In Situ Fabrication Technologies: Meeting the Challenge for Exploration

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Marshall Space Flight Center

Lunar & Martian Fabrication Technologies Development Overview

- Exploration Vision
- Vision Requirements Early in the Program
- Vision Requirements Today
- Why is ISRU Technology Needed?
- ISF and In Situ Resource Utilization (ISRU)
- Fabrication Feedstock Considerations
- Planetary Resource Primer
- Average Chemical Element Abundances in Lunar Soil
- Chemical Elements in Aerospace Engineering Materials
- Schematic of Raw Regolith Processing into Constituent Components
- Power Source Applicability
- Iron, Aluminium, and Basalt Processing from Separated Elements and Compounds
- Space Power Systems
- Fabrication Systems Technologies
- Repair and Nondestructive Evaluation (NDE)
- Habitat Structures
Exploration Vision

President George Bush on January 14, 2004 issued his vision for U.S. Space Exploration with the Goals and Objectives to:

• Implement a sustained and affordable human and robotic program to explore the solar system and beyond

• Extend human presence across the solar system, starting with a human return to the moon by 2020, in preparation for human exploration of Mars and other destinations

• Develop the innovative technologies, knowledge, and infrastructure both to explore and to support decisions about the destinations for human exploration

• Promote international and commercial participation to further U.S. scientific, security, and economic interests.
Vision Requirements Early in the Program

• The In Situ Fabrication and Repair (ISFR) element, as part of the Human System Research & Technology Development Program, was established as NASA moved to align with the President’s vision.

• The ISFR element is comprised of three sub-elements: Fabrication Systems Technologies; Repair and Nondestructive Evaluation; and Habitat Structures.

• This group began working with early concepts of operations and roadmap documents and used these as a requirements ‘push’ up to NASA Headquarters for incorporation into the Exploration Requirements documentation. Used as early guidance were:

  • The Operations Concept Document for Human Exploration of Mars (OCDHEM)
      - Vehicle Autonomy and Automation
      - New Technologies for Surface Operations
      - Contingency Maintenance and Repair
      - General Maintenance including pre-deployment of resources
      - In-Flight Maintenance
      - Mission Logistics
      - Planetary Surface Operations

  • The Bioastronautics Roadmap
      - Radiation shielding for the crew either in transit or in conjunction with habitat
      - Maintainable advanced life support for long duration missions
      - Human factors considerations including use of tele-robotic operations
Vision Requirements Today

Requirements are now starting to mature from NASA Headquarters

The Vision for Space - Document Tree
(partial)

Level 0 Exploration Requirements
(SA-0001)

Exploration System of Systems
Technical Requirements
(ESMD-RQ-0010)

ESS Programmatic Requirements and
Guidelines
(ESMD-RQ-0021)

Crew Transportation System (CTS)
Requirements
Spiral 1
(ESMD-RQ-0011)

Spiral 2
(ESMD-RQ-0012)

Spiral 3
(ESMD-RQ-0013)

CDS Requirements
(ESMD-RQ-TBD)

GSS Requirements
(ESMD-RQ-TBD)

Robotic Precursor System
Requirements
(ESMD-RQ-TBD)

ISS Requirements
(ESMD-RQ-TBD)

DSS Requirements
(ESMD-RQ-TBD)

Robotic Lunar Exploration Program
Requirements
(ESMD-RQ-TBD)
Why is ISFR Technology Needed?

- Longer duration missions without near access to Earth will require increased maintainability of systems
- *Component degradation and failure is inevitable*
- The Space Architect has identified sparing as a principal issue for reducing the mass required for long duration exploration missions
- *It would not be practical to carry a complete spare parts and tools inventory, nor would an extensive collection of spares necessarily fulfill every emergency need*
- Fabrication of new tools *in situ* to cover unforeseen needs will significantly mitigate risk
- Fabrication equipment used for components, parts, and tools can also be used for electronic or biological applications (with proper cleanliness and sterility observed)
- Humans living in reduced gravity and harsh environment for extended periods of time must be able to act autonomously for their survival
- Additional potential for crew injuries requires new medical techniques
- As the distance between Mission location and Earth increases, risk increases, and advanced tool suite will help mitigate some of these
ISFR and In Situ Resource Utilization (ISRU)

- In-Situ Fabrication and Repair (ISFR)
  - Fabrication Systems Technologies
    - Metals, Plastics, Ceramics, and Composites
    - Medical Products
    - Bioplotter
  - Repair and NDE Technologies
  - Habitat Structures
  - Baseline Concept for ISFR uses provisioned feedstocks
  - Utilize ISRU “mined and refined” capability as it matures

- In-Situ Resource Utilization (ISRU)
  - Maximize the use of natural resources through the extraction from and/or transformation of Lunar and Martian regoliths
  - Provide many of the needed ISFR feed-stocks for fabrication processes including
    - Silicon
    - Iron, aluminum, titanium
    - Glass/Ceramics
  - Recycling
Fabrication Feedstock Considerations

- Feedstock quantities required
- Form required: fine powders; engineered shapes such as bars, rod, plate; filaments
- Pedigree of feedstocks: purity of powders, chemical and physical analysis
- Compatibility with micro-G or hypo-G fabrication
- Ability to recycle back into new feedstock
- Mission compatible with existing hardware
- Number of feedstocks types required – should be minimized
- Shifting from supplied feedstocks to in situ resources must be process compatible
- Infrastructure required to process adequate quantities of regolith into usable feedstocks (power, structure, chemicals, retorts and vessels)
- Economics and logistics of ‘make or bring’ feedstocks
### Average Chemical Element Abundances in Lunar Soil

<table>
<thead>
<tr>
<th>Element</th>
<th>Abundance</th>
<th>Element</th>
<th>Abundance</th>
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<tr>
<td>Al</td>
<td>6.80%</td>
<td>Bi</td>
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<tr>
<td>Ca</td>
<td>7.88%</td>
<td>Br</td>
<td>1.18 ppm</td>
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<tr>
<td>Cr</td>
<td>0.12%</td>
<td>C</td>
<td>0.12 ppm</td>
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<tr>
<td>Fe</td>
<td>0.12%</td>
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<td>0.19 ppm</td>
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<tr>
<td>K</td>
<td>5.76%</td>
<td>Cl</td>
<td>28.6 ppm</td>
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<tr>
<td>Mg</td>
<td>0.17%</td>
<td>Co</td>
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<tr>
<td>Na</td>
<td>2.19%</td>
<td>Cu</td>
<td>0.42 ppm</td>
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<tr>
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<td>41.30%</td>
<td>Dy</td>
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<tr>
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<td>0.13%</td>
<td>Er</td>
<td>0.14 ppm</td>
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<td>20.40%</td>
<td>Eu</td>
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## Chemical Elements in Aerospace Engineering

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Iron, Aluminum, and Basalt Processing from Separated Elements and Compounds
Space Power Systems

- Transport of fabrication systems implies transport of power systems capable of supplying adequate power to the fabricators.
- Mass and volume of whole system (fabricator, power, feedstock) must be traded against mission requirements, vehicle capability, redundant systems, carrying spares only)

### Categories of Space Power Systems

<table>
<thead>
<tr>
<th>Primary Batteries</th>
<th>Secondary Battery</th>
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<tr>
<td>Photovoltaic</td>
<td>Flywheel Storage</td>
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<tr>
<td>Thermionic Converter</td>
<td>Thermoelectric Converter</td>
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<tr>
<td>Regenerative Fuel Cell</td>
<td>Fuel Cell</td>
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<tr>
<td>Chemical Dynamic</td>
<td>Solar Dynamic</td>
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<tr>
<td>Nuclear</td>
<td>Radioisotope</td>
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<tr>
<td>Electrodyanmic Tethers</td>
<td>Propulsion-Charged Tethers</td>
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Approximate ranges of application of different power sources.
Lunar & Martian Fabrication Systems Technologies Development Overview

- Fabrication Systems Technologies
- Fabrication Trade Study – Applications
  - Technologies Examined
- Trade Study - Capabilities Summary
- Trade Study Results For Multi-Material Fabricator
- Trade Study - Capabilities Summary
- Trade Study Top Technologies for Processing of Metals, Plastics, Ceramics & Composites
  - Fabrication Technology Summary
- Trade Study Rankings For Electronics Fabricator
- Trade Study - Recommendation For Electronics Fabricator
  - Biological Fabricators - Medical Products
  - Biological Fabricators - Bioplotter (Tissue Printing)
- Trade Study - Recommendation For Biological Fabricator
  - Fabrication Systems Gaps
- Fabrication Technology Performance Validation Test Plan
Fabrication Systems Technologies

- ISFR-Fabrication Systems Technologies Sub-element Purpose
  - Fabricate On-orbit Replacement or Unforeseen Parts
    - ISS, Moon, and Mars missions will benefit from capabilities
    - Reduced sparing possible by component vs. Orbital Replacement Units
    - Rectify design inadequacies that may result from off-nominal scenarios
    - Layered manufacturing techniques may enable unique geometries such as internal cavities or cooling passages as well as future functional gradient materials.

  - Fabricate On-orbit Replacement Electronic Parts
    - Provide Printed Circuit Board (PCB) and embedded electronics capabilities
    - Focus on planar circuitry equivalents for discrete components fabricated on provisioned or fabricated substrates to enable complete PCB replacement

  - Fabricate On-orbit Replacement Medical Devices or Biological Constructs
    - Invasive: pins, plates, stints, catheters, sutures, surgical tools and dental instruments, adhesives for tissue binding and affixing implants
    - Non-invasive: casts, orthodics, tubes, syringes, gloves
    - Dental: fillings, crowns, bridges, dental cement
    - Print viable human tissue on hydrogel or collagen scaffolds
Fabrication Trade Study - Applications

**Composites**
- Aluminum Alloys
- Titanium Alloys
- Stainless Steels
- Superalloys
- Others TBD

**Polymers**
- ABS Plastic
- Elastomers
- Polycarbonate
- Polyphenyl Sulfone
- Others TBD

**Electronics**
- PC Boards
- Discrete Components
- Crew Displays
- Area Lighting

**Functional Gradient Materials**
- Moon & Mars Surface Products
- Replacement Parts
- Unforeseen Tools
- Conformal Repair Patches
- Habitat Fittings
- ECLS Parts
- Electronic Components
- ElastomerSeals

**Ceramics**
- Alumina
- Zirconia
- Silica
- Silicon Nitride
- Misc. Oxides
- Others TBD

**Manufacturing Processes**
- Three Dimensional Printing
- Computer Numerical Control
- Direct Metal Process
- Electron Beam Freeform Fabrication
- Electron Beam Melting
- Fused Deposition Modeling
- Kinetic Metallization
- Laser Engineered Net Shaping
- Laminated Object Manufacturing
- Precision Metal Deposition
- Stereolithography
- Selective Inhibition of Sintering
- Selective Laser Melting
- Selective Laser Sintering
- Ultrasonic Consolidation
- Casting Methods
- Plasma Spray, Chemical Vapor Deposition, etc.

**Products**
- Metals
- Composites
- Ceramics
- Electonic
- Biological
# Technologies Examined

<table>
<thead>
<tr>
<th>Acronym or Process</th>
<th>Process or System Description</th>
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<tbody>
<tr>
<td><strong>Additive Technologies</strong></td>
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<tr>
<td>3DP: Z-Corp</td>
<td>3-Dimensional Printing: Vendor, Z-Corp</td>
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<tr>
<td>3DP: Prometal</td>
<td>3-Dimensional Printing: Vendor, Prometal</td>
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<tr>
<td>Bioplotter</td>
<td>3-Dimensional Printing for Biological Constructs</td>
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<td>CVD</td>
<td>Chemical Vapor Deposition</td>
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<tr>
<td>DMP</td>
<td>Direct Metal Process</td>
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<tr>
<td>EBF(^3)</td>
<td>Electron Beam Freeform Fabrication</td>
</tr>
<tr>
<td>EBM: Arcam</td>
<td>Electron Beam Melting: Vendor, Arcam</td>
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<td>EPMD</td>
<td>Electronic Parts Material Deposition</td>
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<tr>
<td>FDM</td>
<td>Fused Deposition Modeling</td>
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<tr>
<td>KM</td>
<td>Kinetic Metallization</td>
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<tr>
<td>LENS</td>
<td>Laser Engineered Net Shaping</td>
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<tr>
<td>LOM</td>
<td>Laminated Object Manufacturing</td>
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<tr>
<td>MELATO</td>
<td>Metal Laminated Tooling (hybrid system, includes CNC milling)</td>
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<tr>
<td>PAS</td>
<td>Plasma Arc Spray</td>
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<tr>
<td>Photolithography</td>
<td>Process for printing PC board circuits</td>
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<tr>
<td>PMD</td>
<td>Precision Metal Deposition</td>
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<td>Robocasting</td>
<td>Sandia Labs Slurry Extrusion Process (hybrid system, includes CNC milling)</td>
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<tr>
<td>RSP</td>
<td>Rapid Solidification Process</td>
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</table>
# Technologies Examined

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<thead>
<tr>
<th>Acronym or Process</th>
<th>Process or System Description</th>
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<td>SLA</td>
<td>Stereolithography</td>
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<td>SIS</td>
<td>Selective Inhibition of Sintering</td>
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<td>SLM</td>
<td>Selective Laser Melting</td>
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<td>SLS: 3D Systems</td>
<td>Selective Laser Sintering: Vendor, 3D Systems</td>
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<td>SLS: EOS</td>
<td>Selective Laser Sintering: Vendor, EOS</td>
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<td>UC</td>
<td>Ultrasonic Consolidation (hybrid system, includes CNC milling)</td>
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<tr>
<td><strong>Subtractive Technologies</strong></td>
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<tr>
<td>CNC Machining</td>
<td>Computer Numerical Controlled Machining (both milling and lathe operations)</td>
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<tr>
<td><strong>Other Methods</strong></td>
<td></td>
</tr>
<tr>
<td>Casting, Formative Methods</td>
<td>Methods for Casting Materials Into Net Shape</td>
</tr>
<tr>
<td>Cold Forming</td>
<td>Various Techniques for Working Ambient Materials</td>
</tr>
<tr>
<td>Die Casting</td>
<td>Various Techniques for Materials Casting</td>
</tr>
<tr>
<td>Hot Forming</td>
<td>Various Techniques for Working Heated Materials</td>
</tr>
</tbody>
</table>
Trade Study - Capabilities Summary

• Multi- Material Fabricator
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate tools, parts and structural components using provisioned, recycled and refined in situ resources (up to 18” per side in size) resources

• Electronics Fabricator (preliminary assessment)
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate PC boards as well as electronic components using provisioned, recycled and refined in situ resources

• Fabrication, Assembly & Repair Module (preliminary assessment for information only)
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate tools, parts, structural components and electronics using provisioned, recycled, and refined in situ resources

• Biological Tissue Printing (preliminary assessment for information only)
  - Spirals 3, 4, 5: Crew tended in pressurized cabin
  - Fabricate tissue constructs by culturing cells on growth substrates using provisioned, recycled, and refined resources
Trade Study Results For Multi-Material Fabricator

• Hybrid architecture recommended to achieve performance while minimizing gap closure efforts
  - Utilize CNC machining as baseline since it requires least gap closure, can provide finishing for other processes, and partial gravity effects will be minimal
  - Utilize additive methods to minimize feedstock mass as well as support complex geometries and advanced capabilities such as functional gradient materials or internal cavities
  - Remove electronics and biological functions from main fabricator

• Potential hybrid groupings should be investigated in follow-on architecture study
  - Groupings of technologies not analyzed in initial trade study other than as available hybrid units with integral CNC
  - Investigate groupings of integral multiple end-effectors arrangement or of interchangeable end-effectors
Trade Study - Capabilities Summary

Early Concept for a Multi-Material Fabricator Ground Unit (Processing, Metals, Plastics, Ceramics, & Composites)
Trade Study Top Technologies for Processing of Metals, Plastics, Ceramics & Composites

- Top 9 Ranked Technologies Are Shown Below For Processing of Metals, Plastics, Ceramics and Composites

<table>
<thead>
<tr>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>CNC Machining</td>
</tr>
<tr>
<td>Ultrasonic Object Consolidation</td>
</tr>
<tr>
<td>Robocasting</td>
</tr>
<tr>
<td>Fused Deposition Modeling</td>
</tr>
<tr>
<td>Selective Laser Sintering</td>
</tr>
<tr>
<td>Selective Laser Melting</td>
</tr>
<tr>
<td>Casting Methods</td>
</tr>
<tr>
<td>3D Printing, Generic</td>
</tr>
</tbody>
</table>

- Separation of Electronics and Biological Tissue Fabrication Is Assumed Due to Feature Size Differences and Contamination Control Issues
Fabrication Technology Summary

Computer Numerical Controlled
Machining

CNC Lathe System
Fabrication Technology Summary

Ultrasonic Consolidation (UC)

- Horn
- Sonotrode
- Anvil

Basic ultrasonic joining arrangement

Ultrasound vibration
Held stationary by anvil
Interfacial vibration of workpieces caused by ultrasonic excitation

Friction at interface breaks up oxides
Diffusion occurs across atomically clean interface

True metallurgical bond formed

Courtesy of Solidica Inc.
Fabrication Technology Summary

Selective Laser Sintering/Melting (SLS/SLM)
Fabrication Technology Summary

Robocasting

[Image of a robotic casting machine with annotations: z micron stage, syringes, nozzle, x/y stage, 40", 36", 24"]
Fabrication Technology Summary

Casting Methods

Peritectic Alloys (e.g. Amalgams)

Combustion Synthesis Experiments
3D Printing

Fabrication Technology Summary
Trade Study Rankings For Electronics Fabricator

- Top Ranked Technologies Are Shown Below For Processing of Electronics

<table>
<thead>
<tr>
<th>Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electronics Parts Materials Milling (EPMM)</td>
</tr>
<tr>
<td>Electronic Parts Material Deposition (EPMD)</td>
</tr>
<tr>
<td>(General class of 3D Printing methods)</td>
</tr>
<tr>
<td>Photolithographic Methods</td>
</tr>
</tbody>
</table>

- Recommend Separation of Electronics Fabrication As Separate Unit
  - Contamination Control Issues Are More Stringent Than MMF
  - Difference in Features Size of 2 to 3 Orders of Magnitude
Trade Study - Recommendation For Electronics Fabricator

- Additional In-depth Study Recommended
  - This release focused on mechanical ability to create electronic features rather than electrical functionality testing
  - Maturity levels are at research levels for complex circuitry using 3DP methods, thus data was difficult to obtain

- Photolithography To Be Monitored for Emergence of New Processes
  - Emphasize elimination of photo-mask generation, exposure sources and component placement equipment requirements
  - Look for elimination of hazardous etchants and exposure chemicals

- Testing of Fabricated Circuitry is Recommended as Next Trade Study Phase
  - Examine range of feature sizes from interconnects to components
  - Examine range of component types (resistors, inductors, transistors, etc.)
Biological Fabricators - Medical Products

- Target treatment of major and minor injuries
  - Triage for return to Earth
  - Treatment on-site
- Medical Product examples
  - Invasive: pins, plates, stints, catheters, sutures, surgical tools and dental instruments, adhesives for tissue binding and affixing implants
  - Non-invasive: casts, orthodics, tubes, syringes, gloves
  - Dental: fillings, crowns, bridges, dental cement
- Additional capabilities required
  - Sterilization capability
  - Libraries for medical procedures, dental procedures, and medical product specifications
Biological Fabricators - Bioplotter (Tissue Printing)

- Solid Freeform Fabrication (SSF)/Rapid Prototyping (RP) techniques for tissue printing
- Print viable human tissue on hydrogel scaffolds with high throughput, modified COTS inkjet printers
  - Aid in healing process
  - Replace damaged tissue
- Tissue Types
  - Near term capabilities - skin, bone, cartilage, connective tissue and blood vessels
  - Long range capabilities - other smooth muscle, skeletal muscle, and organs
- Potential development and demonstration of a Bioplotter for hypo-g and micro-g

Micrograph of Printed Heart Tissue
Trade Study - Recommendation For Biological Fabricator

- Biological Fabricators have many promising applications being developed and will be monitored as part of this effort
- Further action in the near term has been deferred by MSFC
Fabrication Systems Gaps

- STL Language for additive technologies is not adequate for precision part geometries
- In process NDE / Inspection for more accurate parts on additive fabricators
- Real time control feedback for modification of parameters as additive parts are being fabricated
- Additive Fabricators require secondary finishing by machining
- The most important of all:

  **Lack of industry material standards for the output products of additive fabricators**

The effort to standardize the output of these machines for designers to utilize will be an intensive effort.
Fabrication Technology Performance Validation Test Plan

Purpose

- The test program will validate fabrication technology performance.

- Limited information available outside of vendor-supplied data.

- Supports Technology Development under Concept Formulation/Refinement
System Overview

- Trade Study Assessed 30 Fabrication Processes

-- Distinct gap between "best" 9 technologies and remaining technologies.

-- Emphasis on the following technologies
  - Fused Deposition Modeling (FDM)
  - Selected Laser Sintering (SLS)
  - Ultrasonic Consolidation (UC)
  - Robocasting
  - Computer Numerical Control (CNC)
Test Methods

- The test program will assess dimensional accuracy, material properties, and ability to produce complex geometry.

  -- Part accuracy determined by dimensional laser scanning.
  -- Tensile Pull Tests performed to validate Tensile Strength and % elongation.
  -- Benchmark part assessed to determine ability to produce complex geometry.
Test Parts: Dimensional Accuracy

- Benchmark Part: Determine dimensional accuracy of geometric features, and ability to build complex geometries.

- Simple Gear: Determine dimensional accuracy for component part.

- Heat Exchanger: Determine ability to produce functional part with advanced features.
Test Parts: Material Properties Assessment

- Tensile Test Specimens: Determine tensile strength of materials, including % elongation.

Part built in XY plane
Part built in Z plane
Ground Rules and Assumptions for Initial Testing

- Each process will fabricate parts using materials that are considered standard for the given process.
- Post-processing is limited to system-specific functions.
- Unconstrained test conditions
  - Environmental effects
  - Experience of technician
  - Time between part build and post-curing
  - Cleaning process variation
Test Specifications

- Dimensional Accuracy

- No specification callout
- Accuracy measured through the use of laser scanning technologies
Fabrication Technology Performance Validation Test Plan

Test Specifications: Tensile Pull Tests

-- Plastic Parts per ASTM D638 (pull rate)
-- Test specimens per ASTM D638
-- Results will include Tensile Strength and % elongation

-- Ceramic Parts per ISO 15490
-- Ceramic/Composite Parts per ISO 15733
-- Results will include Tensile Strength and % elongation

-- Metallic parts per ASTM E8 (pull rates)
-- Test specimens per ASTM E8
-- Results will include Tensile Strength and % elongation
Results Analysis – Dimensional Accuracy

-- Laser scanner will provide results data
  • Data collected from “visible” areas
  • Can expect 1 million data points
  • Data is electronically available

-- Post-processing will include detailed report
  • Report provided for each scanned part
  • Color plots showing deviations and locations
Results Analysis – Geometry Validation

Sample Results Table

<table>
<thead>
<tr>
<th>Benchmark Features</th>
<th>Notes</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lattice Feature</td>
<td>Pass</td>
</tr>
<tr>
<td>Inverted cone</td>
<td>Pass</td>
</tr>
<tr>
<td>Bellows</td>
<td>Pass</td>
</tr>
</tbody>
</table>

Simple Gear

Benchmark features

17% of inspection points have deviation > .005."
Results Analysis – Tensile Pull Tests

- Measured material properties will be compared to vendor-supplied data.

- Material properties will be compared to MIL-HNBK-5 and MIL-HNBK-17 properties (transitioning to Metallic Materials Properties Development and Standardization (MMPDS) Handbook).
Current Validation Efforts

- Development of a ceramic (alumina) lattice structure used as a monolithic filter, impregnated with a catalyst.

- This structure may replace a catalyst bed of pelletized clay and zeolite.
Lunar & Martian Repair and Nondestructive Evaluation (NDE) Development Overview

- Repair and NDE Selected Capabilities
- First Priority Capabilities Selection Rationale
- Multi-Material Joining, Patching and Filling
- Multi-Material Joining, Patching & Filling Tech Gaps
- Electrical Repair - Hand-held Tool
- Electrical Repair Hand-held Tool Technology Gaps
- NDE : QA & Safety Inspection and Troubleshooting
- NDE Recommendations
- NDE, QA, and Safety Inspection & Troubleshooting Technology Gaps
Repair and NDE Selected Capabilities

- Multi-Material Joining, Patching and Filling
  - Polymeric material adhesives and fillers
  - Metallic joining and fillers
    - Metals non structural
    - Metals structural

- Electrical repairs
  - Hand held tools
  - Repair station

- Non Destructive Evaluation
  - Handheld diagnostic tools
  - Materials identification
  - Closed loop evaluation of fabricated parts
  - Repair process evaluation
First Priority Capabilities Selection Rationale

- Multi-material Joining, Patching and Filling
  - Responsiveness to safety and performance constraints
  - Responsiveness to materials selection by Exploration Systems Mission Directorate
  - Availability
  - Resource efficient
  - Ease of operations

- Electrical Repair Handheld Tool
  - Alignment with failure analysis results
  - Flexibility to contingency failures
  - Minimal mass and volume solution
  - EVA operations

- NDE QA & Safety Troubleshooting and Maintenance (Hand-Held/Portable)
  - Responsive to early spirals
  - Flexibility
  - Availability
  - Stepwise development of NDE capabilities suite
Multi-Material Joining, Patching and Filling

Capability Description:

- Adhesives, tapes, and amalgams-based repairs of similar materials; including:
  - Metals, plastics, composites, glass/ceramics
  - Single and multi-part systems
  - Manual and automatic mixing systems for two or multi-part components

Product Performance Characteristics

- General
  - 'Toolkit' of multiple bonding agents for pressurized cabin, and possible unpressurized special cases

- Materials
  - Metals: -50 to 300° F
  - Plastics: -20 to 200° F
  - Glass/Ceramics: -25 to 2,500° F service temperatures

- Shelf Life: 6 months minimum
Multi-Material Joining, Patching & Filling Tech Gaps

- Identification of adhesive and amalgam materials
  - Compatible with CEV, habitat, robotic equipment, rovers (currently yet to be determined, although will anticipate materials selections commensurate with good aviation/aerospace practices).

- Bonding agent volatility
  - Manned environment off/out gassing during applications

- Storage temperatures and Shelf Life
  - Frequently, typical temperatures advantageous to assuring storage longevity involve some amount of moderate control, including refrigeration at 0 to 40°F, to cases of compatibility with room temperature.

- Longevity of repair
  - Radiation, such as UV, environmental moisture, and external environmental temperature exposure effects may also be significant in inducing deleterious results to the adhesive material strength and life expectancy.

- Qualification
  - Satisfactory and representative flight adhesive repair techniques via appropriate development and preflight verification plan efforts.

- Unknown Environmental effects
  - Microgravity, low-g, and other pressurized/depressurized environmental material behavior - Adhesive/amalgam application/distribution methods
    - Curing requirements - Viscosity requirements - Material strength modification/derating by void content, porosity, and other factors.
Electrical Repair - Hand-held Tool

Capability Description:

- Ability to make temporary and permanent repairs, using a handheld self-contained repair tool, on electronic equipment printed wiring boards and electrical wiring connections during IVA or EVA

  - Solder Joint Repair
  - Wiring Repair

Product Performance Characteristics:

- Materials: Basic solder families for electronic equipment compatible with flight hardware
- Compatibility: Repair is 100% compatible with base material
- Electrical: Functional per baseline design
- Operating Life: MTBF per baseline design
- Process Availability: Crew utilization from tool suite
Electrical Repair Hand-held Tool Technology Gaps

- Functionality and performance in in-space environments: Vacuum, temperature and microgravity effects are untested

- An ergonomic design of the flight hand-held soldering tool is required; current study based on commercial versions of the tool

- Space-qualified electrical repair tool design; current study based on commercial versions of the tool

- Shelf life under operating environments; the effects of space environments on the stability of the material are untested

- Tool and materials compatible with EVA suit; repair tool and repair materials may damage EVA suit.

- Safety issues associated with molten materials; need to encapsulate or enclose molten solder.

- Higher wattage tool needed; to meet repair requirement (approximately 100 W), and possible variable power settings
NDE: QA & Safety Inspection and Troubleshooting

Capability Description:

- Hand-held NDE equipment for routine inspection of critical components
- Hand-held NDE for QA of adhesive bonding
- Hand-held NDE to check wire insulation for cracks and breakages
- Multi-meter for electronic component test and checkout

Product Performance Characteristics:

- Materials: Inspection of wire insulation, metals, composites, ceramics, plastics, habitat materials (concrete, etc.)
- Size of Hardware: Handled and operated by a single crewperson
- Telemetry: Data capable of downlink to ground for analysis
- Defect Detection: Equivalent to current techniques used in the aerospace industry
- Process Availability: Crew utilization from tool suite
NDE Recommendations

- Crack and flaw detection technologies (12 methods evaluated)
  - Thermographic and Laser Ultrasonic selected
    - Laser Ultrasonics is focus of development
    - Thermographic cameras are "commercially ready" with little enhancement required

- Imaging technologies (9 methods evaluated)
  - Digital Radiography and Micro Millimeter Wave selected
    - Downsizing for hand-held/portable
    - Good potential for future capability applications
    - Evaluation of volumetric hardware.

- Electrical Test and Checkout
  - Multi-meter electronic testers are well advanced for basic electronic equipment checkout
  - Oscilloscopes, power supplies, and other 'standard' test instruments
# NDE, QA, and Safety Inspection & Troubleshooting Technology Gaps

<table>
<thead>
<tr>
<th>Gap Description</th>
<th>Application to Technology</th>
</tr>
</thead>
<tbody>
<tr>
<td>Functionality and performance in space environments is not well established</td>
<td>Laser ultrasonic, microwave-millimeter wave, thermography, digital radiography</td>
</tr>
<tr>
<td>Size of equipment is not compatible with hand held operation</td>
<td>Laser ultrasonic</td>
</tr>
<tr>
<td></td>
<td>Microwave-millimeter wave</td>
</tr>
<tr>
<td>Shelf life under operating environments</td>
<td>All technologies</td>
</tr>
<tr>
<td>Imaging technologies are currently functional for surface evaluation only or penetrate only nonmetallics</td>
<td>Microwave-millimeter wave</td>
</tr>
<tr>
<td></td>
<td>Thermography</td>
</tr>
<tr>
<td>Known reference standards required</td>
<td>Thermography, laser ultrasonics, digital radiography, Microwave-millimeter wave</td>
</tr>
<tr>
<td>Coatings may affect results</td>
<td>Thermography</td>
</tr>
<tr>
<td>Robotic NDE capability</td>
<td>All technologies</td>
</tr>
</tbody>
</table>
Lunar & Martian Habitat Structures Development Overview

- Habitat Structures – Introduction
- Habitat Structures – Interfaces
- Habitat Structures – Construction Products
- Habitat Structures – Sub-element Interfaces
- Habitat Structures - Raw Regolith
- Habitat Structures - Block Structures
- Habitat Structures - Reinforced Concrete
- Habitat Structures - Deployable Metal Structures
- Habitat Structures - Thin Films/Inflatable
- Habitat Structures - Glass Products
- Habitat Structures – Fabrication Challenges
- Habitat Structures - Near-Term Development Activities
- Habitat Structures - Potential Tests Requiring Cryogenics Test Bed
Habitat Structures - Introduction

• Habitat Structures Purpose:
  – Develop Lunar and/or Martian habitat structures for manned missions that maximize the use of in situ resources to address the following agency topics:

  • Bioastronautics Roadmap (BR) risks
    – Risks 31-35 (Radiation Health) & 43-44 (ALS)

  • Strategic Technical Challenges defined in Human & Robotics Technology Formulation Plan, v. 3.0
    – Margins & Redundancy
    – Modularity
    – Robotic Networks
    – Affordable Logistics Pre-positioning
    – Reusability
    – Autonomy
    – Space Resource Utilization
Habitat Structures - Introduction

- **Habitat Structures - Requirements**
  - Support a pressurized (shirtsleeve) environment for the crew
  - Protect the crew from a worst case radiation (GCR & SPE) exposure
  - Protect the crew from micrometeorites and exhaust plumes
  - Initially, be able to be fabricated in advance of a manned crew so as to provide immediate protection (semi-autonomous construction)
  - Early, achievable, and visible milestones and successes are required
  - Development should be evolutionary and scalable
  - Present a psychologically/ergonomically compatible living environment for the crew
Habitat Structures – Construction Products

Raw Regolith

Blocks

Sand Bags

Glass Products

Red Glass

Deployable Metal Structures

Thin Films / Inflatable

Reinforced Concrete
Various combinations of construction elements lead to significantly different habitat structure configurations – trade studies and characterization of materials are the key!
Habitat Structures - Block Structures

Compacted Regolith Blocks

Sintered Blocks

Carved Rock
Habitat Structures - Reinforced Concrete

Lunar Contour Crafting (LCC)

Pre-Cast, Pre-Stressed Panels

Inflatable Concrete Structures
Habitat Structures - Deployable Metal Structures

Foldable Metal Structures

Expandable Structures
Habitat Structures - Thin Films/Inflatables

Nested Inflatables

Sprayed Liners

Stand-Alone Inflatables

Structural Support
Habitat Structures – Fabrication Challenges

- Lunar soil (regolith) is well characterized, but from limited locations (Apollo, Luna, Surveyor)
- Probable South Pole location of Moon base is essentially uncharacterized
- Lack of large quantities of high quality Lunar Regolith Simulant (LRS)
- Design must support high tensile loads due to pressurized environment – habitat is a pressure vessel!
- Unique environment requires unique test equipment/facilities
- Pre-manned mission construction requires complex robotics and teleoperations
- Integration of utilities and radiation shielding materials
- Configuration-specific technical challenges, for example:
  - Reinforced Concrete
    - Extruded in place vs. pre-cast, pre-stressed
    - Steel vs. glass rod reinforcement
    - Water-based vs. waterless concrete
    - Hermeticity
Habitat Structures - Near-Term Development Activities

- Lunar regolith simulant characterization
  - JSC-1 (NASA/JSC)
  - JPT-1890 (Jensan Scientific)

- Concrete development/testing
  - Sulfur & LRS-based concrete testing in work
    - Significant improvements in tensile & compressive strength over Portland cement-based concrete
  - Effects of simulant on materials properties to be evaluated
  - Testing with prototype Contour Crafting system at MSFC

- Compacted block development/testing
  - Binderless compacted JSC-1 LRS block did not hold together
  - Evaluating potential binders

- Radiation shielding modeling/testing of candidate configurations

- Evaluation of all technologies with respect to acceptance criteria (being defined), including TRL and RD³ assessment

- Definition of technology exit criteria
Habitat Structures - Potential Tests Requiring Cryogenics Test Bed

- Mechanical properties of block and concrete formulations as a function of temperature (-125 to +125°C)
  - Tensile
  - Compressive
  - Flexural

- Thermal properties of block and concrete formulations as a function of temperature
  - Thermal expansion
  - Thermal conductivity

- Freeze/thaw effects on property integrity

- Thermal gradient effects