https://ntrs.nasa.gov/search.jsp?R=20070037450 2019-08-30T02:04:19+00:00Z

IAC-07-D3.3.02

Fabrication Infrastructure to Enable Efficient Exploration and Utilization of Space

Mr. Joe T. Howell
National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center,
Huntsville, Alabama, United States, joe.howell@nasa.gov

Mr. John C. Fikes
National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center,
Huntsville, Alabama, United States, john.fikes@nasa.gov

Ms. Carole A. McLemore
National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center,
Huntsville, Alabama, United States, carole.a.mclemore@nasa.gov

Mr. Curtis W. Manning
National Aeronautics and Space Administration (NASA)/Marshall Space Flight Center,
Huntsville, Alabama, United States, curtis.w.manning@nasa.gov

Mr. Jim Good
Teledyne Brown Engineering,
Huntsville, Alabama, United States, jim.good@tbe.com

ABSTRACT

Unlike past one-at-a-time mission approaches, system-of-systems infrastructures will be needed to enable ambitious scenarios for sustainable future space exploration and utilization. Fabrication infrastructure will be needed to support habitat structure development, tools and mechanical part fabrication, as well as repair and replacement of ground support and space mission hardware such as life support items, vehicle components and crew systems. The fabrication infrastructure will need the In Situ Fabrication and Repair (ISFR) element, which is working in conjunction with the In Situ Resources Utilization (ISRU) element, to live off the land. The ISFR Element supports the entire life cycle of Exploration by: reducing downtime due to failed components; decreasing risk to crew by recovering quickly from degraded operation of equipment; improving system functionality with advanced geometry capabilities; and enhancing mission safety by reducing assembly part counts of original designs where possible.

This paper addresses the fabrication infrastructures that support efficient, affordable, reliable infrastructures for both space exploration systems and logistics; these infrastructures allow sustained, affordable and highly effective operations on the Moon, Mars and beyond.

INTRODUCTION AND BACKGROUND

NASA's Vision has as a cornerstone the establishment of an outpost on the moon where humans will take up permanent residence rather than just make temporary trips as done during the Apollo era. This outpost will provide the necessary planning, technology development and training for a manned mission to Mars, the next stepping stone beyond the moon. As part of the overall activity, NASA is investigating how in-situ resources can be utilized to improve mission success by reducing up-mass, improving safety, reducing risk and bringing down cost for the overall mission. Marshall Space Flight Center (MSFC) is supporting this endeavour by exploring how the lunar regolith can be mined for uses such as construction, life support, propulsion, power and fabrication. Figure 1 depicts the possible role that regolith has in being able to live off the land just as early pioneers did when settling the United States.

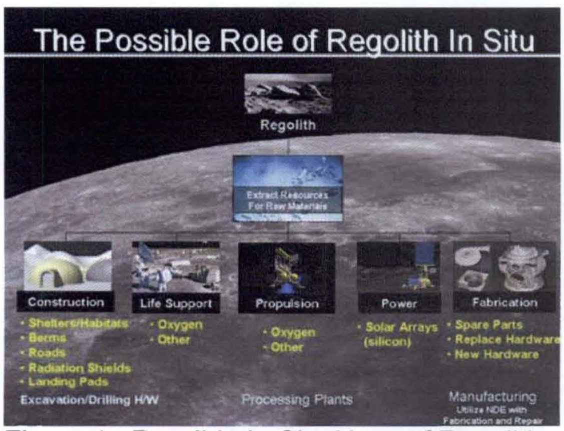


Figure 1. Possible In Situ Uses of Regolith

The technology required that will allow regolith to be processed for oxygen and other volatiles are currently being developed within NASA. As part of the lunar architecture planning, NASA is also evaluating ways to use the regolith for construction of shelters, radiation protection, landing pads and roadways. This paper will focus on the fabrication block shown above in Figure 1. Long-term missions increase the risk of parts, tools, and other vital components breaking. These components are essential to the safety of the crew and vital to long term mission success. As a result, methods to efficiently supply the mission and crew with a reliable source of replacement parts are currently being investigated. Of these methods, rapid manufacturing with Electron Beam Melting (EBM) technology shows promising results. This process is shown in Figure 2 by going from art (CAD model file) to a finished part ready to be utilized by the crew.

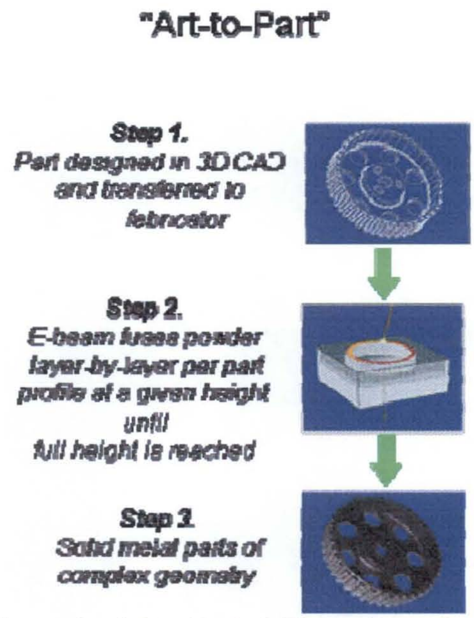


Figure 2. Art to Part: A Three Step Process

EBM technology utilizes an electron beam in a vacuum to melt metal powders and fuse them solidly together. A CAD file is loaded into the machine and once the parameters are all set up properly, an electron beam begins to melt a tub of metallic powder layer-by-layer, additively 'growing' a three dimensional, fully dense object in a matter of hours. Since the part is built additively (layer-by-layer) as opposed to subtractive (milling down a block of metal), extremely complex parts are possible. Besides the benefit of producing parts in record time, minimal material is wasted as well. Also, since a single source material (powder metals) is used or possibly derived from the lunar regolith, a significant reduction in up-mass can be achieved for future space missions. Replacement parts and stock material (metal tubing, sheets, etc.) do not have to be hauled from Earth to the moon.

FABRICATION PROCESSES

Through fabrication technology trade studies performed at MSFC, it was determined that there is no one process that can do it all. Currently, a majority of space-flight hardware is fabricated using typical subtractive processes such as Computer Numerically Controlled (CNC) machining that provides excellent dimensional accuracy and surface finish. On the negative side, this process requires feedstock material that must be larger than the outer envelope of the final part. Additionally, tooling such as hold-down fixtures are needed to perform the machining, and are custom made for each specific part. The total material mass required to arrive at the final part can be substantial. It is anticipated that the best approach for fabrication on the moon will involve a combination of additive and subtractive technologies thereby taking advantage of both processes in order to provide the necessary fabrication capabilities for space exploration.

The additive techniques are similar in nature in that they typically involve building parts layer-by-layer using filaments, powders, liquids or stacked sheets of feedstock materials and are successively joined together to build up a part in three dimensions. In comparison to subtractive technologies, the advantages are clear. No support structures are needed to fabricate a part; the material requirements are less and can be in the form of powders. A bucket of metal or plastic powder can represent many types of parts and eliminates the need for blocks of material or even bar stock. Additionally, in many instances the unused powder can be recycled and used once again. Current additive limitations include reduced accuracy and surface finish compared to traditional machining. Incorporating additive methods with light CNC machining processes, integral to the system design, is currently envisioned to address these limitations. These two techniques, functioning in tandem, would thus provide improved capability over either single process. Based on a materials utilization study already performed, the initial focus of Marshall's fabrication technologies development is on metallic components.

THE ELECTRON BEAM MELTING (EBM) TECHNOLOGY

The EBM technology was chosen for further in-house development due to its ability to produce a fully-dense metal material that yields high strength properties. While surface finish is not at the level desired by many industries or customers, this can be addressed through secondary processes such as CNC machining as discussed above. NASA-MSFC is investigating promising post-processing techniques in order to address the surface finish limitations. Some components used in the aerospace field do not require a polished finish as a requirement, but merely for aesthetic purposes. As this technology advances and becomes established as a viable solution to component manufacturing, the designers must change the way these components are designed.

The EBM process uses a power source to heat a bed of powder layer-by-layer to additively "grow" a part. The source of power used to melt the metal powder resulting in a finished part is the Electron Beam. For similar processes such as Selective Laser Sintering (SLS), a laser is used and has been the backbone of the powder-based systems. The electron beam gun is used in the Arcam machine to fully melt the metal powder. The electron beam has several advantages over the laser, and its popularity is increasing as the early adopters have had success in parts fabrication and material characterization. The efficiency of the electron beam is five to ten times more energy efficient than laser technology. This is important as it results in less power consumption and lower maintenance and manufacturing costs. It is the power of the electron beam that results in the full melt of the powder that allows for good material properties at high build speeds.

The EBM process starts with the pre-heating of the powder bed. The 4 kW electron beam gun is used to perform the pre-heat by using a low beam current but a high scan speed. The pre-heat is performed for two reasons:

1. The pre-heat lightly sinters the metal powder to hold it in place for the build-up of subsequent layers to fabricate the part.
2. The pre-heat provides heat to the fabricated part during the build which reduces the thermal gradient between the last melted layer and the previously melted layers. The consistent temperature of the build will reduce the chance of residual stresses.

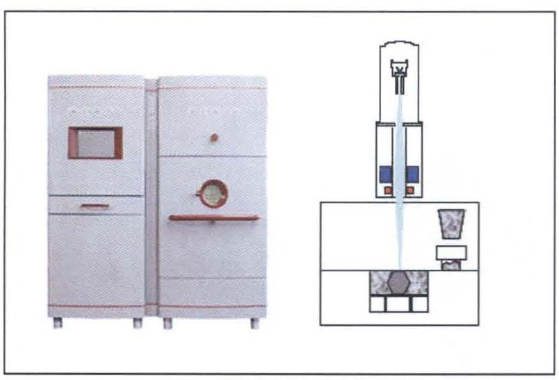


Figure 3. Arcam EBM Machine and Schematic

How does the beam get to the powder bed? The beam is generated by the electron beam gun which is fixed to the top of the vacuum chamber. The beam is deflected appropriately to reach the entire build volume (see Figure 3). The deflection is achieved by a set of two magnetic coils. The first magnetic coil acts as a lens and focuses the beam to the desired diameter. The second magnetic coil deflects the beam to the desired location on the powder bed. Take note that no moving parts are needed to deflect the beam. After proceeding through the magnetic coils, the beam begins melting the powder layer for the part being fabricated. After each layer is melted, the build platform lowers to an amount equal to one thickness layer. A rake distributes the powder across the platen where it is then melted onto the previous layer. This pattern continues until the part has been completed. At this point a helium purge is initiated to minimize the cool-down time. While this is considered an optional feature, the helium purge reduces the cool-down time significantly. Without this option, the part may require in excess of 20 hours to cool, but with the addition of the helium, purge wait times are reduced to three to eight hours depending upon the part size. The height of the part can effect the cool-down time also. After cool down, the door is opened and the loose powder is removed from the part. The part is then bead-blasted to remove any stubborn powder attached to its surface. Now, the part is ready for post-processing of any critical interfaces, such as machining a good surface at a mated interface.

It is important to note that the finished part comes out of the machine fully dense, resulting in high strength values. Again, this is the major difference between the EBM and other powder-based processes. Another characteristic of these processes is the ability to produce unique and complex geometries such as internal cavities that can be used as conformal cooling channels. These channels cannot be easily produced via conventional CNC machining. The EBM process, however, can fabricate a part that contains a lattice core with a solid shell, effectively having a hollow part supported with an internal scaffold. This is a situation where CNC machining is not an option. An example of this type of part, which was made on MSFC's ARCAM machine, is shown in Figure 4. This Environmental Control and Life Support System (ECLSS) part illustrates a scaffold integrated within the four chambers of the flanged component. The scaffold provides a flow path where surface area is maximized, but pressure drop is reduced. This is advantageous for space exploration as life support systems can become more efficient, thereby freeing up power consumption and up-mass. These are important benefits for future Mars missions.

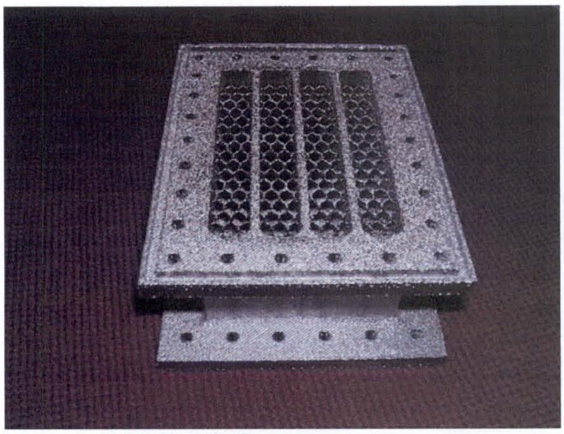


Figure 4. ECLSS Component.

Figure 5. Turbopump Component

Figure 6. Small Engine Block

MATERIALS SET

Before evaluating specific additive techniques, the desired material set was first defined by MSFC. NASA-MSFC researched existing data to determine which materials were primarily used in the fabrication of spaceflight hardware. Another source of information used to determine the initial material set to be investigated was a compilation of failure data representing selected space vehicles. This list contained failed components as well as the component material. The list provided insight into the type of components that may require future repair or replacement, as well as the type of components requiring fabrication, during a long-duration stay on the Moon or Mars. The primary set of metallic materials was identified as shown in Table 1.

Table 1. Primary Metallic Materials Set Targeted for Fabrication Technologies Development

MATERIAL	ALLOY
Aluminum	6061
Aluminum	7075
Titanium	Ti6Al4V
Stainless Steel	316
Stainless Steel	17-4PH
Inconel	625
Inconel	718

Currently, titanium (Ti6Al4V) is the primary material being used with the EBM machine at MSFC. Other materials have not yet been investigated on this particular machine in an attempt to reduce mixing powders of different materials in the same machine, thus, potentially contaminating a part build. However, the Arcam EBM machine is versatile in that it is capable of melting a wide range of materials, and other materials as specified in Table 1 are planned to be utilized in the future. NASA-MSFC has been involved in the development efforts of several of these materials including aluminum alloys, and even lunar regolith simulants, which will be discussed further in this paper. The aluminum development is ongoing and has been a material in high demand from both industry and the military. NASA-MSFC will continue to be on the front-end of this activity in order to direct the development in the most advantageous manner for both NASA and industry.

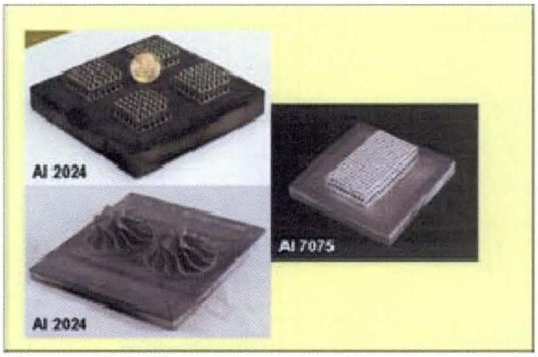


Figure 7. EBM-Fabricated Aluminum Samples

CERTIFICATION OF THE ELECTRON BEAM MELTING PROCESS

The In Situ Fabrication and Repair (ISFR) project at MSFC is advancing technologies to provide fabrication and repair capabilities for space mission equipment with the long-term goal of operating in extraterrestrial environments. Additionally, ISFR activities include fabrication of mechanical components and assemblies on Earth as well as in-transit phases of flight. The current research effort has benefited from the early investigations performed by NASA-MSFC as applied to spaceflight activities. The level of maturity of this technology, even as recent as a few years ago, left a large gap between early state-of-the-art additive manufacturing techniques and techniques achievable now. Although this is true, MSFC was still looking forward in the 1990s and, hence, investigated the possibility of microgravity manufacturing using additive fabrication techniques. Additionally, applications in outer space were investigated and these efforts provided a foundation for the current development program. All of the research investments made by both MSFC and others have enabled significant rapid manufacturing techniques and material development advancements over the last two years, thereby lending weight to performing serious investigations in determining the feasibility of in situ manufacturing for space applications. Although there are still technology gaps and challenges that need to be addressed, the future looks optimistic for in situ manufacturing.

The advancement in additive manufacturing techniques, and especially the EBM technology, has allowed the technology gap to narrow whereby steps for certifying the EBM process as a viable manufacturing method for spaceflight hardware has begun. NASA-MSFC has committed resources to fulfill the certification process for EBM parts made from titanium. MSFC has teamed with the Boeing Company and has begun a testing program that will provide the volume of data required to statistically validate the process. To ensure consistency between parts manufactured on different machines, a process specification will be developed specifying build-to parameters that will constrain the part to meet certain tolerances and yield predictable results as shown in Figure 8.

Initial test coupon data have shown good repeatability and good mechanical properties. Testing is on-going and results will be reviewed and analyzed further.

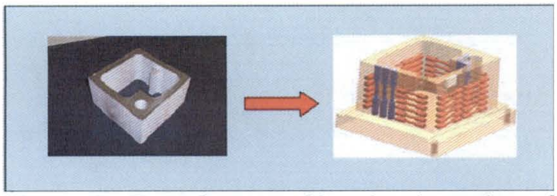


Figure 8. Test Coupon Showing Location of Individual Test Specimens

The certification of the EBM process will provide a significant manufacturing alternative to standard manufacturing processes. Cost of tooling may no longer be a prohibitive factor in making small-run components. This EBM technology provides a means to cost-effectively manufacture a single component needed to get an aging airplane back in the air. Many of these planes have needed parts that require tooling which is no longer available. Traditional manufacturing of tooling for a single part would most likely be so cost prohibitive that the plane would be grounded rather than repaired; however, EBM technology could provide such a part without the additional cost of tooling.

The early results of the certification effort have shown much promise. A large amount of testing, though, must still be completed to have enough reliable data to ensure consistency and confidence in this manufacturing process. The interest and confidence is growing and the continued work by NASA-MSFC and Boeing will further the trend and knowledge base.

IN-SITU FABRICATION USING LUNAR REGOLITH

One of the goals of the ISFR team is to provide manufacturing capabilities on the lunar surface and, subsequently, on the surface of Mars. Additionally, a long-term goal of the ISFR team is to perform manufacturing on the moon and Mars using in situ materials. The lunar regolith is comprised of many components, some of which contain metals such as titanium, aluminum, and iron that could be mined and used as feedstock for an EBM machine on the moon. Obviously, in the near-term, provisioned materials will be the feedstock of choice until more data can be gathered on the success of utilizing and processing in situ lunar materials. There is a significant reduction of up-mass by relying less on spares and depending more on additive manufacturing processes where metal powder could be used to manufacture parts. Analyses of available data from past missions show that a large percentage of failed parts are of sufficient geometry and material-type to be manufactured, in situ, using a process such as the EBM. While this is a great improvement over flying spares, it would also be advantageous to live off the land and develop the ability to mine the metals from the lunar regolith and use it for fabrication of replacement parts, as well as new parts needed.

Some preliminary efforts have been made to determine the feasibility of using regolith as a feedstock material for the EBM machine. Just recently, some lunar regolith simulant, developed by MSFC, was used as feedstock in an EBM machine for processing a part. Interestingly, the preliminary results appear to be quite favorable. Those involved in this trial run assumed that the regolith would not melt, and the beam would blow the material away from the build plate. The general consensus was that a binder (possibly 10%) might be required to get a melt started. However, this was not the case. Initial studies found that sintering occurred in the build. While this was a promising start, there is a lot more work to be done before definitive determinations can be made.

The early results may not be duplicated for different types of regolith or regolith simulants. Not all regolith is comprised of the same chemistry or minerals; thus, possibly producing variance in manufacturing processes and results. Currently, three differing compositions representing three regions or locations on the moon are undergoing analysis using the

EBM process. NASA-MSFC is committed to continue investigating the feasibility of using the lunar regolith as a viable feedstock for EBM processing on the moon.

CONCLUSION

For NASA to accomplish the goals of the United States Exploration Initiative of returning to the moon and establishing a lunar outpost, technologies that take advantage of and utilize the in situ lunar resources will be required. The lunar regolith is a valuable resource. In-situ resource utilization will mine the regolith for not only oxygen and propellants, but also the metals. Building materials for shelters, landing pads, berms, and other infrastructures will utilize the lunar regolith. This research has shown that the fabrication of parts for replacement of failed parts or better designed parts is needed and is feasible. Continued development of this technology will prove to be not only beneficial, but also critical, in establishing an extended human presence on the moon and enabling human exploration to Mars and beyond. NASA-MSFC will continue to research and advance the certification process for various materials used in the EBM machine, investigate better surface finishing options, and gather more data on eventually using raw regolith (or some subset of regolith) for manufacturing parts in situ on the moon.

REFERENCES

Developing Fabrication Technologies to Provide On-Demand Manufacturing for Exploration of the Moon and Mars; M.S. Hammond, J.E. Good, S.D. Gilley, R.W. Howard; 44th AIAA Aerospace Sciences Meeting and Exhibit, Reno, Nevada, USA, January 2006

Rapid Manufacturing with Electron Beam Melting (EBM) – A Manufacturing Revolution?; U. Lindhe, O. Harrysson; Rapid Manufacturing: Utilizing Direct Metals, Dearborn, Michigan, USA, August 2003

Extending Rapid Prototyping Past the Horizon: Applications in Outer Space; K.G. Cooper; Society of Manufacturing Engineers, Dearborn, Michigan, USA, January 2001

Microgravity Manufacturing Via Rapid Prototyping Techniques; K.G. Cooper; Georgia Tech Rapid Prototyping and Manufacturing Symposium, Atlanta, Georgia, USA, October 2001

MSFC-497-Presentation

Marshall Space Flight Center

NASA

FABRICATION INFRASTRUCTURE TO ENABLE EFFICIENT EXPLORATION AND UTILIZATION OF SPACE

International Aeronautical Congress (IAC) 2007 (Aerospace)
Hyderabad International Convention Centre, India
September 24-28, 2007

Presenter: Joe Howell / NASA - Marshall Space Flight Center
joe.howell@nasa.gov

Fabrication Technology Development Overview

CONTENT

- History
- In Situ Fabrication and Repair (ISFR)
- Why is ISFR Technology Needed?
- The Possible Role of Regolith In Situ
- Material Set Definition
- lectron Beam Melting (EBM) Technology
- ication Technologies External Interfaces
- a Viable Feedstock for the EBM Process
- The Mission at Hand...
- rication, Assembly, and Repair Module

A Little Bit of History……….

Exploration Vision for NASA

To go out beyond Earth orbit for purposes of human exploration and scientific discovery

In Situ Fabrication and Repair (ISFR)

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 has focused on 2 primary areas:

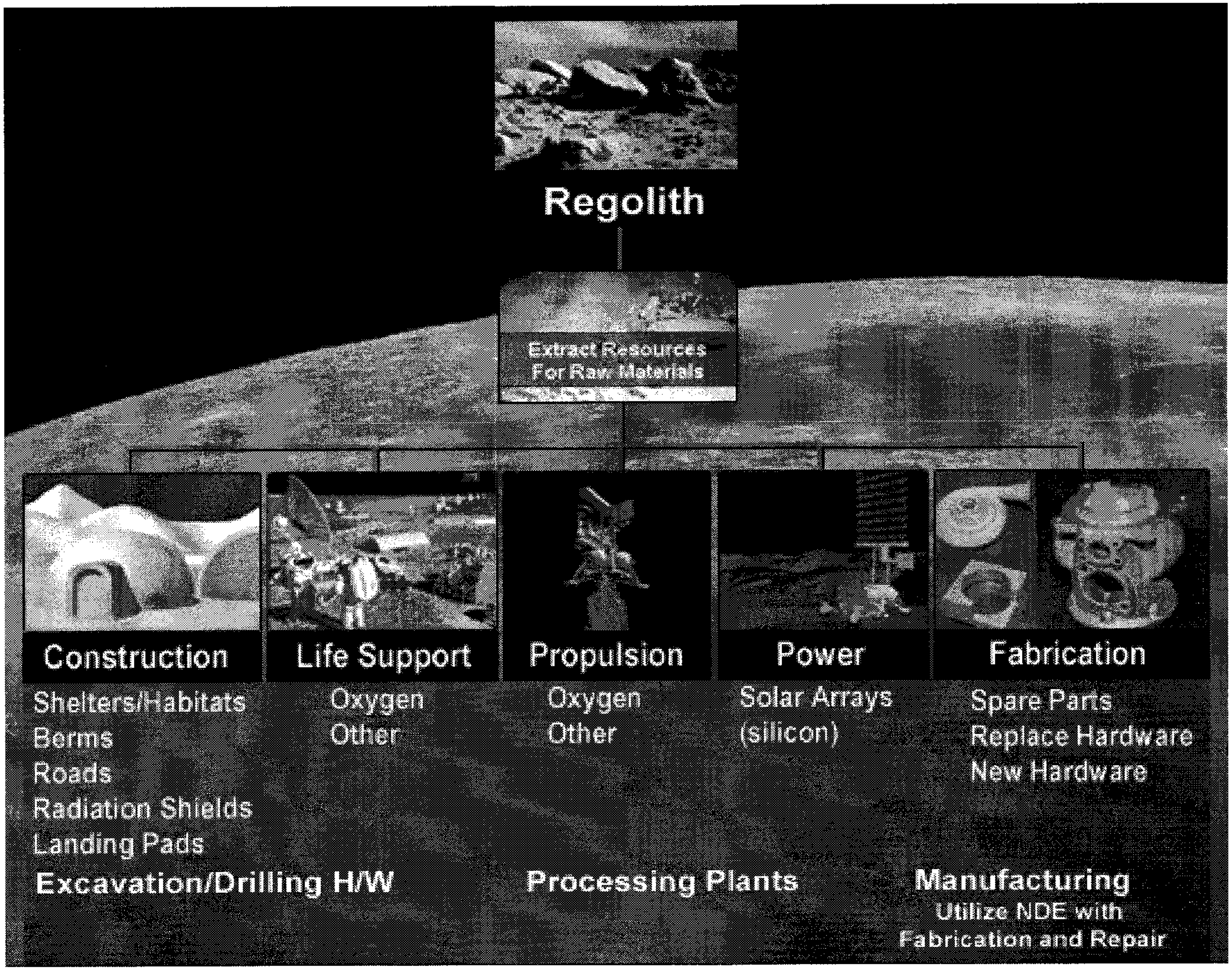
- **Fabrication Technologies**
- **Repair and Nondestructive Evaluation (NDE)**

to go out beyond Earth orbit for purposes of human exploration and scientific discovery

Why is ISFR Technology Needed?

- Longer duration missions without near access to Earth will require increased maintainability of systems
- *<u>Component degradation and failure is inevitable</u>*
- The Space Architect has identified sparing as a principal issue for reducing the mass required for long duration exploration missions
- *<u>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</u>*
- 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)
- <u>Humans living in reduced gravity and harsh environment for extended periods of time must be able to act autonomously for their survival</u>
- 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

The Possible Role of Regolith In Situ



Material Set Definition

The main goal of Fabrication Technologies is to provide rapid manufacturing of parts and tools via a quality-controlled approach that may be a single process or a hybrid mix of additive and subtractive processes.

The set of materials needed to manufacture parts and tools was determined by:

- Failure Analysis Results
- Analysis of Material Identification and Usage Lists (MIUL) of Space Station and Space Shuttle Mid-Deck Payloads
- TIMs with flight-hardware development programs at NASA/MSFC

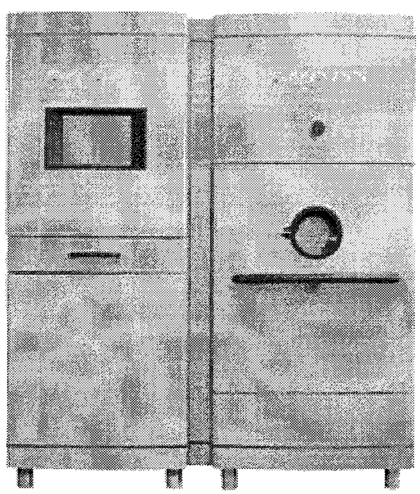
Metallic Material Set Targeted for Fabrication Technology Development

Material
Aluminum
Titanium
Stainless Steel
Inconel

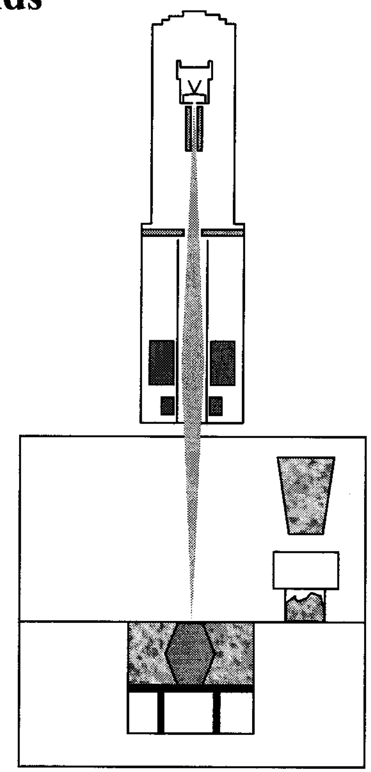
The Electron Beam Melting (EBM) Technology

The EBM Technology was chosen for further in-house (MSFC) development due to its ability to produce a fully-dense metal material that yields good strength properties.

- Surface finish needs improvement
    - Machining of critical interfaces required
- Support structure used for overhangs
- Parts built in a vacuum
- Helium purge reduces cool-down time



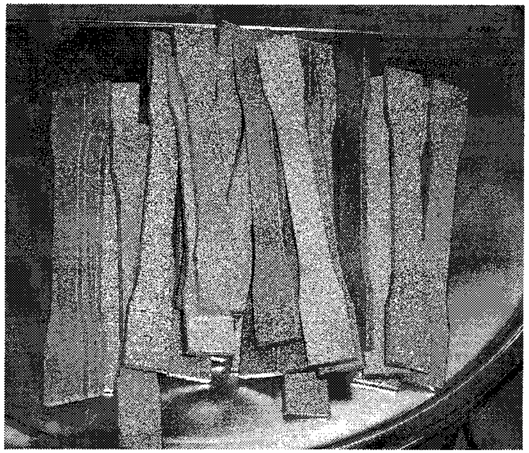
Arcam S12 EBM Machine



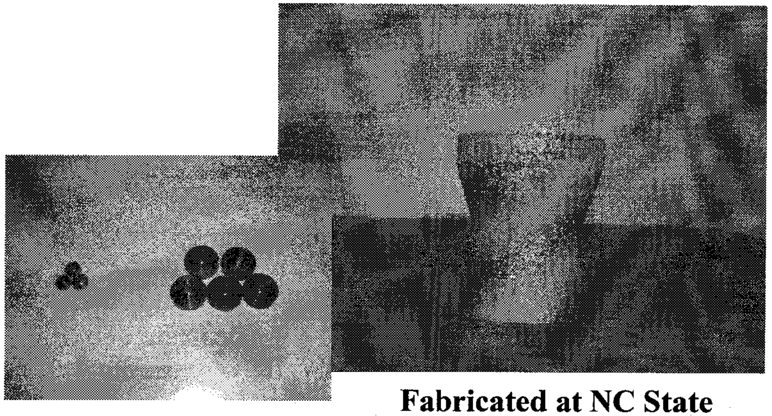
EBM Process

The EBM process uses a power source (Electron Beam Gun) to melt a bed of powder layer-by-layer to additively "grow" a part.

The Electron Beam Melting (EBM) Technology

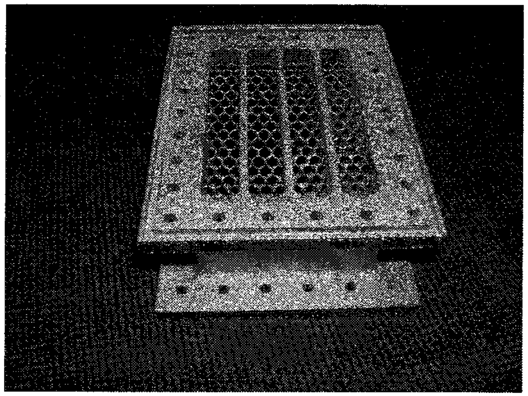


Titanium Tensile Specimens

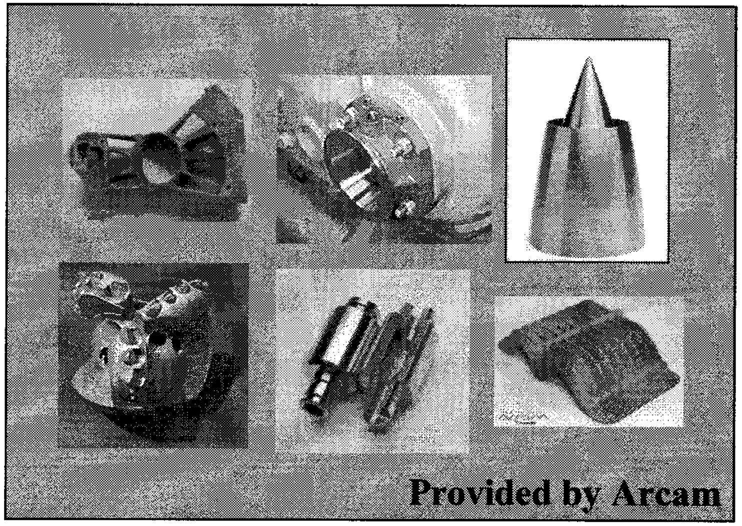


Fabricated at NC State

GRCOP-84 Test Samples
& Development Build



Lattice Structure Test Component



Provided by Arcam

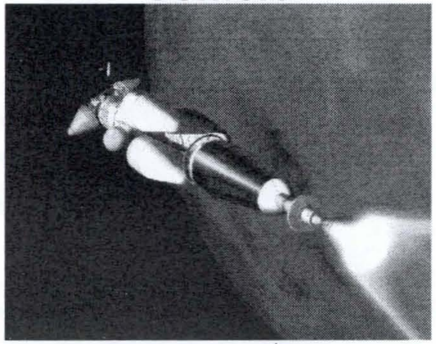
Fabrication Technologies External Interfaces

Crew

Fabrication → Crew
- Replacement/Repair parts

Crew → Fabrication
- Facility Operations
- Assembly, maintenance and repair support

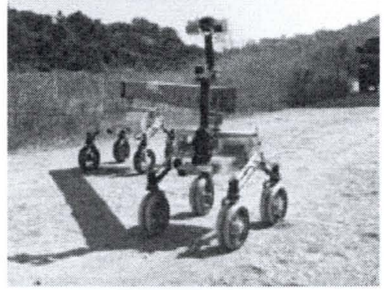
Vehicle



Fabrication → Vehicle
- Repair parts

Vehicle → Fabrication
- Equipment Transport
- In-flight manufacturing and resources

Robotics



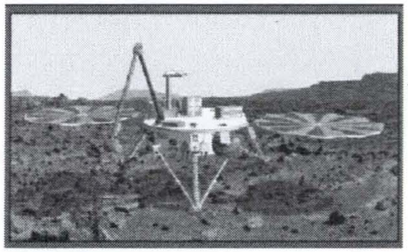
Fabrication → Robotics
- Repair parts

Robotics → Fabrication
- Semi-autonomous Part Manufacturing

ISFR

- Fabrication
- Repair
- NDE/NDI/NDT
- Recycling

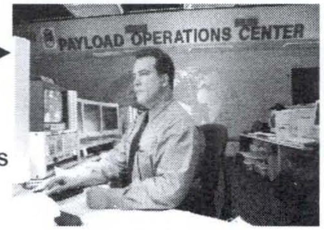
ISRU



Fabrication → ISRU
- Spare parts & repair materials

ISRU → Fabrication
- Feedstock for fabrication and repair materials

Ground Ops



Fabrication → Ground
- Exploration Planning
- In-Situ feedback analysis

Ground → Fabrication
- Operations & Decision Support

Future Applications

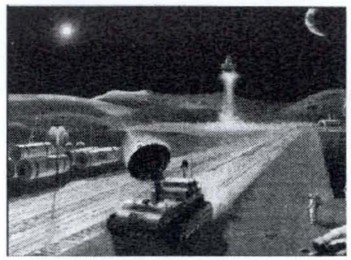
Fabrication → Future
- Technology Development for Future Applications
- Technology Maturation and Extension

ECLSS

Fabrication → ECLSS
- Repair parts

ECLSS → Fabrication
- Power
- Cooling
- Heating

Logistics



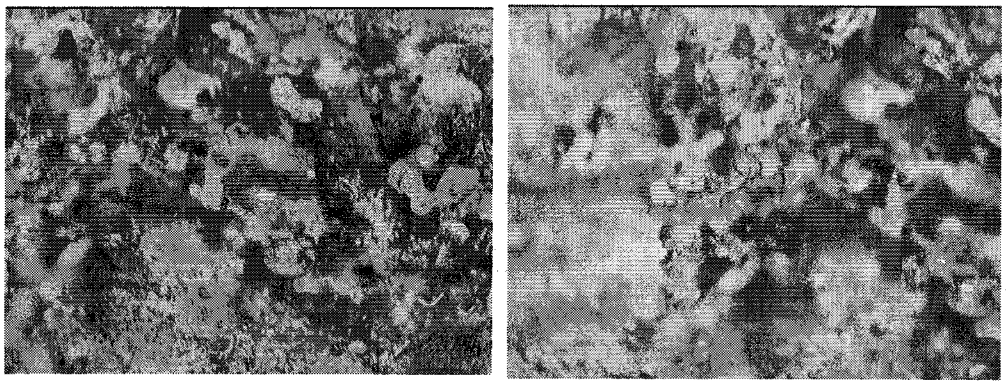
- Provisions
- Parts and Supplies

Fabrication Technologies

Can Lunar Regolith Be a Viable Feedstock for the EBM Process

- Preliminary EBM processing of lunar simulant shows sintering occurs
- Metal Binders in the form of powder can be added for improved melting
- Metal alloys can be extracted from regolith and used as a feedstock material
  -- Some provisioned material would be needed for select alloys
- Not all regolith is the same -- Material characterization is needed for each regolith type

Lunar Simulant LHT-1 was successfully sintered using the EBM process at NC State University



The Mission At Hand...

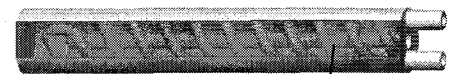
Continue Development of Fabrication Technologies That Can Assist Ongoing Space Programs By Enabling:

- Weight Savings (Honeycombs & Lattices)
- Part Count Reduction (Single Piece Builds)
- Unique Geometries (Internal Passages/Cavities)
- Embedded Components (Sensors, Wires, Inserts)
- Reduced Fabrication and Assembly Resources

Issues!?!

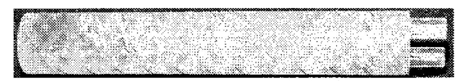
- Process certification is needed and is being addressed
- Further development of Lunar Regolith Fabrication using the EBM process is needed

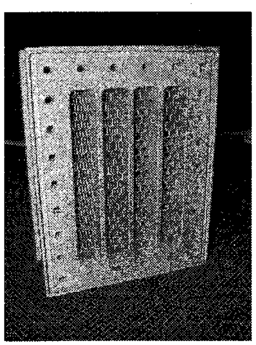
CAD Model



Internal Flow Passages & Cavities

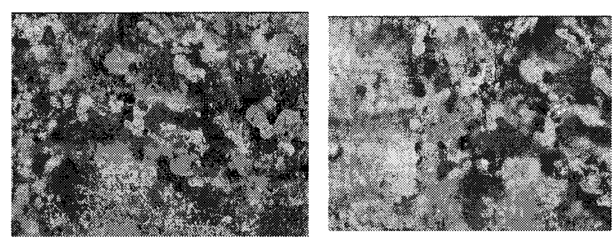
Fabricated Part



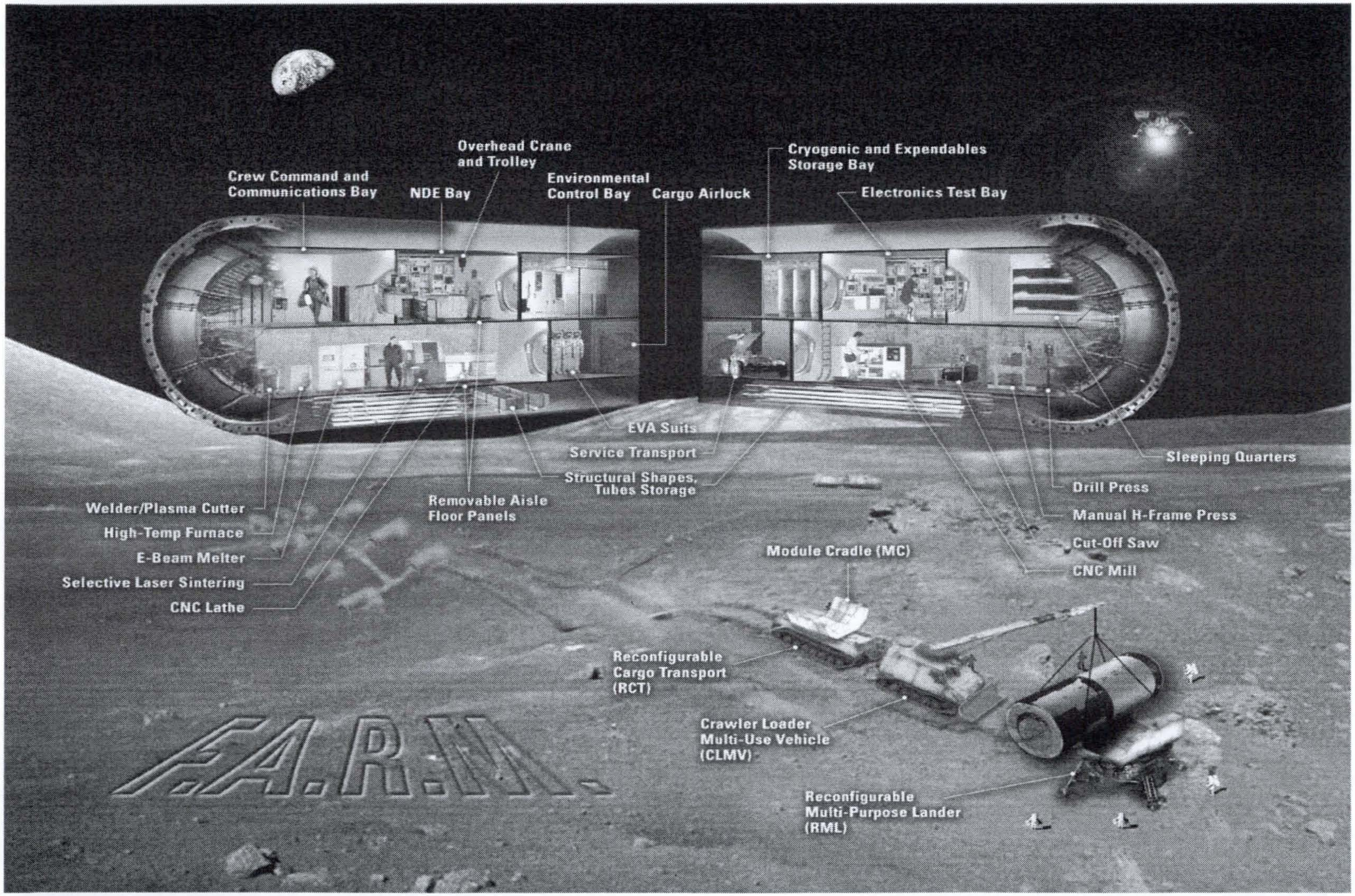


Lattice Structure Test Component

Initial EBM fabrication of lunar regolith simulant reflecting a light sintering



Conceptual Fabrication, Assembly, and Repair Module



Conceptual Rendering **Conceptual Rendering**

Fabrication Technologies