IN SITU MANUFACTURING IS A NECESSARY PART OF ANY PLANETARY ARCHITECTURE. J. Edmunson[1] and C. A. McLemore[2], [1]BAE Systems/NASA Marshall Space Flight Center (Jennifer. E.Edmunson@nasa.gov, Huntsville AL 35812), [2]NASA Marshall Space Flight Center (Carole.A.McLemore @nasa.gov, Huntsville AL 35812).

Introduction: The key to any sustainable presence in space is the ability to manufacture necessary tools, parts, structures, spares, etcetera in situ and on demand. Cost, volume, and up-mass constraints prohibit launching everything needed for long-duration or long-distance missions from Earth, including spare parts and replacement systems. There are many benefits to building items as-needed in situ using computer aided drafting (CAD) models and additive manufacturing technology:

- Cost, up-mass, and volume savings for launch due to the ability to manufacture specific parts when needed.
- CAD models can be generated on Earth and transmitted to the station or spacecraft, or they can be designed in situ for any task. Thus, multiple people in many locations can work on a single problem.
- Items can be produced that will enhance the safety of crew and vehicles (e.g., latches or guards).
- Items can be produced on-demand in a small amount of time (i.e., hours or days) compared to traditional manufacturing methods and, therefore, would not require the lengthy amount of time needed to machine the part from a solid block of material nor the wait time required if the part had to be launched from Earth.
- Used and obsolete parts can be recycled into powder or wire feedstock for use in later manufacturing.
- Ultimately, the ability to produce items as-needed will reduce mission risk, as one will have everything they need to fix a broken system or fashion a new part making it available on a more timely basis.

The ability to produce items on demand from CAD drawings provides the ability to adapt to any kind of need. For example, a bezel tool was needed to remove an airlock input valve cover in the Microgravity Science Govebox on the International Space Station (ISS). Because this failure was not identified or predicted (i.e., an unknown risk), there was no tool manifested on the ISS to perform the operation, nor was there any way to fabricate the tool on orbit. Therefore, the crew had to wait until the tool could be designed, built, flight certified, and flown on the next available launch to the ISS. An analysis of the Problem Reporting and Corrective Action System for failures on the ISS revealed that 82% of those failures could have been remedied and hardware put quickly back into operation with on-board fabrication and repair capability technologies [1]. Luckily for the ISS, Earth is less than 260 miles away. This luxury will not be afforded to those exploring Mars, the Moon, or asteroids; or those living at Lagrange points.

Additive Manufacturing: Additive manufacturing (AM) is the process of building something layer-by-layer, currently with materials such as plastics, concretes, or metals in a much shorter timeframe than traditional manufacturing allows. The general term AM refers to a collection of layer building technologies including fused deposition modeling (a hot glue gun-like device that builds plastic parts), electron beam melting and free form fabrication (metal powder and wire feedstocks, respectively), stereolithography (using ultraviolet light to solidify photo-sensitive liquid polymer), 3D printing (an inkjet printer that sprays bonding material on layers of powder) and contour crafting (building large scale structures by deposition; concrete has been used on Earth but other non-water-based materials have been tested for planetary use).

Current Status of Additive Manufacturing: To date, no AM technology has reached the desired Technology Readiness Level (TRL) 9. Fused deposition modeling is the only AM technology that has achieved a TRL 6; thirteen years ago, K. Cooper was the first to try fused deposition modeling on parabolic KC-135 flights [2]. This set of flights proved that fused deposition modeling could work in low to zero gravity. To date, the only people who have repeated this work are from the commercial company Made in Space, Inc., whose goal is to bring commercial fused deposition modeling technology and applications to space platforms. Other AM technologies are also being readied for use in space. For example, a small electron beam free form fabrication device is currently under development at Langley Research Center. In recent years, the Marshall Space Flight Center experimented with electron beam melting of various proportions of lunar regolith simulant and aluminum 6061 alloy to create a viable material for in situ resource utilization on the Moon. Laser sintering technology is being vetted by a group at Johnson Space Center.

Mars Exploration Challenge Area 2: Innovative Exploration Approaches: The purpose of this abstract is to address challenges in the area of "concepts for public-private partnerships to provide infrastructure, services, instruments, or investigation platforms that can lower the cost and/or risk of future Mars exploration". Having an AM device to produce hardware on demand directly lowers cost and decreases risk by having exactly the part or tool needed in the time it takes to print. More understanding regarding Mars regolith properties, and how to mine specific materials for use as feedstock to be used in manufacturing processes in situ, is mandated. This calls for Mars regolith sample returns to Earth and/or better characterization on Mars. Demonstrations of in situ fabrication are required as well. This knowledge is key to implementing fabrication and sustainability on Mars.

Precursor Science Analysis Group Strategic Knowledge Gaps A4 and B9: Strategic Knowledge Gaps identified by the P-SAG addressed by this abstract include Group A, Gap 4, "Technology: To/from Mars System (1) sustain human life during long duration flight to/from Mars and around Mars" as well as Group B, Gap 9, "Technology: Mars Surface (2) sustain humans on the surface of Mars". Providing a way to fabricate parts on demand in spacecraft and on planetary surfaces, with the ability to create new parts as needed, is imperative for long-duration missions.

Additive Manufacturing on Planetary Surfaces: All AM technologies, with the exception of stereolithography, are candidates for in situ resource utilization technologies. Fused deposition modeling and electron beam free form fabrication can use melted and/or processed regolith as feedstock to build parts and spares. Electron beam melting and 3D printing can use small grains directly from the regolith with little to no pre-processing steps. Contour crafting only requires handling technologies for the regolith and a bonding material that can cure in little to no atmosphere. It is not too far fetched to propose that AM on Mars can one day produce habitats and items to accommodate crew living, tools, parts, spares, radiation shields, robots, rovers, experiments, science instruments, etcetera and even additional or new AM machines (i.e., replicators and transformers). The ability to fabricate and/or repair items on Mars including the recycling/repurposing of hardware and materials is not optional; it is a requirement for survival and sustainability.

Steps to Developing AM for Space: A Critical Enabling Technology for Mars Exploration: The following steps outline a plan that will lead to the use of AM technology on Mars.

- Encourage NASA and commercial company cooperation for development of AM for space platforms.
  - This is being done with commercial company Made In Space as part of both a Small Business Innovative Research grant and a partnership with Marshall Space Flight Center in the area of fused deposition modeling (plastics).
- Develop metallic AM techniques.
  - As part of the Manufacturing Innovation Project funded by the Office of the Chief Technologist, a small electron beam free form fabrication device is being developed, and research is being performed with the electron beam melting machine.
- Test AM in the ISS.
  - This will be accomplished in the next couple of years by Made In Space.
  - The ISS proves the concept in a relevant microgravity environment.
- Develop electronics printing and AM technology for in situ resource utilization.
- Develop recycling technology for spent materials (plastics, food containers, filters, used tools, etcetera) to be used as feedstock for AM.
  - Ionic liquids show great potential for recycling of materials.
- Fly an AM demonstration device that proves in situ resource utilization technology can work for martian materials.

Conclusions: In a communication to Dr. R. G. Clinton on 30 November 2011, Dr. M. L. Uhran is quoted:

> *"Fabrication or manufacturing in space is a necessary functionality for deep space exploration missions in addition to providing a substantial mass savings in the logistics and spares areas. The ability to build tools and parts to replace broken or lost items is essential for such missions. … This functionality can also provide an additional level of safety, especially for items needed sooner than the long-lead times required for launching from Earth. … I strongly endorse this effort and believe that it is a needed and prudent investment towards NASA's future exploration goals."*

Additive manufacturing can be on any space platform, and is particularly applicable to Mars missions because of the distance from Earth and the resulting need for independence of the astronauts from Earth-launched materials and parts. It is a critical technology that must be advanced now and incorporated into the Mars exploration architecture for survival and sustainability of all missions to, and a human presence on, Mars.

References: [1] NASA/MSFC Concept of Operations for ISFR, Volumes 1, 3, and 4, 480RPT0198 (2004); [2] Cooper K. G. and Griffin M. R. (2003) NASA/TM-2003-212636.