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On-Site Fabrication Infrastructure to Enable Efficient Exploration and Utilization of Space

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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. So what do we do when we get to the moon for sustainable exploration. On-site 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 on-site 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 has worked closely with the ISRU element in the past year to assess the ability of using lunar regolith as a viable feedstock for fabrication material. Preliminary work has shown promise and the ISFR Element will continue to concentrate on this activity. Fabrication capabilities have been furthered with the process certification effort that, when completed, will allow for space-qualified hardware to be manufactured. Materials being investigated include titanium and aluminum alloys as well as lunar regolith simulants with binders.

This paper addresses the latest advancements made in the fabrication infrastructures that supports efficient, affordable, reliable infrastructures for both space exploration systems and logistics; infrastructures that allow sustained, affordable and highly effective operations on the Moon and beyond.

INTRODUCTION AND BACKGROUND

The U.S. Space Exploration Policy 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 can play in being able to live off the land just as early pioneers did when settling the United States.

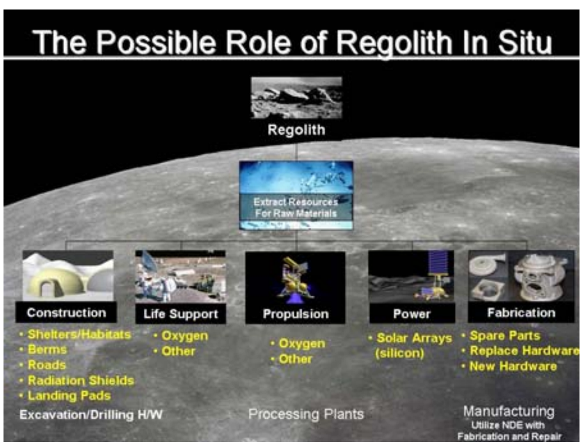

Figure 1. Possible In Situ Uses of Regolith

The technology required that will allow regolith to be processed for oxygen, other volatiles and metals 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 and actually build new systems on-site 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.

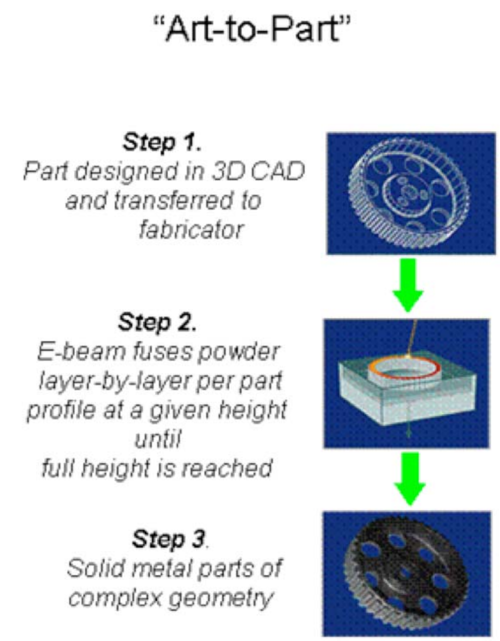

Figure 2. Art to Part: A Three Step Process

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 on-site 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 subtractive 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 focused on metallic components.

THE ELECTRON BEAM MELTING (EBM) TECHNOLOGY

The EBM process is one of a few additive manufacturing processes that fabricate parts by melting metal powders layer-by-layer. The basics are similar in that the input to the process is a CAD model of the part, which is sliced into many horizontal 2-D layers. The laser, or electron beam in our case, sinters or melts each successive layer. After the layer is melted, the build platen is lowered and a rake system applies a new layer of powder whereas the next layered geometry is lasered or heated with the electron beam. This pattern continues until the part is complete. After a cool down, the part is removed from the bed of powder and cleaned.

The EBM process stood out from the crowd by producing a 100% dense part. The laser-based processes sinter the part and results in porosity of the part. This will affect the overall strength characteristics and will not be suited for certain applications. A trade study was performed on all additive manufacturing techniques that could process metals. The EBM scored the highest because of the material properties as well as the number of metal materials that can be processed in the machine.

The EBM machine is capable of fabricating complex geometries, Figure 3, such as a lattice structure or can provide an internal passage, which are both geometries that cannot be fabricated using traditional methods. Additionally, where an assembly is designed based on manufacturing, the EBM allows more freedom to design based on function. For example, a 10-piece assembly can be re-designed as a single piece when considering the capabilities of the EBM technology. This coulld prove to be an invaluable resource while on the moon.

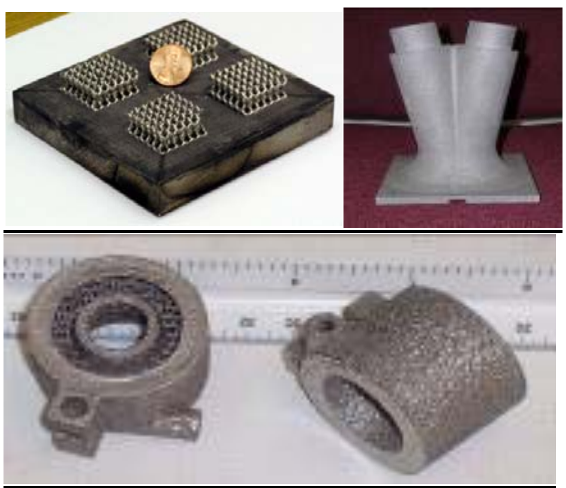

FIGURE 3. EBM-Fabricated Components

EBM FABRICATION OF LUNAR REGOLITH SIMULANT

There are a few ways to approach the use of regolith using the EBM process. The most advantageous method would be to use the raw regolith, as mined from the lunar surface, and processed to a fine powder for use. The regolith has aluminum, titanium, and iron among its mineralogy and will work well in the EBM process. The question is whether there is enough to get a good melt resulting in a structurally adequate part or will the part become too brittle. This is just one of the questions that will be answered as part of the effort underway at MSFC. In addition to the raw regolith builds, investigation of a binding material is being assessed. Initially, pure aluminum was chosen as a binder.

The use of a binder also brought up questions and complications. Initially, the aluminum binder was mixed with the LHT-1M regolith. It was mechanically rolled in a bucket in order to get a homogenous mixture. The EBM system melted a layer of the mixture and an assessment of this mixture was made. The layer held together and showed that sintering occurred. It was also noted, under the microscope, that the melt was not homogenous and there existed sections of melted regolith and sections of melted aluminum. The next round of builds would consist of regolith and aluminum that had been alloyed by passing the regolith and binder through a ball mill. The regolith was coated with the aluminum. The ball mill successfully combined the materials and the resulting melt reflected better consistency.

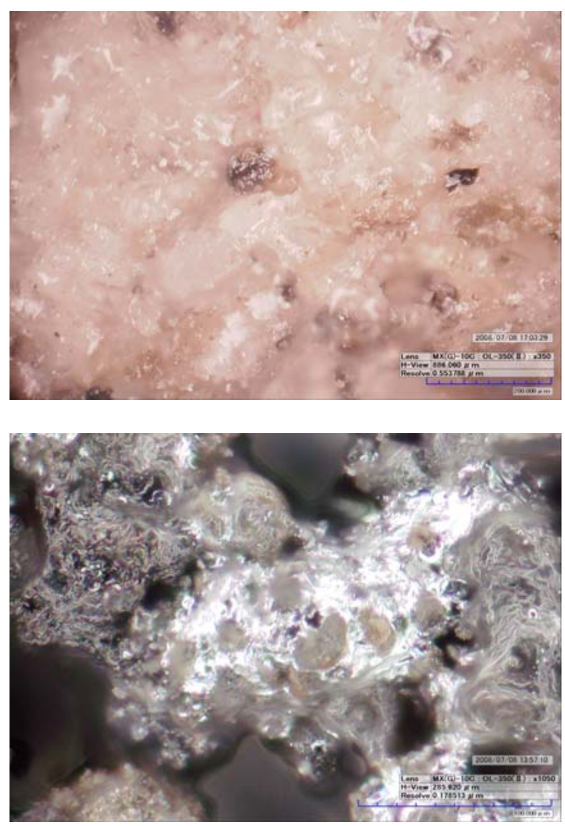

FIGURE 4. Raw Regolith Sintered and Regolith Trapped in Aluminum

The initial builds have been limited to single layer melts. An understanding of the melt can be achieved by analyzing a single layer and the turn-around time for subsequent builds can be minimized. Several iterations, varying beam speed and current, have been performed and the melt has been optimized. Multi-layer builds have been achieved and showing progress. Upcoming builds will optimize the proper ratio of regolith to binder. The optimal ratio would limit the amount of aluminum required in the mixture. In the best possible situation, no binder would be needed. This appears unlikely based on the preliminary results.

As the optimized parameters are determined, tensile specimens will be fabricated and tested for structural integrity. Tweaking of the parameters will be assessed through continued mechanical testing.

There is an interest in the LHT-1M simulant and the bulk of the assessment will focus on this specific regolith type. The JSC-1 has undergone preliminary melts and will be assessed further. The LHT-1M simulant represents the region found at the lunar poles and this area is seen as a possible location for the lunar outpost. This project has acquired approximately 90 pounds of the LHT-1M regolith with the possibility of additional powder required for on-going assessment.

Once the builds have been optimized, a chemical analysis will be performed in order to determine if any constituents have been evaporated. How close is the chemistry before and after the build? That will be determined prior to the end of this activity.

FUTURE WORK

This activity will be completed at the end of the 2008 calendar year. This will, however, not end the need for more development work with the regolith and the goal of living off the land. This effort concentrates on using the raw regolith simulant and binder to arrive at a feedstock capable of producing a structurally-adequate part. A complementary effort will look at specific metals that can be extracted out of the regolith. Beneficiating specific elements out of the regolith would provide a pure material for various needs on the lunar surface. With respect to fabrication, it would provide the EBM system with a suite of materials available for repair, replacement, or the fabrication of new designs. What materials are capable of extraction? Table 3 on the following page provides a list of materials that can be mined and/or produced on the lunar surface. Some provisioned materials may be needed to provide specific alloys. Table 3 will show which materials need provision materials and how much. This provides an idea of the most promising materials available for in situ manufacturing.

Future work will involve demonstrating the feasibility of melting these in situ materials using the EBM system. There may be readily available in situ materials that are not good candidates for the EBM system. Which ones are they? This must be determined.

Oxygen extraction will be a critical activity and needed resource on the moon. The oxygen would provide life support for the inhabitants as well as a needed component for fuel. This extraction process results in a byproduct consisting of metals. On the lunar surface, efficiency is extremely important and the ability to recycle this "waste" is significant. The ability of the EBM process to manufacture parts using the metal waste would show the value of such an in situ manufacturing capability.

The EBM process can produce a fully dense part that exhibits wrought properties for titanium alloys. Also, with the ability to produce complex geometries, the EBM process can play an important role in the manufacturing of spaceflight hardware. A collaborative effort between MSFC and Boeing-St. Louis has involved validating the

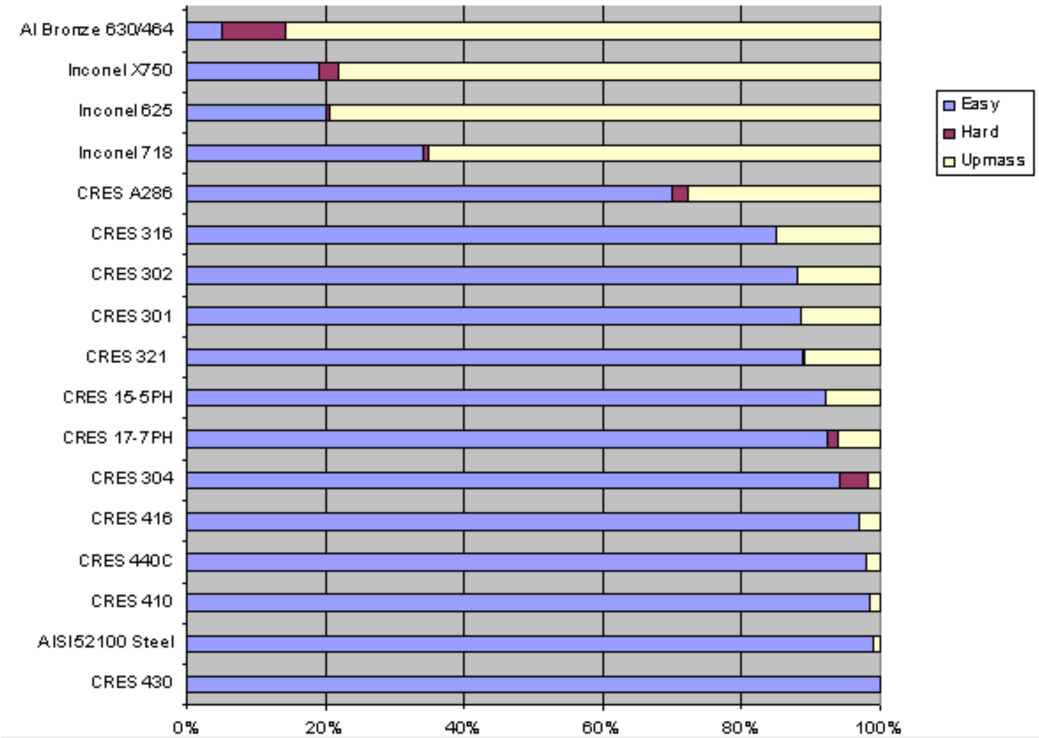

TABLE 3. Potential Materials Extracted from Lunar Regolith

EBM process through mechanical testing. That is the first step in certifying the EBM process. The next section will discuss this effort further.

PROCESS CERTIFICATION EFFORT

As previously mentioned, MSFC and Boeing-St. Louis has collaborated on an effort to certify the EBM process for the fabrication of spaceflight hardware. The testing was based on the AMS 4999 specification, which is a material spec for deposited TI-6Al-4V. Additionally, the draft spec has been modified to include the EBM process.

The mechanical testing of coupons, Figure 5, has been successfully completed and the results satisfy the requirements of the AMS 4999 specification.

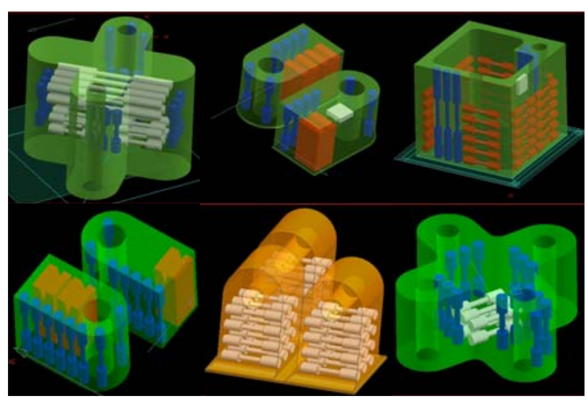

FIGURE 5. EBM-fabricated blocks and individual test coupons

CONCLUSION/SUMMARY

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. At the time of publication, this paper presented the activity performed, to date, involving the EBM fabrication using lunar regolith simulant. The end result should produce the optimal parameters to achieve the best possible lunar regolith EBM build. The ratio between regolith and aluminum (binder) should be determined. The ability to use lunar regolith as feedstock for long-duration missions to the moon or beyond will be a significant capability. Current results show the regolith will sinter and the addition of a binder increases the quality of the melt.

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 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.

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Contents

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- In-Situ Fabrication Team
- Teledyne Brown Engineering
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- North Carolina State University

History

U.S. Space Exploration Policy

To go the moon and beyond for purposes of human exploration and scientific discovery

In Situ Fabrication and Repair

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 U.S. Space Exploration Policy.

The ISFR Element was focused on 2 primary areas:

- Fabrication Technologies
- Repair and Nondestructive Evaluation (NDE)

Why an ISFR On-Site Infrastructure?

To sustain a presence on the Moon an on-site infrastructure will be needed to take advantage of in-situ resources rather than depending on bringing everything from Earth.

- Reduce up-mass requirements
- Produce spare parts on site as needed
- Shorten failed systems downtime
- Increases operational capabilities and flexibility
- Manufacture tools on site
- Overall reduction in life-cycle costs
- Enhances mission safety
- Enables human missions beyond the Moon

Technologies That Enhance A Sustained Presence On The Moon

Regolith Simulants

Potential Customers:

Internal: Constellation, ETDP, SMD

O_2 Production & H_2O Extraction

Potential Customers:

Internal: Lunar Payload, Constellation, ETDP, SMD

Fabrication

Potential Customers:

Internal: ECLSS, LAS, Orion, Ares I, Ares V, ETDP

External: DoD

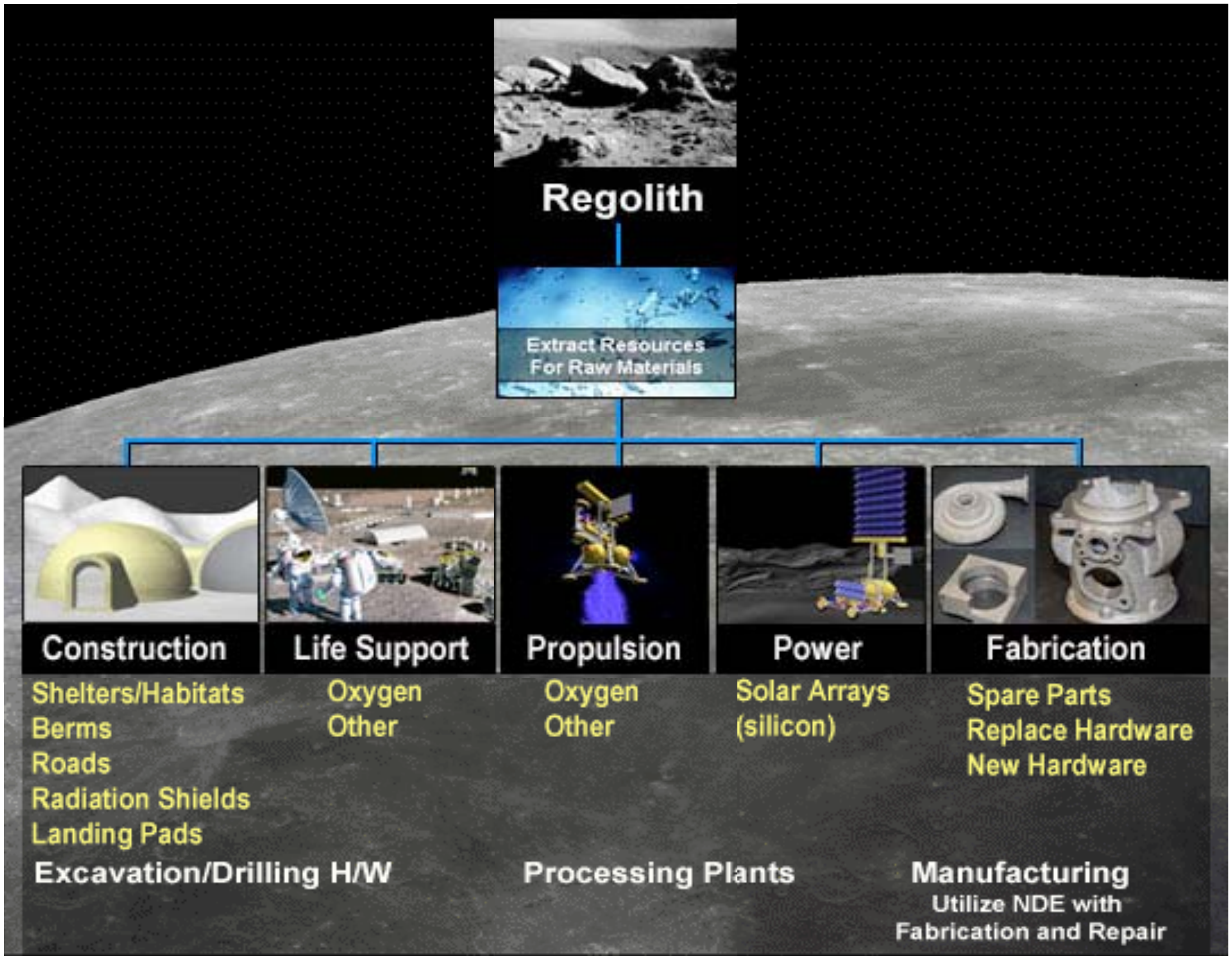
Non-Destructive Evaluation

Potential Customers:

Internal: STS/ISS, ETDP Constellation

External: DoD

The Possible Role of Regolith In Situ



On-Site Fabrication on Moon

Options for spare parts on the moon:

- Risk free – bring spares
- Some risk - provision feedstock
- Greater risk - mine the regolith for metals

Options for reducing risk:

- Risk mitigation – certifying processes on Earth
- Using simulants and binders
- In future, plan demos on Earth and possibly precursor missions

Challenges to implement EBM fabrication on the Moon:

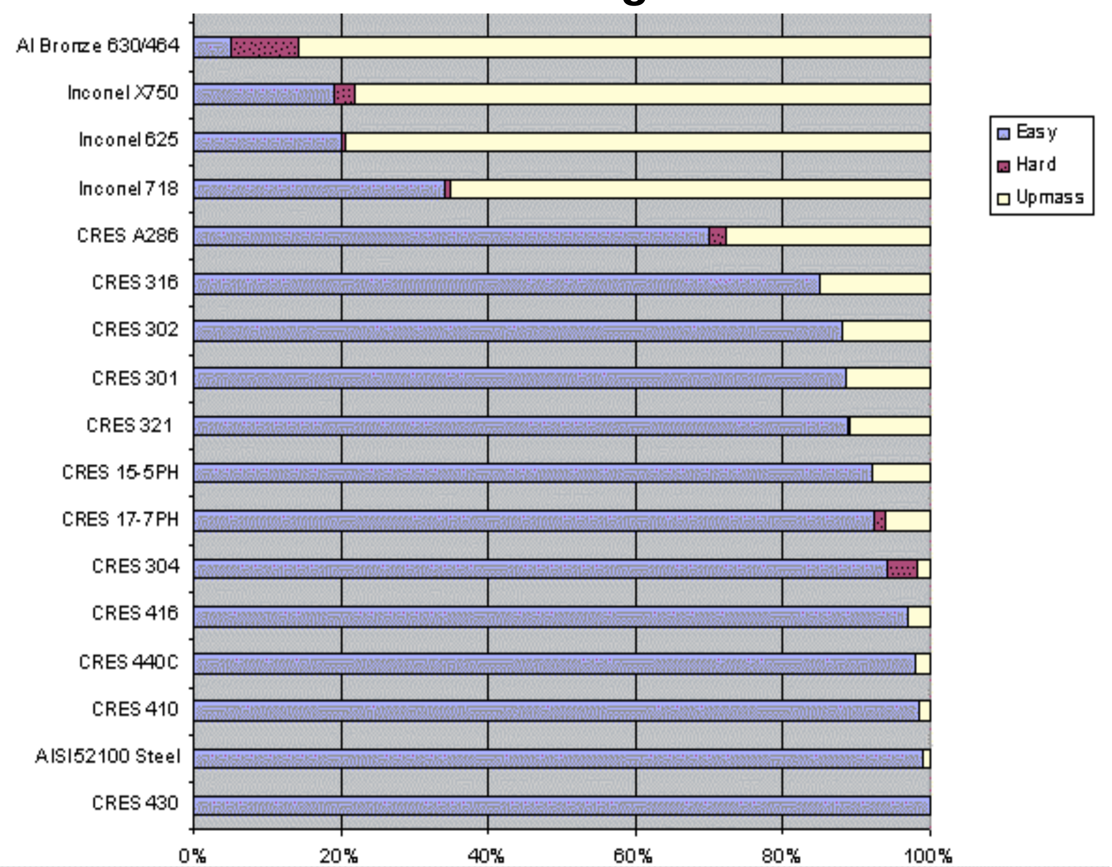
- Reducing power requirements
- Mass and volume
- Portability
- Skill requirements and ease of use
- Surface finish
- Quality assurance (NDE)
- Reliability

On-Site EBM Fabrication from Lunar Regolith

Chart reflects the ease or difficulty of producing the selected material using lunar regolith and the percentage of provisioned materials needed
(noted as "upmass")

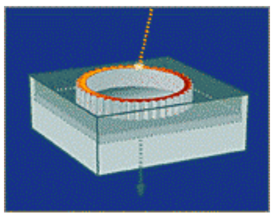
Table reflects **CRES 430** as the most capable material derived from lunar regolith

Potential Materials Available from Lunar Regolith



EBM Fabrication Process Overview

Step 1.
Part designed in 3D CAD and sent to fabricator



Step 2.
E-beam fuses powder layer-by-layer per part profile at a given height until full height is reached

Step 3.
Solid metal parts of complex geometry

Materials Used in EBM Machine

- Each material behaves differently in the EBM machine
- Appropriate settings/parameters (current, voltage, speed, etc.) must be determined in order to certify the actual manufacturing process for each specific material
  - Titanium Alloy (Ti6Al4V)
  - Aluminum Alloy (6061)
  - Lunar Regolith Simulant (development and characterization discussed in next presentation)
  - Combinations of Al Alloy and Lunar Simulant
  - Metals retrieved from O2 Extraction Processes (Future)
  - Future Materials being considered

EBM Fabrication of Lunar Regolith Simulant

- Raw simulant sintered using the EBM Process
- Current results show a binder will improve melt
  - Pure aluminum used as a binder
- Both JSC-1A and LHT-2M simulants are being used in this activity
- Mixing the pure aluminum and the simulant did not provide a homogeneous powder and the melt reflected this fact
  - A ball mill alloyed the powders and provided a better mixture

Fully Sintered Pure Simulant

Simulant Mixed With Aluminum After Sintering

This work will continue with emphasis to on-site infrastructure capabilities using lunar regolith for fabrication.

Summary

The Mission At Hand…

- Continue Development of Technologies for On-Site Fabrication Using In Situ Resources That Can Assist Ongoing Space Programs By Enabling:
  - Weight Saving Parts (Honeycombs & Lattices)
  - Part Count Reduction (Single Piece and on-site Builds)
  - Unique Geometries (Internal Passages/Cavities)
  - Embedded Components (Sensors, Wires, Inserts)
  - Reduced Fabrication and Assembly Resources

- Sustaining Exploration Missions Using On-Site Infrastructure To:
  - Reduce the Up Mass Launched From Earth
  - Produce spare parts on site as needed
  - Shorten failed systems downtime
  - Increases operational capabilities and flexibility
  - Manufacture tools on site
  - Overall reduction in life-cycle costs