

## **Fabrication in Space – What Materials are Needed?**

In order to sustain life on the moon, and especially on Mars, the inhabitants must be self-sufficient. As on Earth, electronic and mechanical systems will break down and must be repaired. It is not realistic to “send” parts to the moon or Mars in an effort to replace failed ones or have spares for all components. It will be important to have spares on hand and even better would be to have the capability to fabricate parts in situ. The In Situ Fabrication and Repair (ISFR) team is working to develop the Arcam Electron Beam Melting (EBM) machine as the manufacturing process that will have the capability to produce repair parts, as well as new designs, and tooling on the lunar surface and eventually on Mars.

What materials will be available for the inhabitants to use? What materials would be most useful? The EBM process is versatile and can handle a multitude of materials. These include titanium, stainless steels, aluminums, inconels, and copper alloys. Research has shown what parts have failed during past space missions and this data has been compiled and assessed. The EBM machine is fully capable of processing these materials of choice. Additionally, the long-term goal is to use the lunar regolith as a viable feedstock. Preliminary work has been performed to assess the feasibility of using raw lunar regolith as a material source or use a binder combined with the regolith to achieve a good melt.

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Abstract for Arcam User's Group Meeting  
Simi Valley, California  
November 14-15, 2007

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Marshall Space Flight Center



# ***Fabrication in Space***

## ***What Materials are Needed?***

**Arcam User's Group Meeting  
Simi Valley, California  
November 14-15, 2007**

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# Fabrication Technology Development Overview



## AGENDA

- History
  - In Situ Fabrication and Repair (ISFR)
    - Why is ISFR Technology Needed?
    - ISFR Scope
- Fabrication Technologies External Customers
  - Historical Failure Analysis
  - Material Set Definition
- Material Feasibility Studies of Selected Materials
  - Special Studies – Lunar Regolith Fabrication
  - The Mission at Hand...







## A Little Bit of History.....

### Exploration Vision for NASA

President George Bush on January 14, 2004 issued his vision for U.S. Space Exploration:

*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*

### 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)







## 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
- To keep Jim Good Employed!



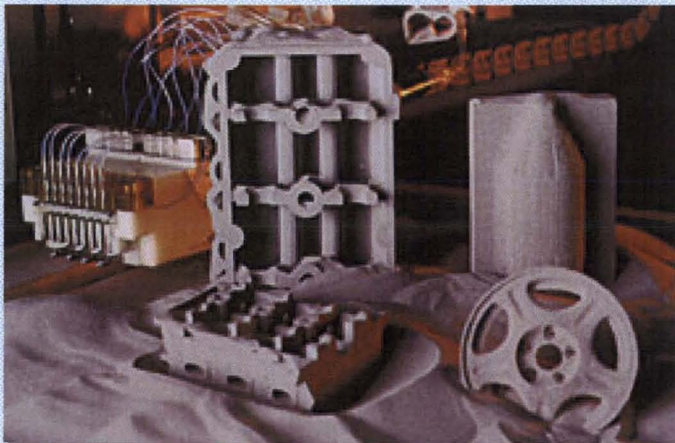
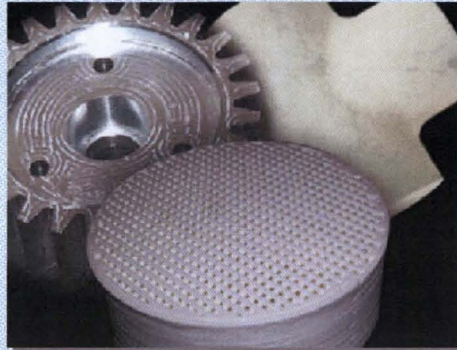


# In Situ Fabrication & Repair (ISFR) Scope

## Fabrication Technologies

capabilities with the following emphases:

- Net shape parts, tools, components with specified geometrical tolerances, strength, and integrity
- Autonomous operation, with the exception of feedstock change-out, normal maintenance, and parts removal
- Integral non-destructive evaluation functions
- Concentration on metal materials
- Replacement parts, unforeseen tools, advanced-life-support parts, habitat fittings



## Repair & Non-Destructive Evaluation (NDE)

capabilities with the following emphases:

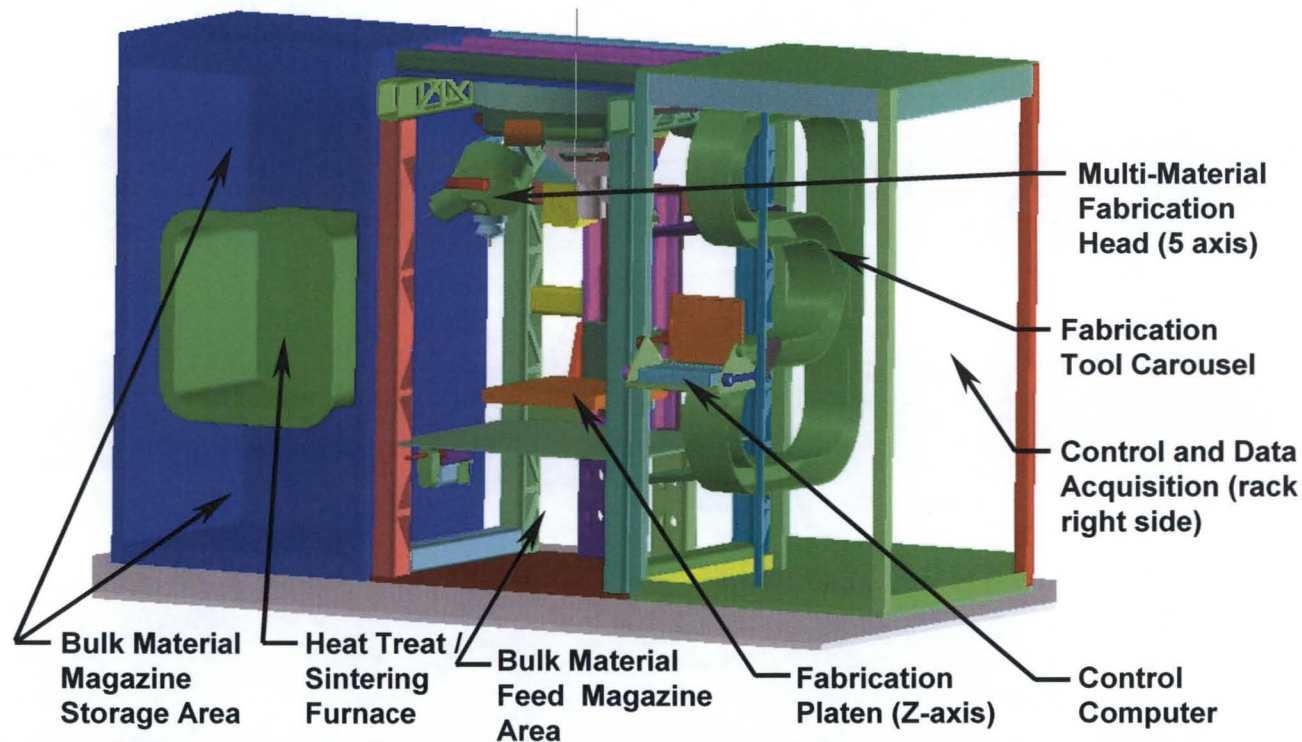
- Multi-material repair by joining, patching, or filling of metals, composites, or plastics
- Handheld soldering tool
- Portable or robotic metal-joining systems
- Portable or handheld NDE systems to perform QA and safety inspections
- Chemical analysis or closed-loop control of in situ processes





## In Situ Fabrication & Repair (ISFR) Scope

- Initially, the Fabrication Technology team concentrated on In Situ Fabrication



**Early Concept for a Multi- Material Fabricator Ground Unit  
(Processing, Metals, Plastics, Ceramics, & Composites)**



## In Situ Fabrication & Repair (ISFR) Scope

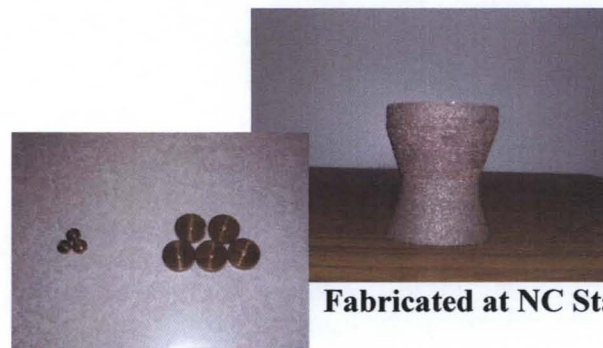
- Currently, the ISFR team has concentrated on near-term applications
  - NASA budget focused on new vehicles
  - Fab Technologies need validation and credibility



**Lower Barrymount**



**Hydrogen Pump Discharge for  
Ascent/Descent Engine**



**GRCOP-84 Test Samples &  
Development Build**

**Fabricated at NC State**



**ECLSS Subscale Test  
Component**



**Titanium Tensile Specimens**



**Damaged part**



**Cylinder Block**







# 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



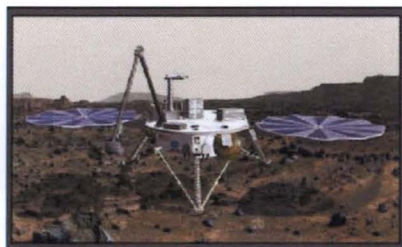
Fabrication → Robotics

- Repair parts

Robotics → Fabrication

- Semi-autonomous Part Manufacturing

## ISRU



Fabrication → ISRU

- Scrap Materials

ISRU → Fabrication

- Feedstock for fabrication and repair materials
- Regolith by-products (glass, metals, thin films, etc.)

## ISFR

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

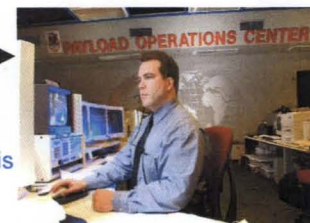
## Ground Ops

Fabrication → Ground

- Exploration Planning
- In-Situ feedback analysis

Ground → Fabrication

- Operations & Decision Support



## ECLSS

Fabrication → ECLSS

- Repair parts

ECLSS → Fabrication

- Power
- Cooling
- Heating

## Spiral "N" Applications

Fabrication → Spiral N

- Technology Development for Spiral "N" Applications
- Technology Maturation and Extension



## Logistics



- Provisions
- Parts and Supplies





# Historical Failure Analysis



**First phase of the Failure History Analysis has been completed**

- Investigated recent failures in space and space-like equipment.

## **Purpose of the Analysis:**

- Initiated in response to BCPR requirements for risk mitigation by reducing the number of unrecoverable failures.
- Investigate existing failure data to determine the percentage of failures that ISFR technologies would be able to either prevent or repair.

## **Analysis Approach :**

- First phase of the Analysis activity focused on ISS Problem Report and Corrective Action (PRACA) database, primarily due to applicability, availability, and ease of querying the data.
- Analysis was directed towards identification of problems resulting from broken or damaged components.
- Identified equipment which are high risk candidates for failure on a mission.
- Follow-on Analysis will occur





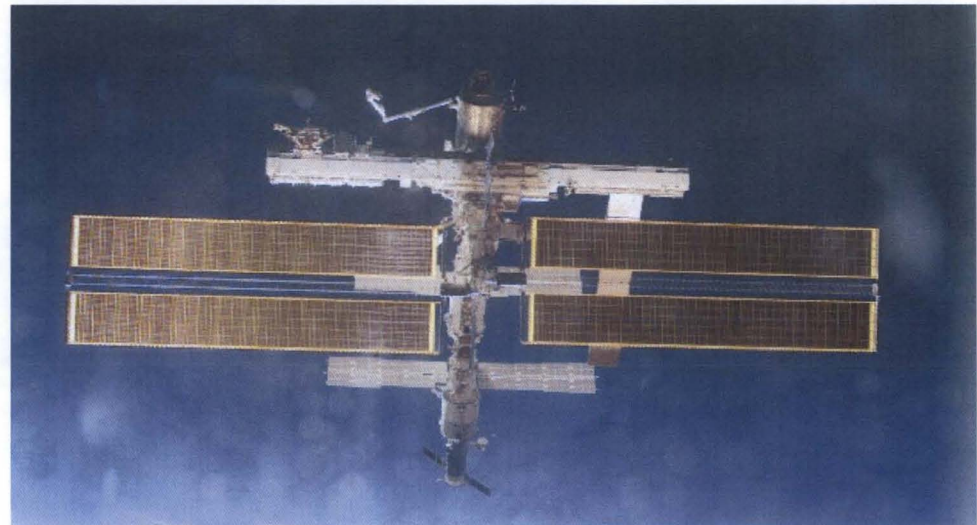


# Historical Failure Analysis



## Summary of Results :

- Phase 1 data concentrated on Environmental Control and Life Support System (ECLSS) and Crew Health Care System (CHeCS)
- Significant percentage of ISS failures could be addressed with ISFR Technologies- Fabrication and Repair/NDE
- Composed a list of materials involved in the failures.
- Charted highest-use materials for the failures.
- This determined the material set of interest for ISFR





## 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	Alloy
Aluminum	6061
Aluminum	7075
Titanium	Ti-6Al-4V
Stainless Steel	316
Stainless Steel	17-4PH
Inconel	625
Inconel	718







# Material Feasibility Studies of Selected Materials

Marshall Space Flight Center contracted Arcam to perform feasibility studies on selected materials that are of interest in the aerospace industry, as well as the military.

- The deliverable consisted of a final report concluding whether the material is a viable candidate for EBM fabrication. Additionally, the “theme” is provided for use in future development efforts.

## Materials Available and Under Development for the EBM Process

Material	Comments
<b>316L</b>	Feasibility Study Performed by Arcam
<b>IN 625</b>	Feasibility Study Performed by Arcam
<b>IN 718</b>	Feasibility Study Performed by Arcam
<b>17-4PH</b>	Feasibility Study Performed by Arcam
<b>Al 6061</b>	Feasibility Study Performed by Arcam
<b>Al 7075</b>	Development Effort Currently Underway by NC State University
<b>AL 2024</b>	Development Effort Currently Underway by NC State University
<b>Ti-6Al-4V</b>	Powder Available through Arcam
<b>Ti-6Al-4V ELI</b>	Powder Available through Arcam
<b>CoCr</b>	Powder Available through Arcam
<b>GRCOP-84</b>	Feasibility Study Performed by NC State University



# Material Feasibility Studies of Selected Materials

## 316L Stainless Steel

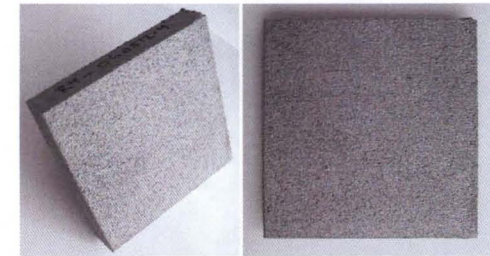
*The feasibility study shows that stainless steel 316L powder behaves well in the Arcam EBM process. The powder has good melting properties and the process has proven stable over several hundreds of melting layers.*

### Tensile Properties

Tensile Properties (RT)	Wrought 316L (ASM Handbook)	Vertical Tensile Bars			Horizontal Tensile Bars		
		060510	060512	060515	060510	060512	060515
Tensile Strength, Ult, Mpa	450-620	539	549	554	384	255	239
Tensile Strength, Yld, MPa (@ .2% offset)	170-310	304	290	287	254	209	190
Elongation at Break, %	30-40	34.5	40.0	34.5	14.5	37	37
Reduction of Area, %	40-50	41	42	40	11	4	3

### Microstructure and Porosity

- No macroscopic porosity in the build material, neither powder-induced nor process-induced
- The material is anisotropic. A layered structure composed of remaining weld lines are seen in the Z cross-sections. The grain structure is austenitic and elongated in the Z direction, resembling columnar grain growth.
- Vertical intergranular cracks are seen in the samples. The crack lengths are up to a few millimeters in the Z direction.
- Small particles are seen in some grain boundaries. This might be segregated material leading to grain-boundary embrittlement.



↑ Build Direction  
→ Layer Direction

↑ Build Direction  
→ Layer Direction

↑ Build Direction  
→ Layer Direction







# Material Feasibility Studies of Selected Materials

## 17-4 PH Stainless Steel

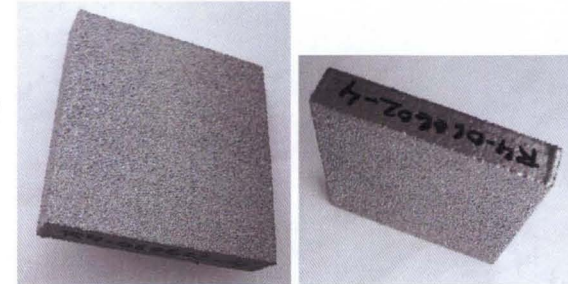
*The feasibility study shows that 17-4 PH metal powder behaves well in the Arcam EBM process. The powder has good melting properties and the process has proven stable over several hundreds of melting layers.*

### Tensile Properties

Tensile Properties (RT)	Wrought 17-4 PH (ASM Handbook)	Horizontal Tensile Bars		Vertical Tensile Bars	
		R4-060602	R4-060607	R4-060602	R4-060607
Tensile Strength, Ult, Mpa	795-1310	1274, 1293	477, 1251	1259, 1267	1174, 577
Tensile Strength, Yld, MPa (@ .2% offset)	515-1170	428, 488	322, 426	473, 495	428, 338
Elongation at Break, %	10-18	12.5, 11.5	1.5, 5.5	14.5, 15.5	13, 3
Reduction of Area, %	35-55	30, 33	3.9	40, 48	24, 5

### Microstructure and Porosity

- There is no visible spherical porosity in the build material.
- There are no visible macroscopic defects (voids, cavities, cracks, inclusions,...)
- The built 17-4 PH material is anisotropic. A layered structure composed of remaining weld lines are seen in the Z cross sections. The grain structure is elongated in the Z direction.
- The material is martensitic with quite small grain size. A coarser microstructure is seen when cooled faster down to room temperature.
- Small dark particles have segregated to the grain boundaries. These might be particles associated with precipitation-hardening.



↑ Build Direction  
→ Layer Direction



↑ Build Direction  
→ Layer Direction



↑ Build Direction  
→ Layer Direction







# Material Feasibility Studies of Selected Materials

## Inconel 625

*The feasibility study shows that IN 625 metal powder can be used in the Arcam EBM process. The powder has good melting properties and the process has proven stable over several hundreds of melting layers.*

### Tensile Properties

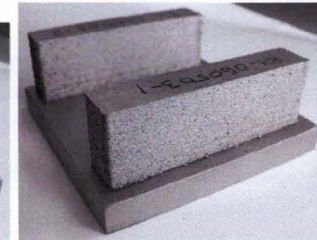
Tensile Properties (RT)	Wrought IN 625 1)	Cast IN 625 2)	051207	060428	060502	060503
Tensile Strength, Ult, Mpa	930	710	702, 673	773, 780	784, 789	746
Tensile Strength, Yld, MPa (@ .2% offset)	517	350	349, 355	423, 424	426, 430	395
Elongation at Break, %	42.5	48	34.5, 27	41.4, 44.5	38.5, 40	44.5
Reduction of Area, %	Not specified	Not specified	37, 28	59, 66	41, 66	61

1) Annealed – ASM Handbook, 10<sup>th</sup> Ed., Vol. 1, P. 984

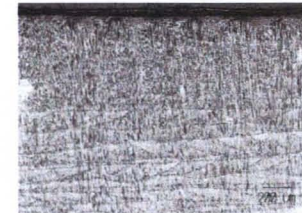
1) Cast – ASM Handbook, 10<sup>th</sup> Ed., Vol. 1, P. 958-960

### Microstructure and Porosity

- There is no visible spherical porosity in the build material using the P227 powder. Spherical pores are seen in the build material using the P175 powder.
- There are no visible macroscopic defects (voids, cavities, cracks, inclusions,...)
- The built IN 625 material is anisotropic. A layered structure composed of remaining weld lines are seen all over the cross sections. The layered structure gradually fades from the top to the bottom of the builds, indicating a thermal ageing of the material.
- The microstructure is predominantly aligned parallel to the Z direction, resembling directional solidification (columnar grain growth).



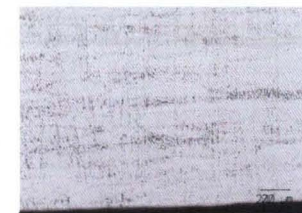
↑ Build Direction  
→ Layer Direction



↑ Build Direction  
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# Material Feasibility Studies of Selected Materials

## Inconel 718

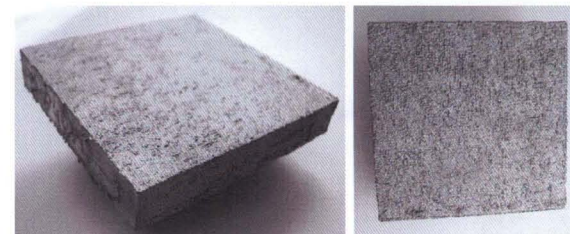
*The feasibility study shows that IN 718 metal powder can be used in the Arcam EBM process. The powder has good melting properties and the process has proven stable over several hundreds of melting layers, provided that the build temperature is kept very high, close to 1000°C.*

### Tensile Properties

Tensile Properties (RT)	Horizontal Tensile Bars			Vertical Tensile Bars		
	R4-060919			R4-060919		
Tensile Strength, Ult, Mpa	1077	1074	1030	675	908	950
Tensile Strength, Yld, MPa (@ .2% offset)	832	840	794	518	701	787
Elongation at Break, %	23	23	18.5	7	5.5	5.5
Reduction of Area, %	28	32	15	38	11	12

### Microstructure and Porosity

- The grain size is fine and anisotropic. The grains are very elongated in the build direction, resembling directional solidification (columnar grain growth).
- A layered structure showing remaining weld lines are seen all over the cross sections. The layered structure gradually fades from the top to the bottom of the builds, including a slow thermal ageing of the material.
- There are areas of poor interfusion between layers, indicating that further process optimization and/or better vacuum are needed.
- The material appears dense when inspected in a polished condition.



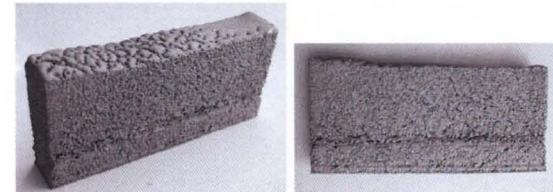




# Material Feasibility Studies of Selected Materials

## Aluminum 6061

*The feasibility study shows that there are three basic problems to be solved with the AL 6061 from metal powder, using the Arcam EBM machine. The powder distribution system does not work well for the tested powder. Too much magnesium is evaporated. Large vertical cracks, probably hot cracks, exist in the built material.*

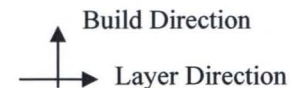
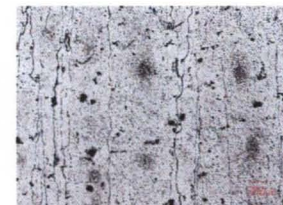
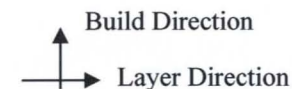


## Tensile Properties

**The built material broke during machining. The fracture surfaces indicate that the machining failure is due to large vertical cracks in the material.**

## Microstructure and Porosity

- Etched cross sections in the build direction (Z) and in the layer direction (XY) are not of good quality and show a pronounced columnar grain growth.
- The grains are coarse and very elongated in the build direction. It is likely that the vertical cracks have propagated along the vertical grain boundaries.







## Special Studies – Lunar Regolith Fabrication



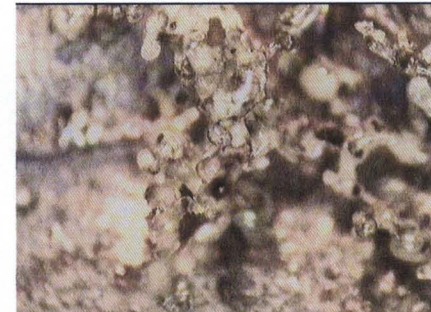
### • In Situ Resource Utilization (ISRU)

*The ISRU works to establish, evaluate and assess the in situ resources available on the moon and Mars and the **technologies needed to utilize and exploit these resources.***

Marshall Space Flight Center (MSFC) is playing a significant role involving the Lunar Regolith

- Defining the Requirements for the production of lunar regolith simulant
- Overseeing the production of several tons of lunar simulant

The ISFR team seeks to determine the feasibility of lunar regolith as a viable feedstock for the fabrication of component parts.

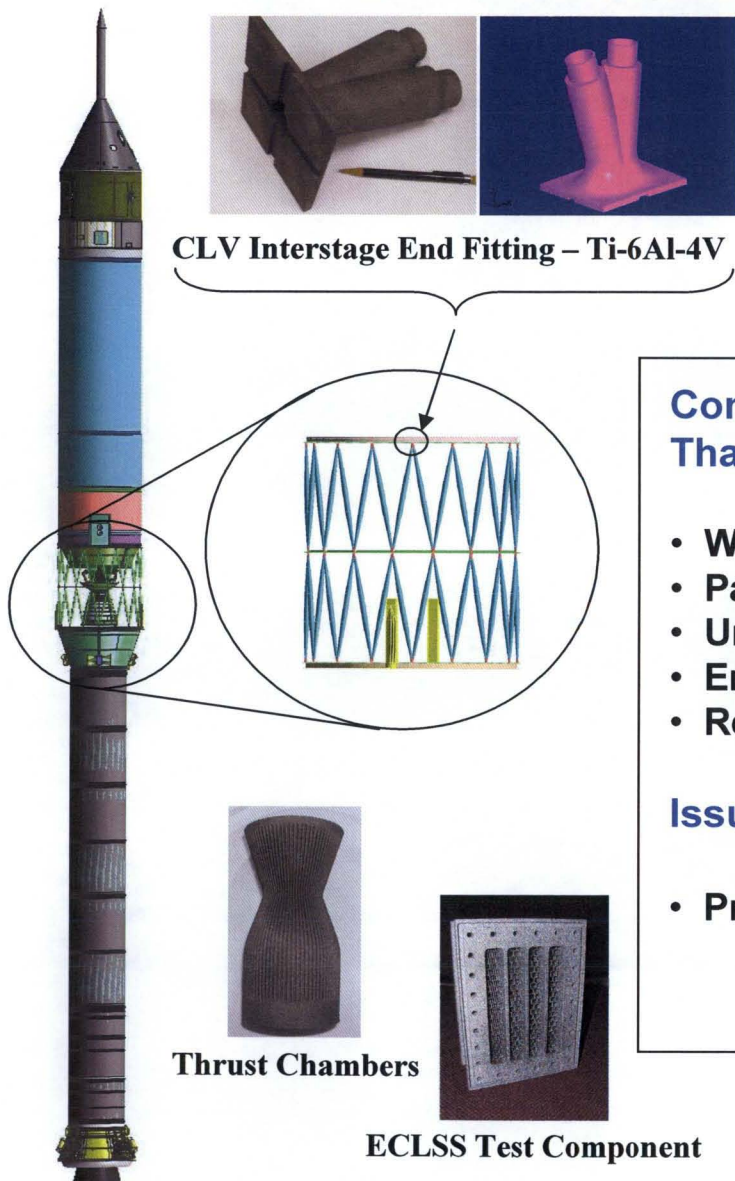


North Carolina State University has performed a “quick-look” assessment using the EBM machine and a small portion of lunar simulant, as provided by MSFC. Arcam has a small volume of simulant and will perform a similar study with a simulant that represents a different recipe.





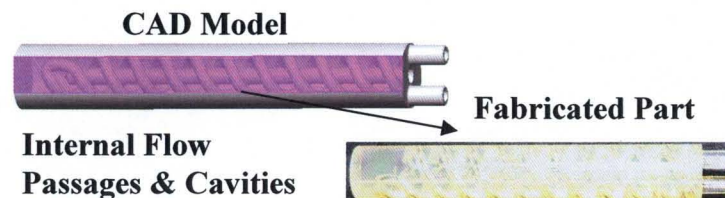
## The Mission At Hand...



CLV Interstage End Fitting – Ti-6Al-4V

Thrust Chambers

ECLSS Test Component



CAD Model

Fabricated Part

Internal Flow  
Passages & Cavities

### 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

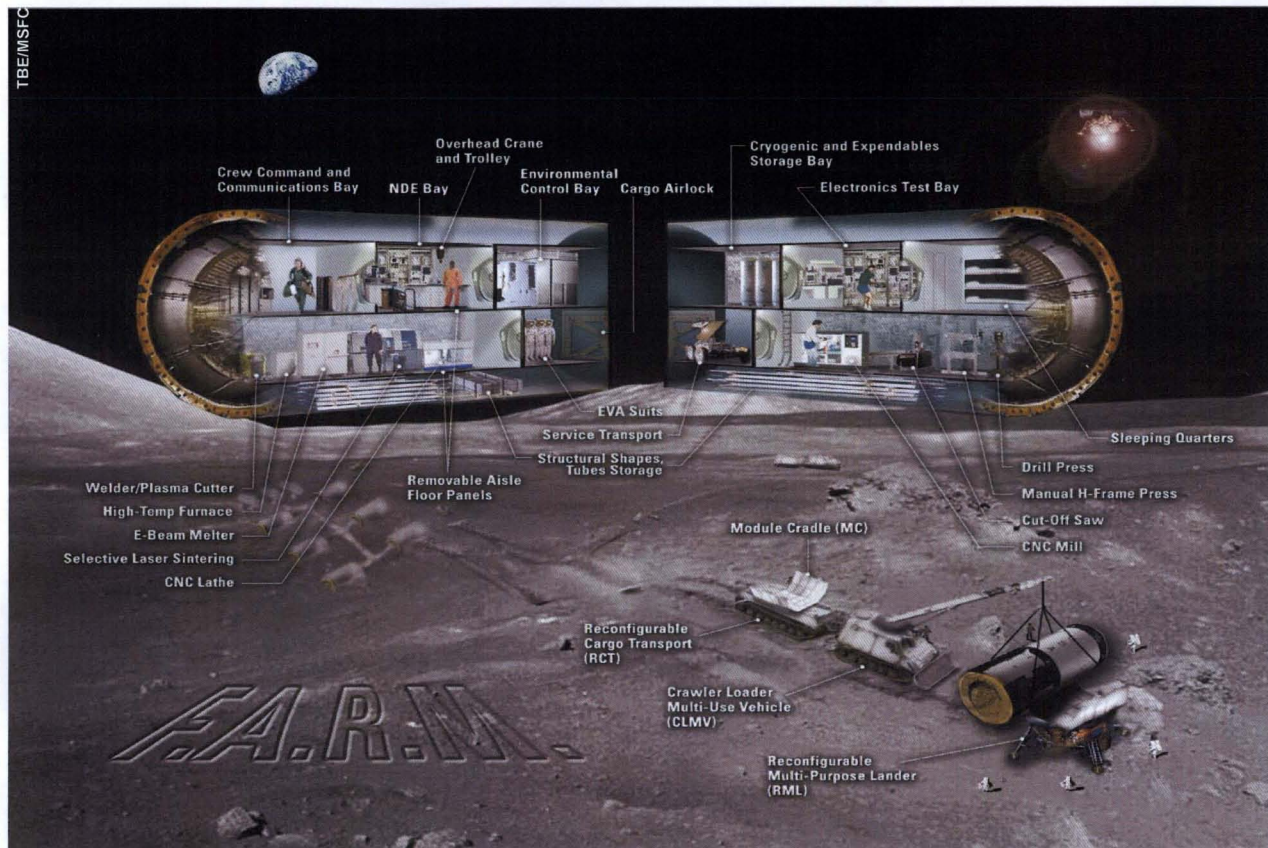
### Issues!?!

- Process certification is needed.
  - Teamed with Boeing-St. Louis to certify titanium components fabricated using the EBM process.





# Fabrication, Assembly, and Repair Module



For more information: **Carole McLemore, Project Manager**  
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