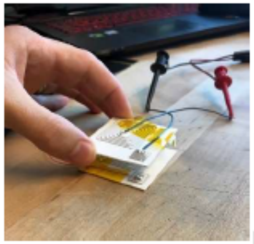


IN-SPACE RECYCLING, STERILIZATION, AND COMMON USE MATERIALS

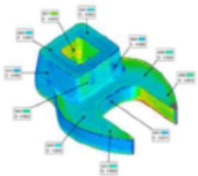
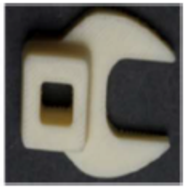


MULTIMATERIAL FABRICATION LABORATY AND IN-SPACE METALS MANUFACTURING


PRINTED ELECTRONICS

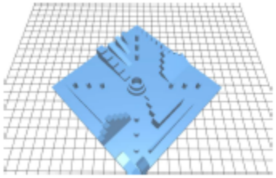



IN-SPACE V&V PROCESS AND COMPUTATIONAL MODELING

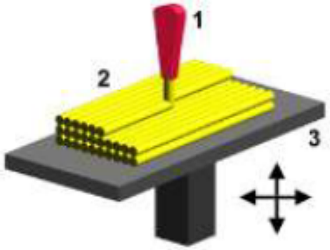
EXPLORATION DESIGN DATABASE & TESTING





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

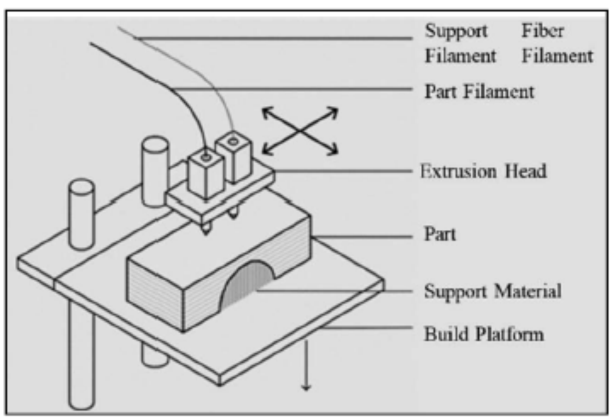
Illustration of the FFF process

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

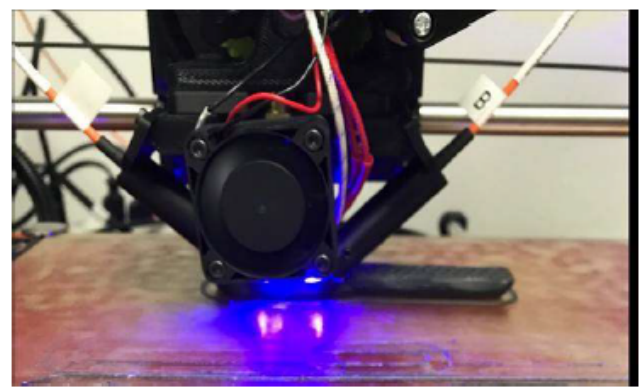
In-space manufacturing of polymers

***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.

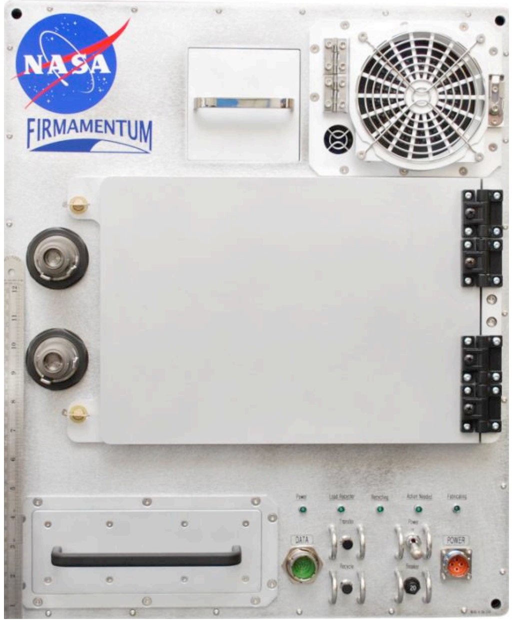


Retrofitted FFF head with laser printing PEEK wrench. Image credit: Actuated Medical, Inc.

In-Space Recycling

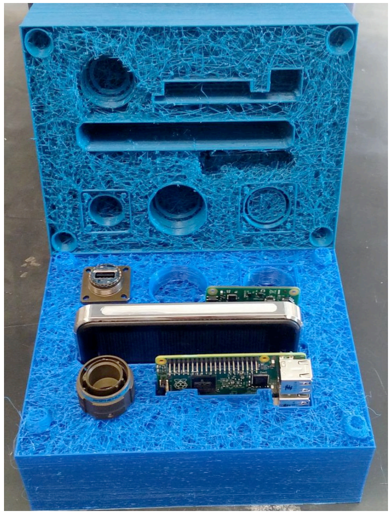
- **Recycling is a critical piece of the puzzle to enable long duration, long endurance missions.**

- **ReFabricator- Tethers Unlimited (TUI)**
  - Installed 2019
  - Integrated 3D printer and recycler
  - Developed under SBIR (small business) contract
  - Extrudes blocks of ULTEM 9085 (PEI/PC) as filament feedstock through a process called Positrusion.

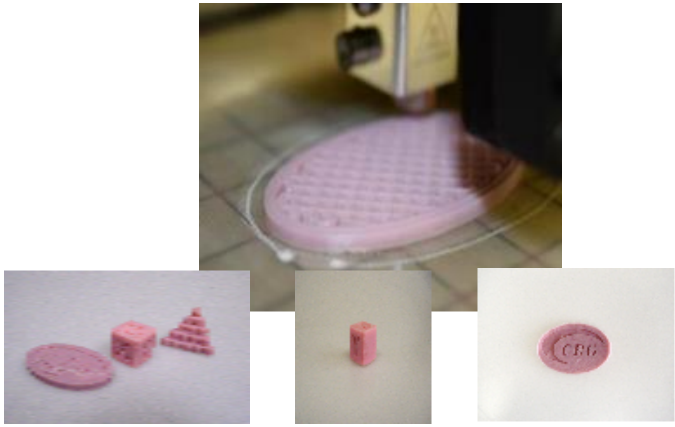


Common Use Materials

- **Common use materials:** launch packaging materials intended to be reused and recycled
- **Cornerstone Reseach Group (CRG) developed a thermally-reversible polymer material compatible with fused filament fabrication (FFF) systems.**
  - Designed to be recycled, blended, and extruded
  - The RVT material can be printed in a film or foam form
  - Additives can be combined with existing waste packaging, enabling reclamation of filament
- **ReFabricator (Expansion of Capability)**
  - SBIR phase II to expand recycling capabilities of the Refabricator payload
    - PET-G, PC, ABS, RVT (material developed by Cornerstone Research Group), and ULTEM 1010 (PEI).
    - 3D printing of foam packaging
    - Vibration testing of various foam configurations and materials



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)

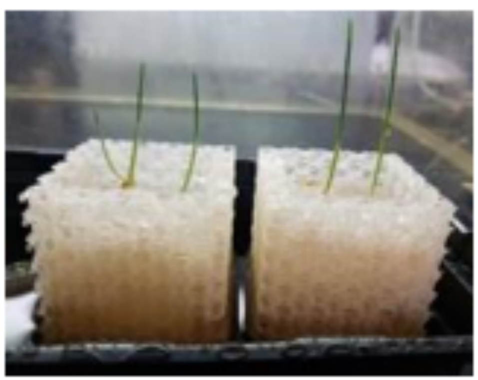
In-Space Sterilization

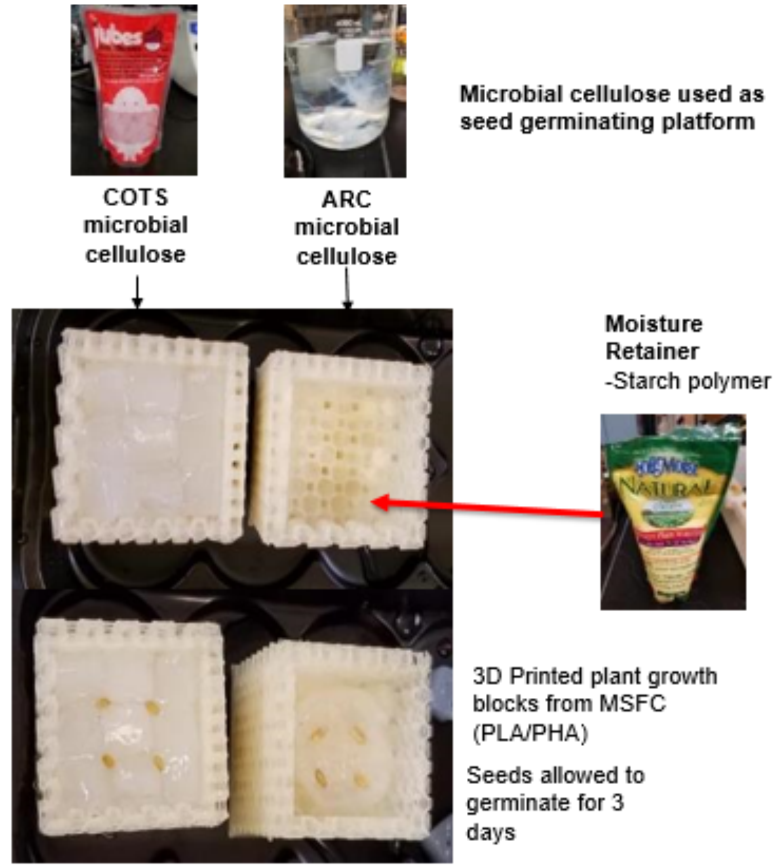
- **ERASMUS-Tethers Unlimited**
  - NASA SBIR Phase II
  - Medical-Grade and Food-Safe Plastic Recycling and Sanitization System
    - **Goal:** Enable recycled materials for medical grade and food-safe applications in space.
    - Bacteria and viruses are more virulent in space and crew immune systems tend to be compromised.
  - 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.

3D Printing with Biologically Derived Materials

- **Goal:** Use biologically derived filament materials and/or materials from inedible plant mass to create 3D printed substrate blocks for plant growth
- Collaborative activity
  - VEGGIE project/payload - KSC
  - Synthetic Biology team - ARC
  - In-Space Manufacturing team - MSFC





In-Space Manufacturing of Metals

- **Vulcan – Made in Space**
  - SBIR phase II
  - Hybrid additive (wire + arc) and subtractive (5-axis CNC) system
  - Materials demonstrated to date: Titanium and Aluminum ER4043.
  - Has ability to print both plastic and metal and removal of part from baseplate
  - Environmental Control unit for debris capture
  - Robotic capability for part manipulation

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
  - Room temperature
- Ultrasonic energy removes the oxide layer between adjacent layers of metal foil and creates a metallurgical bond
- Early tests produced quality material in 6016 T6 and 7075 T6 and enabled material production at significantly lower power and forces

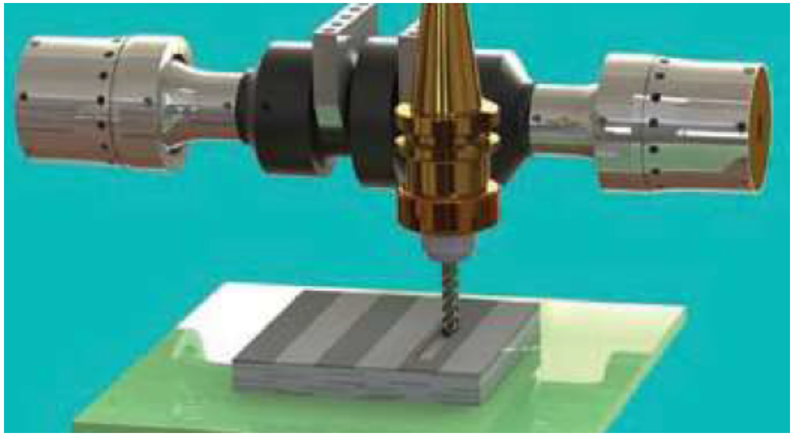
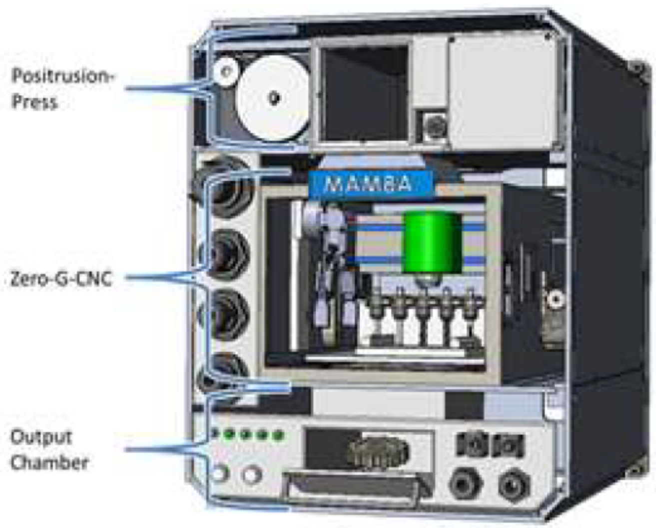


Illustration of UAM process.
Image courtesy of UltraTech

In-Space Manufacturing of Metals

Phase II SBIR MAMBA (Metal Advanced Manufacturing Bot-Assisted Assembly)

- Consists of three technologies integrated into a double locker
  1. **Press** that processes virgin or scrap material into a metal ingot
  2. **CNC mill** designed to operate in microgravity
  3. **Robotic assistant** to facilitate automated processing of material/parts through the subsystems

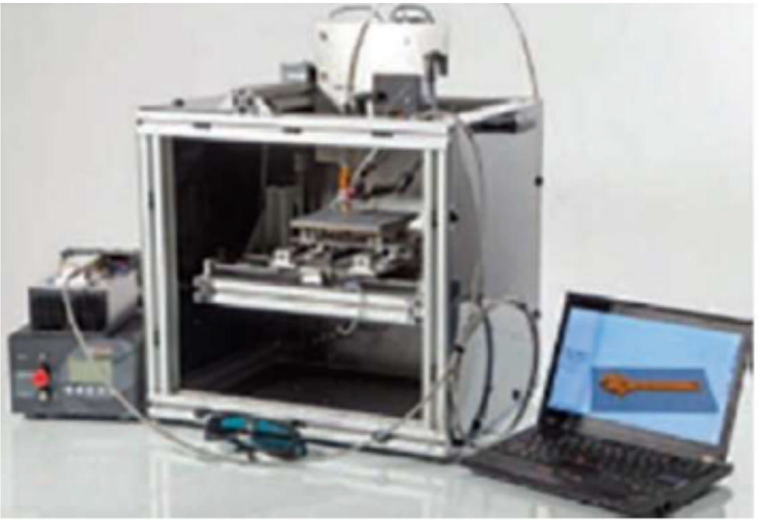


Schematic of MAMBA system. Image courtesy of TUI

In-Space Manufacturing of Metals

Sintered Inductive Metal Printer with Laser Exposure (SIMPLE) - 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

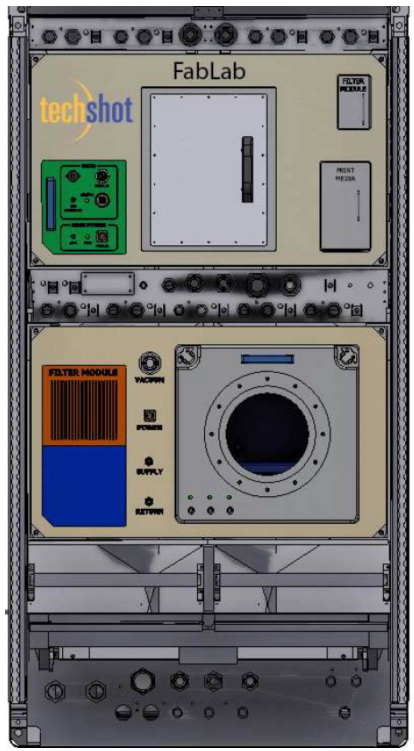


Sintered Inductive Metal Printer with Laser Exposure (SIMPLE). Image courtesy of Techshot.

In-Space Manufacturing of Metals

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 focuses on demonstration of a metal manufacturing capability that is compatible with ISS constraints**
  - System must fit in an EXPRESS rack
    - 2000 W maximum
    - 576 lb maximum
    - 16 cubic feet
  - Include an inspection capability
  - Minimization of crew time for part handling and processing
- Techshot, Inc. and Interlog, Inc. are funded under separate 18-month activities for phase A.
- Priority materials are: Ti-64 and AA 7075.

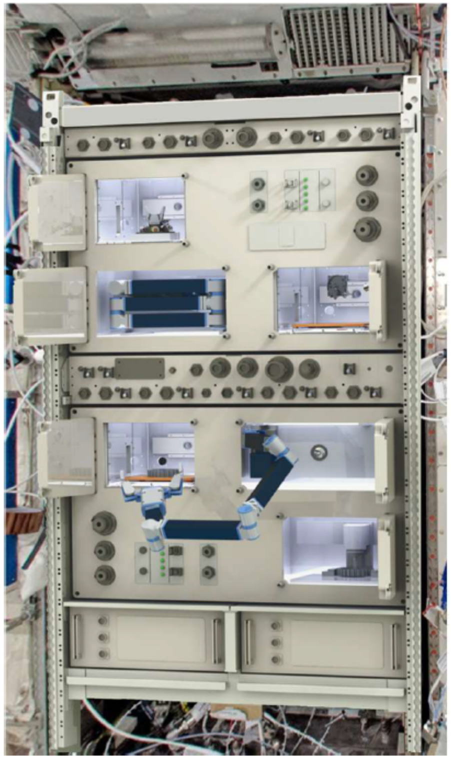


Techshot, Inc. Fabrication Laboratory. Image courtesy of Techshot.

Verification and Validation: Empyrean Fabrication Laboratory

Empyrean FabLab - Tethers Unlimited, Inc. (TUI)

- **Goal:** increase astronaut efficiency by providing autonomous processing and verification and validation services in a system designed for microgravity operation.
  - Robotic handling
  - Quality control
  - Autonomy
  - teleoperation capabilities.

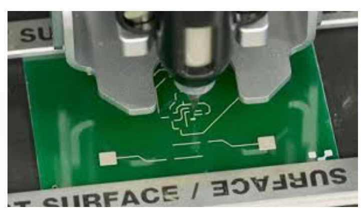


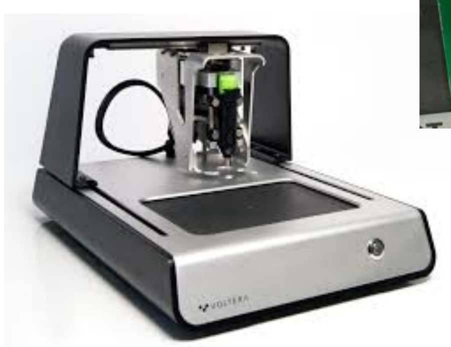
TUI Empyrean Fab Lab (image courtesy of TUI). Partners include IERUS technologies and Olis Robotics.

Printable Electronics

Material processing

nScrypt 3D Multi-Material Printer





Voltera electronics printer

nScrypt 3D multi material printer

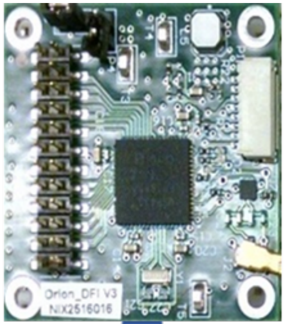
- 4-head capability:
  - SmartPump for ink feedstock
  - 2 filament extruders
  - Pick & place
  - CNC Milling Head
- 300x300x150mm build volume
- Laser sintering capability.

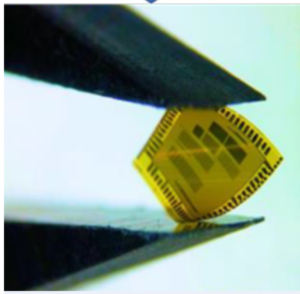
Voltera Electronics Printer

- Quick-turnaround prototyping of sensors and testing of inks.

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.

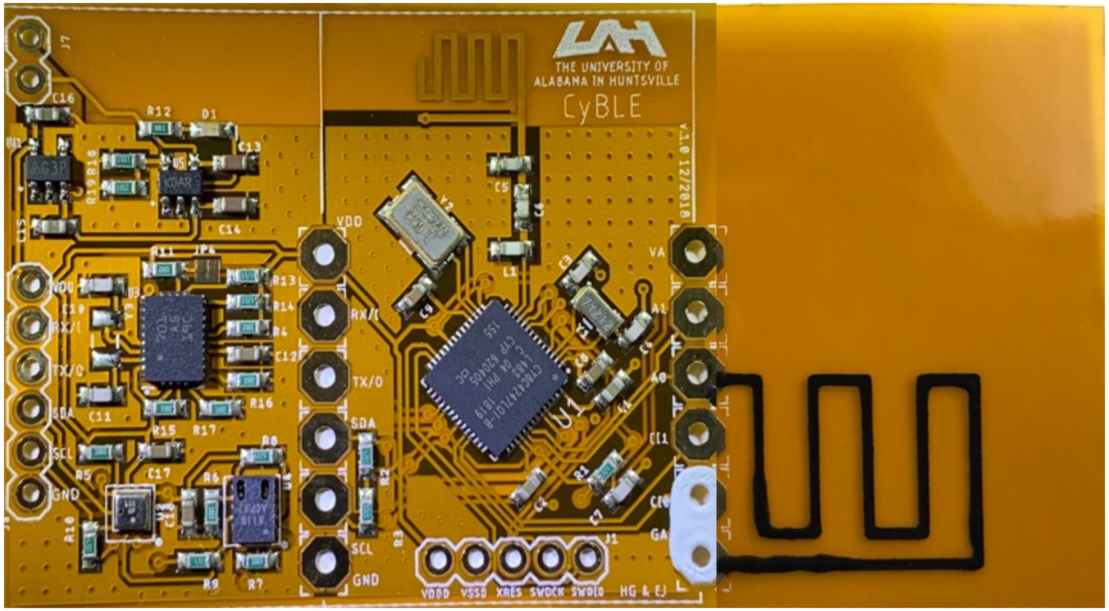




Flexible Electronics Sensors

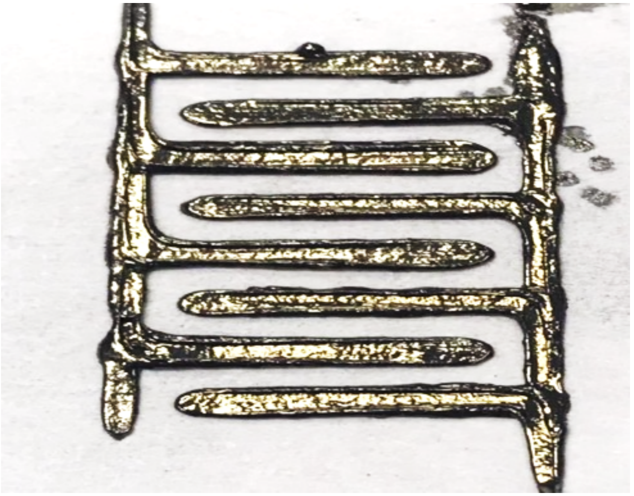
Printable Electronics

First Generation Personal CO_2 Monitor



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

Printable Electronics



3D-Printed Al-Fe_3O_2 Nanothermite Sintered CO_2 Sensor

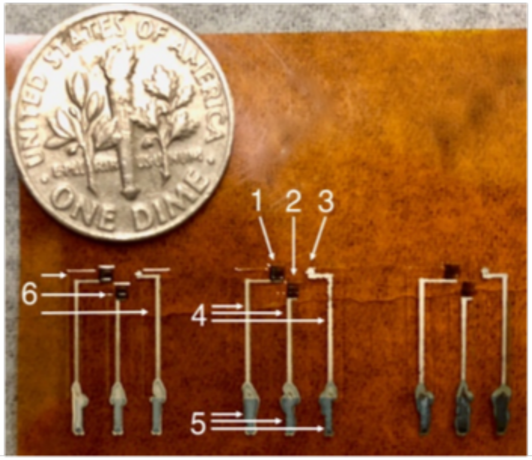
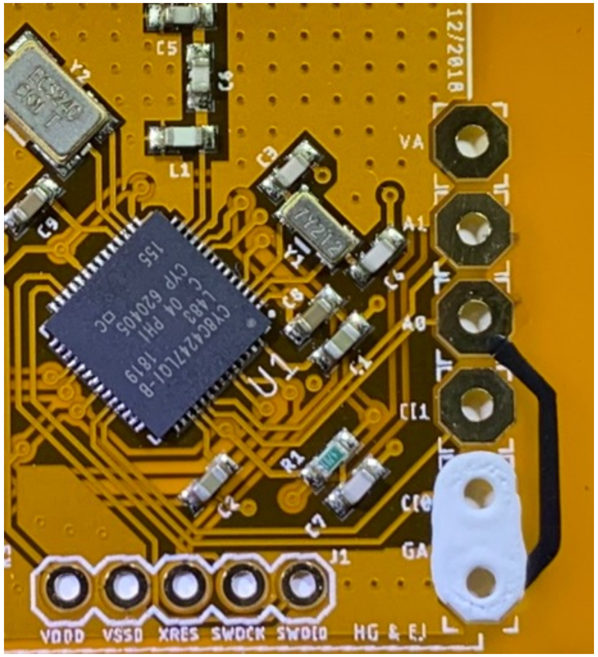
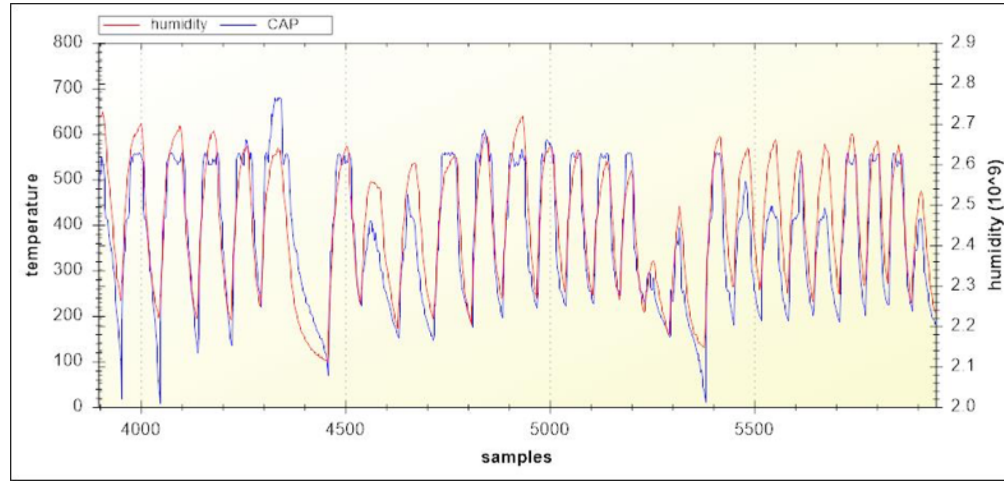


Figure 1. Printed electrochemical biosensor in polyimide substrate. 1) Counter electrode; 2) Working electrode; 3) reference electrode; 4) SU-8 layer; 5) Silver connection lead; 6) Connection pads.

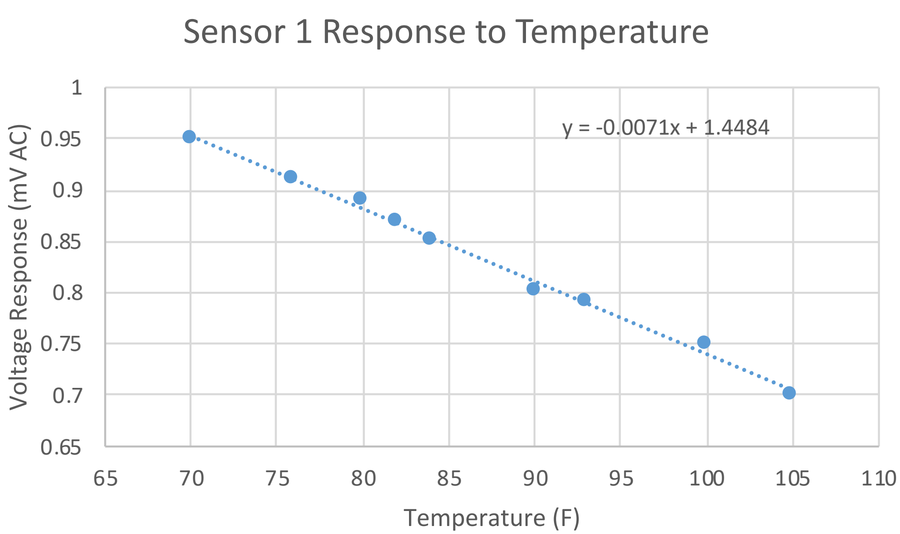
3D-Printed Cortisol Biosensor

Printable Electronics



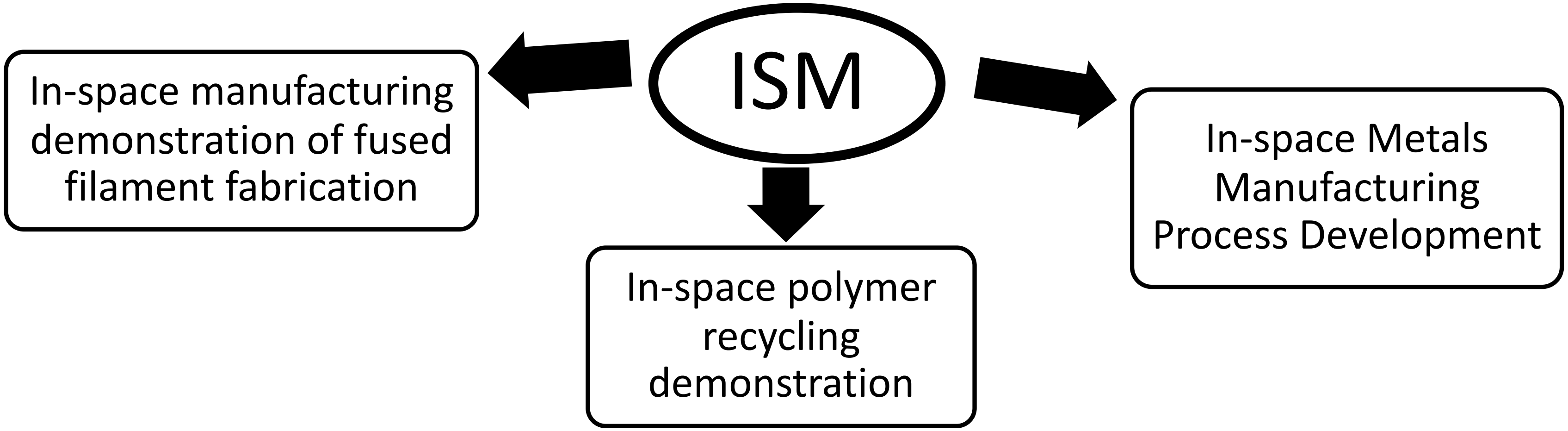


Humidity/Respiration Sensor



Composite Temperature & Pressure Sensor

Computational Modeling



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

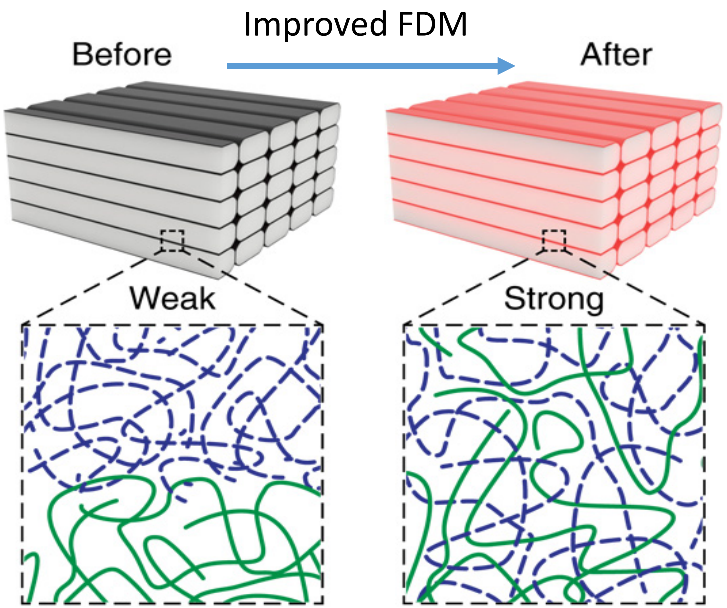
- Development and validation of computational models to support understanding of processes in zero-G environments
- Reveal specific features of materials manufactured in micro-gravity that are distinct from earth-processed specimens
- Enable physics based analysis of payloads before launch.
- Reveal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

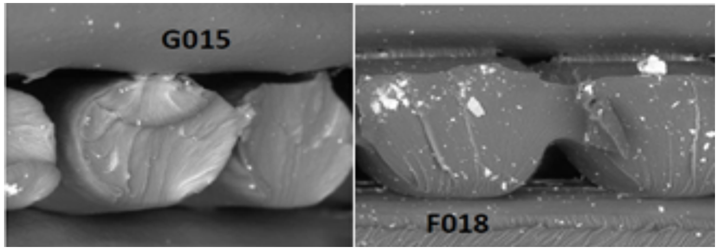
Computational Modeling of FFF

Mechanical properties (elastic moduli, fracture strength and toughness, anisotropy, plasticity etc.) are determined by the properties of **material and filament interfaces**.

The interfacial properties are controlled by welding which is controlled by entanglement and diffusion of polymers which strongly depend on:

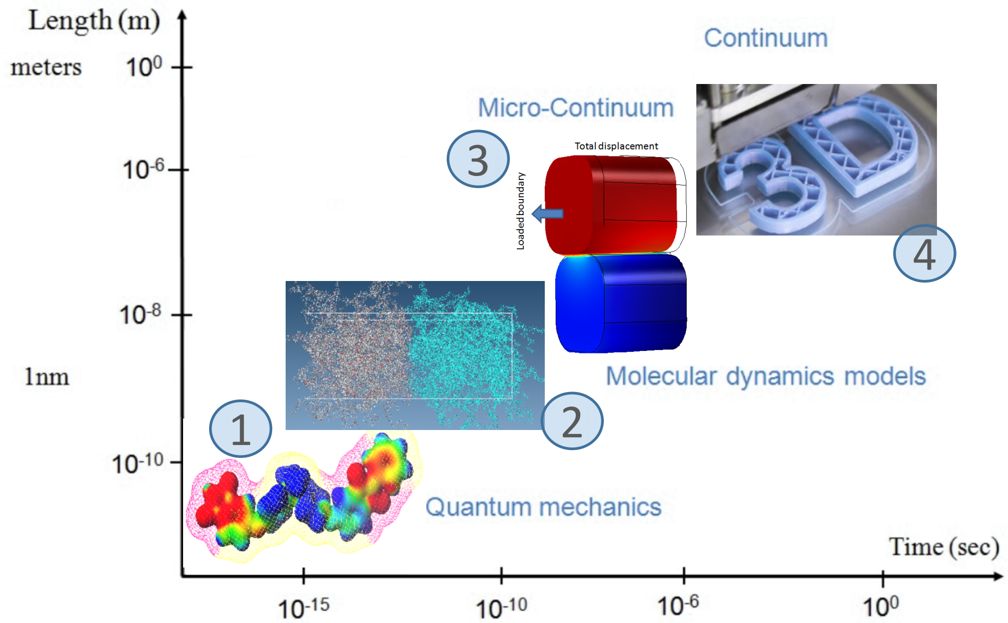
- Molecular conformation
- Temperature - glass transition temperature
- Molecular orientation in deposition flow
- Polymer alignment
- Rheology of entangled polymers: Non-Newtonian and non-linear properties



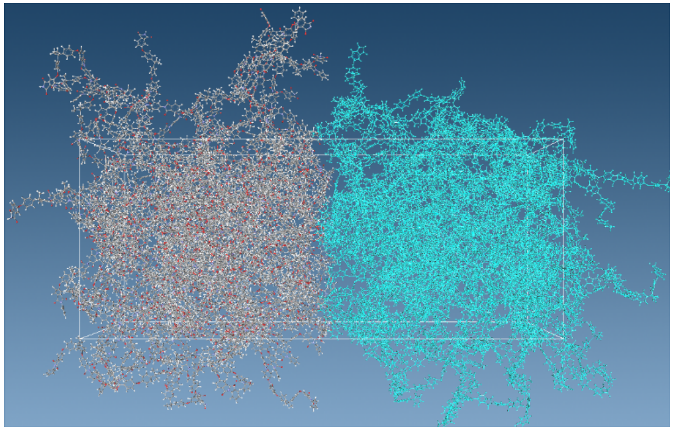


Computational Modeling: Multiscale approach

- ARC developed a multiscale approach to support additive manufacturing of polymers in space.
    - The models 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.
- Currently extending the approach to encompass analysis of a metal manufacturing process

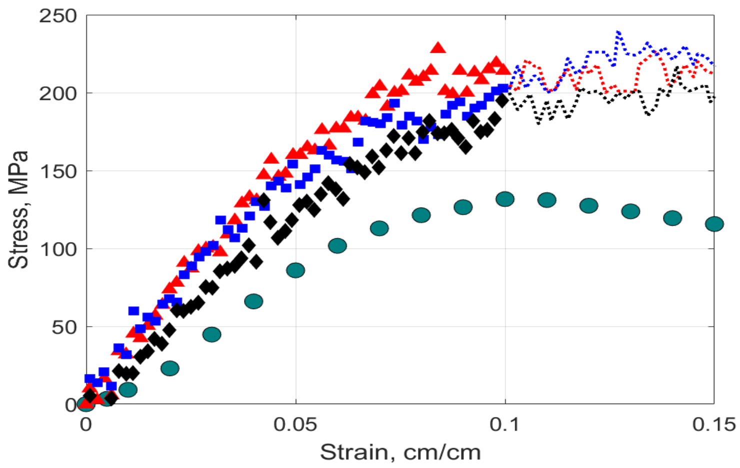


Computational Modeling: Molecular Dynamics modeling for ULTEM 9085

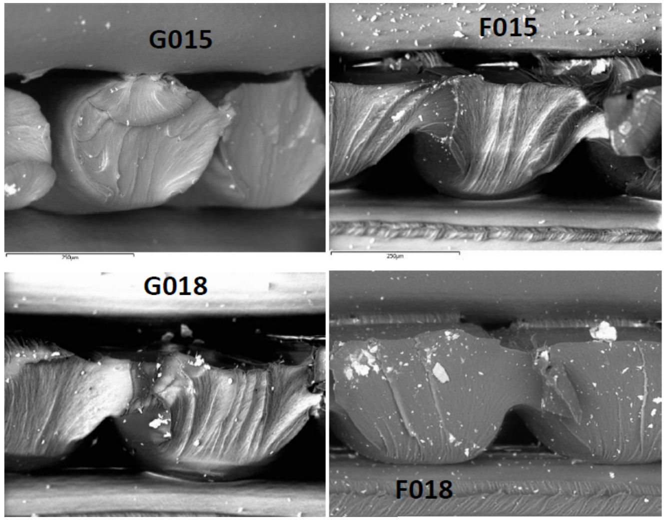


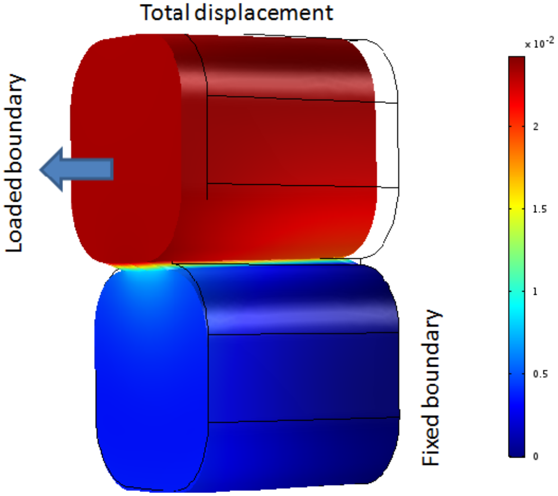
- Fully atomistic model of the interface in polyetherimide/polycarbonate blends (Ultem 9085)
- Estimates:
  - Interdiffusion rate
  - Strain-stress curves
  - Shear viscosity
  - Property dependence on welding time

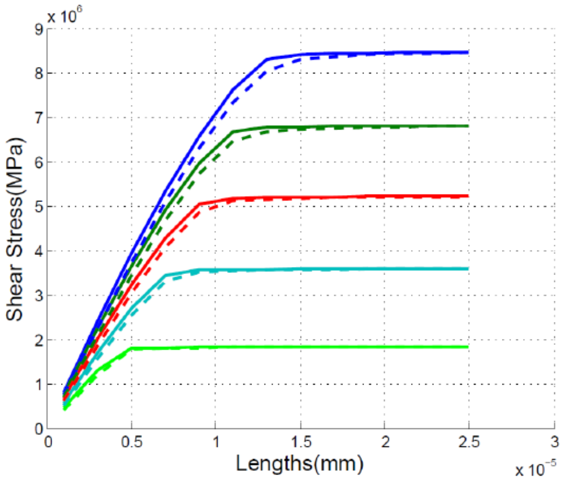
- Validated by comparison of the predicted (i) glass transition temperature, (ii) bulk modulus, (iii) coefficient of thermal expansion, (iv) IR spectra, and (v) heat capacity with experimental data

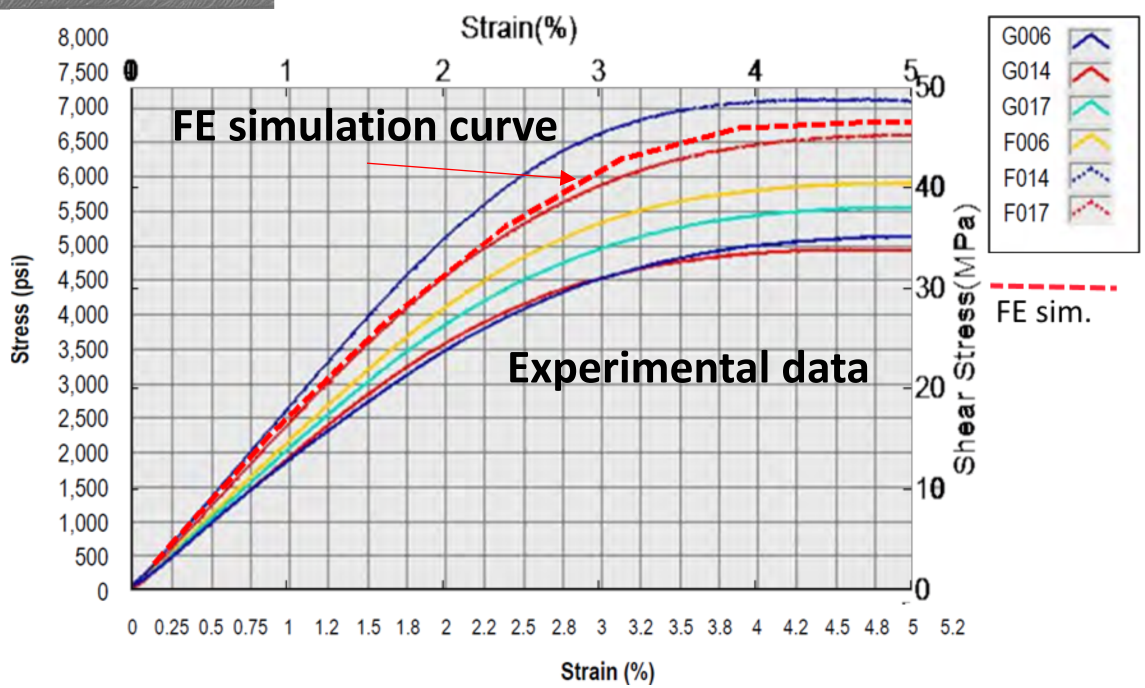


Computational Modeling: Anchoring data







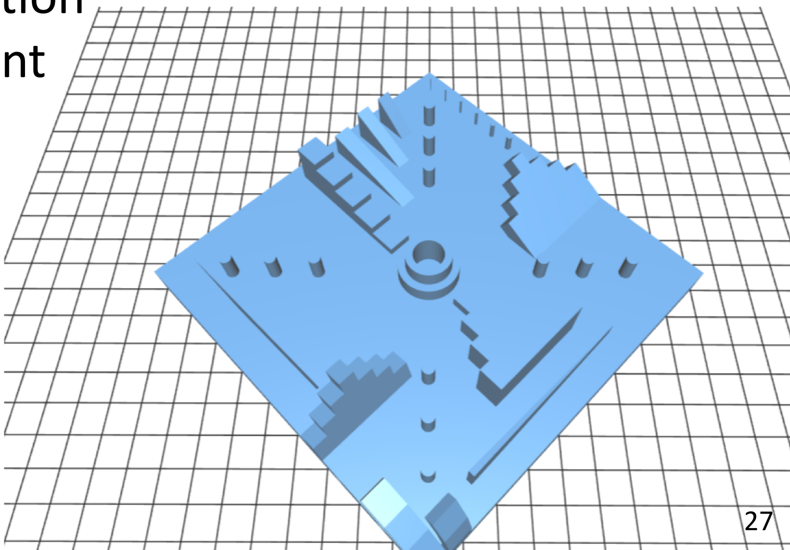


Design Database: "What We Make"

- 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
  - Components requiring frequent replacement or have incidences of failure
  - Items from the medical tool kit

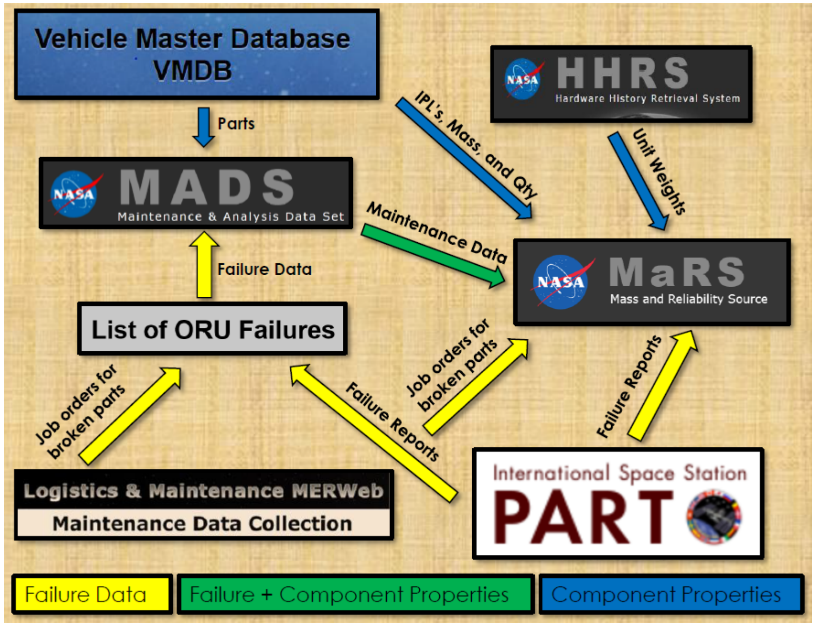
- Fabrication Laboratory work includes the production and testing of five "challenge parts" that represent use cases for in-space manufacturing on long duration space missions.



ISS Databases & NSTRF Activity

NASA Space Technology Research Fellowship (NSTRF) activity

- **Goal:** 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.
- May help to define requirements, such as production rate and reliability, for future ISM systems



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)]

Future Work (of interest)

- Sterilization, sanitization, and development of antimicrobial filaments
- Biomedical device fabrication for exploration medical applications
- Feedstocks made from biological materials
- 3D printing of food
- 3D printing of pharmaceuticals

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.