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In situ Manufacturing derived from Bioregenerative Life Support Systems

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In situ resources from planetary sources can be used in conjunction with a bioregenerative life support system to produce surplus biomass. Combined with miscellaneous waste streams this biomass can be used as a feedstock for manufacturing numerous items necessary to support and expand a planetary habitation. Materials that can be fabricated include: structural materials like beams, joists, wall studs, structural cables, and wall and floor panels; furniture items such as tables, chairs, cabinets, beds, and shelves; geotextiles, fabrics for clothing, cushions and bedding; numerous specialty items like filters, plastics, thermal and sound insulation; and useful biochemicals like lubricants, detergents, alcohol, protective coatings, and adhesives. These materials can also be used as feedstock for several manufacturing technologies such as compression forming, extrusion, and 3D additive manufacturing. One example is straw fiberboard, which is formed by fiberization and compression, with or without binding agents, and is used commercially as a renewable construction resource. More exotic materials can be produced through genetic engineering or synthetic biology techniques, using modified organisms to produce materials that could not otherwise be produced in a remote setting. Required processes for using biomass feedstocks can be evolved from similar processes now or previously used commercially, or that have been developed in the laboratory. A biomanufacturing system could provide a tool to reduce costs of maintaining and expanding a planetary outpost by eliminating the need to transport from Earth either finished items or the raw materials needed to fabricate those items on site. It also provides the means and flexibility to respond to sudden, unanticipated needs including repair or replacement of damaged items, and supports NASA's philosophy for long duration planetary bases to "make what you need where you need it.".

Nomenclature

ALS = Advanced Life Support
BLSS = Bioregenerative Life Support System
CEA = Controlled Environment Agriculture
ESM = Equivalent System Mass
FPL = Forest Products Laboratory
ISRU = In situ Resource Utilization
SBIR = Small Business Innovative Research
USDA = United States Department of Agriculture

I. Introduction

Many concepts for the evolutionary development of long-duration Mars bases include the use of bioregenerative life support systems to provide food, atmospheric revitalization, waste processing, and water purification. However, an additional value of bioregenerative life support systems to a long duration Mars base is that, used in combination with planetary in situ resources, they can generate surplus biomass as a feedstock for on-site manufacturing capabilities. This mechanism provides the means to convert planetary resources and mission generated "waste" into versatile construction and utility materials, and supports NASA's philosophy for long-duration planetary

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bases to “make what you need where you need it.” A mixture of green plants, microorganisms, in situ resources such as carbon dioxide and water, and materials taken from existing waste streams, combined with advanced manufacturing and biomanufacturing techniques, can be used to manufacture many of the components necessary to support and expand a long-duration planetary base. A diagram illustrating the concept and providing examples of materials that could be produced in situ is provided in Figure 1. The benefits of a large scale biomanufacturing capability integrated into a planetary base would be numerous, allowing the on-site production of many materials important to providing a truly habitable environment but that cannot be feasibly supplied from Earth. It also provides a capability for on-site repair or replacement of damaged components and provides the flexibility to respond to sudden, unanticipated needs. This development would meet the goals of Advanced Life Support (ALS) technologies for long-duration missions to reduce life-cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources, and will improve the life cycle equivalent system mass.

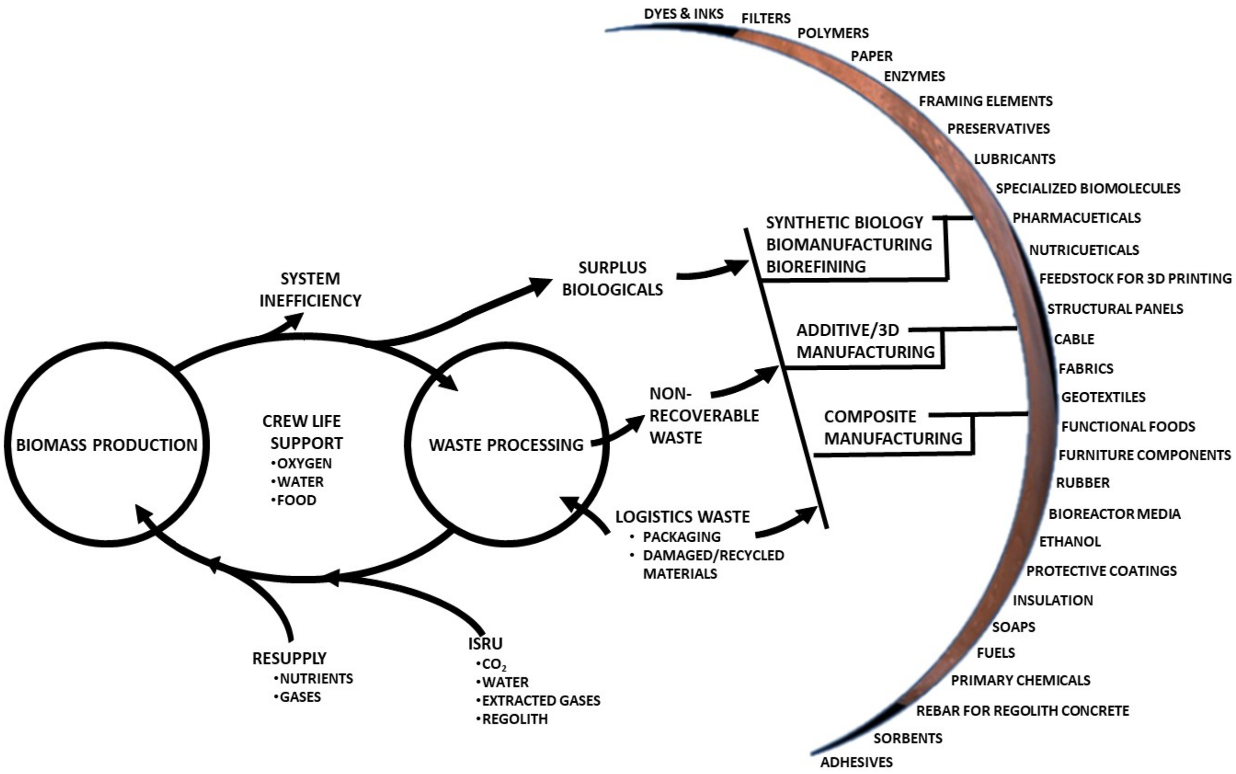

Figure 1. Planetary-base manufacturing capability based on in situ resources and biomass production.

II. Biomanufacturing Concept Overview

Biomanufacturing is a type of manufacturing that utilizes biological systems to produce a broad spectrum of commercially important (or in the case of a planetary base - useful) bio-based products. Much current work called “biomanufacturing” refers to microbial based systems (e.g. bioreactors), but the term can also be extended to the generation of useful materials from higher plants. An extension of this concept is “biorefining”, the process of multiple products (either naturally occurring or derived using genetic engineering or synthetic biology techniques) being produced using biomass as a feedstock or raw material. The biomass is fractionated through sequential levels of processing to maximize the number and value of co-products obtained. Biomanufacturing and biorefining are being explored terrestrially as a replacement for, or to supplement current raw materials derived from petroleum based chemicals.

Terrestrially, a large number of primarily nonfood crop plants, often referred to as industrial crops, are used to produce important materials such as fuels, biochemicals, and biocomposites[1]. Over time, hydrocarbon feedstocks for producing many materials have shifted from plants to petrochemicals (due to cost and convenience), but the knowledge exists to use higher plants and microbial organisms to produce alternative feedstocks. In fact, many non-metal materials that would be required or useful in an advanced planetary base can be produced from materials created from these biological organisms. One example of a crop heavily used in biomanufacturing terrestrially is the soybean (one of the eight primary life support crops identified by NASA). Soybean oil and protein are used in food, feed, and industrial products. Hundreds of different products can be fabricated from this species, examples of which include food and nutraceutical ingredients, coatings, fiber, lubricants, release agents, ink, paper, rubber, fuels, absorbents, cleaning agents, and solvents[2,3,4]. Soy-based lubricants are as good as petroleum-based lubricants, but can withstand higher heat, and are non-toxic and renewable. Soy protein can also be used to produce a variety of polymeric materials, including adhesives and plastics[5].

Advances in genetic engineering of crop plants and cells (plant, algae, fungi or bacteria) offers significant opportunities for development of new or improved materials in the future, increasing the usefulness of biological organisms for biomanufacturing. Genetic manipulation enables new capabilities, including modification of plants to produce fibrous animal proteins such as collagen, keratin, silk, and elastin, which have very good strength, toughness, elasticity, and biocompatibility and can therefore be used to produce novel biopolymers as a replacement for oil-based plastics[6]. A significant amount of work is now underway investigating industrial bio-processes for fine chemical production using "cell factories" developed through metabolic engineering and synthetic biology. The use of high throughput techniques and automation for the design of cell factories has played an important role in the transition from laboratory research to industrial production. Some of these bio-based chemicals are now reaching the market and key metabolic engineering tools are allowing these industrial production processes[7]. Genetic engineering is also currently being used to target physiological pathways that could be manipulated to modify crop photosynthesis to improve photosynthetic yield potential, which would further the potential of both food and non-food products[8,9].

Most planetary in-situ resource utilization (ISRU) efforts supported by NASA have emphasized production of materials such as fuels and life support gasses. However, there have been sporadic efforts related to manufacturing a broader array of materials in space using in situ resources. Menezes et al.,[10] calculated the utility of deploying non-traditional biological techniques to harness available volatiles and waste resources on manned missions to Mars using novel technologies that decrease cost and reduce risk, increasing the probability of mission success. Compared with anticipated non-biological approaches, it was determined that for a 916 day Martian mission using in situ resources that cyanobacteria and other bacteria species could reduce the mass of a Martian fuel manufacture plant by 56%, decrease the shipped wet-food mixed-menu mass for a Mars stay and a one-way voyage by 38%, reduce the shipped mass to additively manufacture a 120 m^3 six-person habitat by 85%, and produce enough acetaminophen in a few days to completely replenish expired or irradiated stocks of the pharmaceutical. The analyses the authors conducted provide insight into the potential of 'space synthetic biology'. The efforts by NASA to expand space synthetic biology knowledge included formation of the Center for the Utilization of Biological Engineering in Space (CUBES)[11] which was "developed to leverage partnerships between NASA, other federal agencies, industry, and academia to support biomanufacturing for deep space exploration, advance the practicality of an integrated, multi-function, multi-organism biomanufacturing system on a Mars mission; and to showcase a continuous and semiautonomous biomanufacturing of fuel, materials, pharmaceuticals, and food in Mars-like conditions".

Most current NASA biomanufacturing activities are oriented toward development of more complex and exotic materials. However NASA has also explored the use of less exotic materials to produce necessary products for a Mars base. Raw materials that could be produced in relatively large quantities as a bioregenerative life support system comes on line includes inedible plant biomass fiber. Access to carbon dioxide and water from the Mars environment could support production of biomass in excess of that needed to meet basic life support functions of food production, atmospheric revitalization, and water purification. Biofibers can be used with relatively simple equipment (e.g. grinders, presses, extruders, 3-D printers) to make a broad range of useful products that would be difficult to transport from Earth due to excessive mass and volume.

III. Role of Biofibers in Planetary Habitats

Concept-art of hypothetical long duration Mars habitats commonly shows internal volumes filled with the many mundane items required for a comfortable habitat environment—objects for example such as partitions, shelves, desks, beds, and tables. Extrapolation from standard university or military housing configurations provides some concept of the basic items needed to provide an acceptable level of crew comfort in a long term habitat (Table 1), assuming that long term quarters should be a step above transport vehicle type quarters over a long duration planetary stay. In the evolutionary process of expanding an initial planetary outpost to a larger base, all these items will have to come from somewhere. One option is that they be transported from Earth. However, this is not an efficient way to provide all the objects and supplies needed to support a long duration base. Therefore an alternative is being explored using a biology based "economy" to produce these structures by feeding excess carbon dioxide and water collected from in situ Mars resources into bio-based regenerative life support systems to produce the excess biomass that can be formed into necessary products.

Table 1. Habitat furnishings for suite with three double sleep areas (extrapolated from student housing, military housing).

Item	Quantity
Table	1
Chair	6
Couch	1
Lounge chairs	3
Shelf/storage units	6
End tables	4
Drawer storage units	6
Desk units	6
General shelf/locker storage	6
Wall partition	6
Bed structures	6

Crop-based biofibers, or “agricultural fibers”, are non-wood fibrous materials that can be extracted from crop components such as cereal straw (e.g. wheat, oats, rice, rye), cornstalks, cotton stalks, kenaf, and rice husks. Cereal straw has been of particular interest as a fiber source for building components like low-density board, medium density fiberboard, and hardboard (Figure 2)[12]. Two cereal crops that have seen significant use terrestrially for structural fibers are wheat straw and rice straw, both of which have been identified by NASA as key life support species (based on food value)[13]. These fibrous materials have the composition, properties and structure that make them suitable for use as raw materials for making manufactured items as shown in Table 2. Geotextiles are fabrics used for stabilizing exposed soil and could play a role in covering regolith near entry ways to minimize dust, for stabilizing regolith, or for production of sandbags for shelters. Medium and high-density filters have been developed for particulate removal or for use with chemicals as air cleaners and could serve a similar role in reducing particulates in a habitat. Sorbents being studied for oil clean up and to absorb contaminants in water could be used for spill cleanup in habitat work areas. Structural composites have been used in building interiors and could be used to support expansion of pressurized and non-pressurized volumes. A variety of materials, such as packaging plastics, are available within a waste stream that can be used with biofibers to produce biocomposite materials. Nonstructural composites have been used in objects such as doors, ceiling tiles, and automotive liners and would be useful for acoustic and thermal insulation. Molded products have been used for items like egg cartons and fruit trays and could be used for packaging specimens and supplies. Agricultural fibers have also been incorporated with other materials, such as plastics, and into concrete for strengthening[14], similar to the way other materials such as fiberglass have been used. Possibly they could serve as reinforcement (“rebar”) for concrete made from native Mars regolith. In addition, biofibers can be used as feedstock for additive manufacturing (3-D printing)[15,16].

Table 2. Products that can be formed from biofibers[17].

Category	Items
Hardboard	panels, shells, flooring
Structural composites	structural trusses, beams, walls and decking
Medium density fiberboard	furniture (desk, chairs, tables, beds, shelves)
Low-density non-structural board	sound insulation, thermal insulation, coarse filters, floor mats
Paper (sanitary)	sanitary tissues, paper towels, bathroom tissue, facial tissue, wipes, napkins, cleaning towels
Paper (general)	writing/printing paper, molded fiber trays and products, packaging, particulate filters
Textiles	clothing, bedding, towels
Geotextiles	regolith covers, dust screens, sandbags
Safety items	protective headwear (inside habitat use), absorbents, sealants, coatings
Feedstock	for 3-D printers, bioreactors

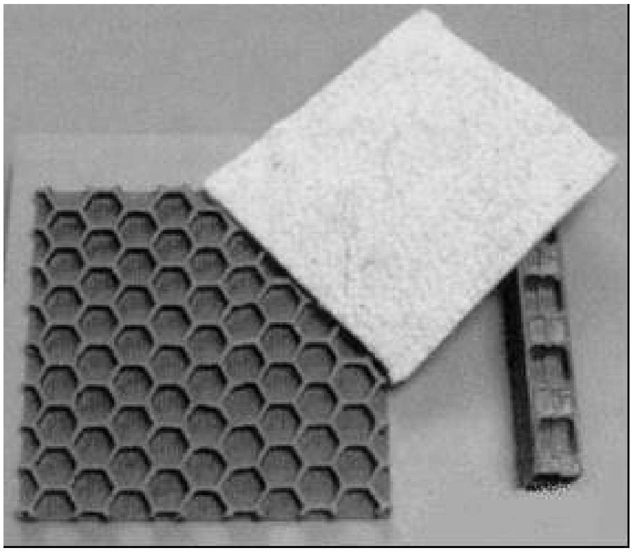

Figure 2. Examples of materials fabricated from agricultural fibers; (L>R) 3D hardboard, medium density mat, small truss assembled from two hardboard shapes (from Rowell et al. [17]).

Research has shown plant fibers can be bonded together naturally to form a dense structural material without the use of resins. In a controlled, medium humidity environment, these components can have a useful service life of years. If changes are needed to the living space, the material can be recycled and made into new structural components, i.e. recycled. By fabricating interior living components from inedible plant biomass already in the ALS system, resupply of interior components can be significantly reduced. Estimates for inedible biomass production in a bioregenerative life support system are 1.85 kg/person-day[18]. Total inedible biomass for a crew of 6 would be approximately 11 kg/day of material. High-density panels made from paper and plant fibers have a density of 1000 kg/m3. Variations on panel geometry and size obviously will determine total amount of material used, but based on a 3 mm thick 0.5 m x 1 m panel, up to 7 structural panels a day could be generated from the available inedible plant material. On site production also provides the capability for on-site repair or replacement of damaged components and the flexibility to respond to sudden needs that were not anticipated. This technology development would meet the goals of ALS technologies for long-duration missions as recommended by the National Academy of Sciences[19] to reduce life-cycle costs, improve operational performance, promote self-sufficiency, and minimize expenditure of resources for long-duration missions and improve life cycle equivalent system mass.

Fiber formed structures can be made in a variety of 3D shapes and sizes. Panels can be fabricated using a wet or semi-wet forming process and bonded naturally without resin. High pressure is applied to the formed fiber sheet or 3D structure while it dries. The addition of pressure significantly increases the fiber-to-fiber bond and thus produces significantly improved mechanical properties. Generating fiber composites without binders is generally accomplished by variations on the process of pulp molding. Low-density materials are generated at room temperature by low-pressure compression and water extraction, followed by drying. Higher density materials can also be generated at room temperature by increased pressures. To increase binding strength in high-density composites without using binders, high pressure/high temperature compression with steam injection is used, which causes the lignin in the plant material to actually become the binding agent. Panels 3 mm thick made from corn fibers[20], using a wet-forming process, and without resin, were shown to have a sonic modulus of elasticity 2 times higher than that of commercial high-density hardboard. By varying process parameters, panels can be fabricated that range in performance from low-density products similar to egg-cartons to high-density products similar to commercial hardboard (Figure 3). In addition, these products could be made in a 3D mold to near-final or final shape, form, and function (Figure 4). Three-dimensional structures have been fabricated using a wet-forming process with paper, agricultural, and recycled fibers for products or applications such as a floor sections[21], structural panels[22], and pallets[23].

The primary hazards of formed fiber structures are flammability, respiration hazards (inhalation of particulates and mold spores), and physical injury from the processing equipment (rotating cutting edges, high pressure presses). Straw fiber structures are somewhat similar in flammability to commercial press board so adequate fire precautions will be required. One technique for reducing fire hazard are to incorporate fire retardants (e.g. boron, phosphorus, sulfate) into fiber structures. These retardants reduce temperature of pyrolysis, resulting in a char layer that limits flame spread. The other likely hazards can be controlled through extension of standard industrial safety techniques.

Overall, one of the key materials that would be produced in a planetary biomanufacturing system, fiberboard, has demonstrated good fire resistance (similar to commercial pressed board or plywood), acoustical properties, and structural and thermal performance in tests—all key to these materials being useful in a habitation setting.

Figure 3. "Surplused" structures (root/shoot barriers, seed plugs, panels, truss members, and fiber mats) derived from formed wheat fiber. These materials were reprocessed into new structures.

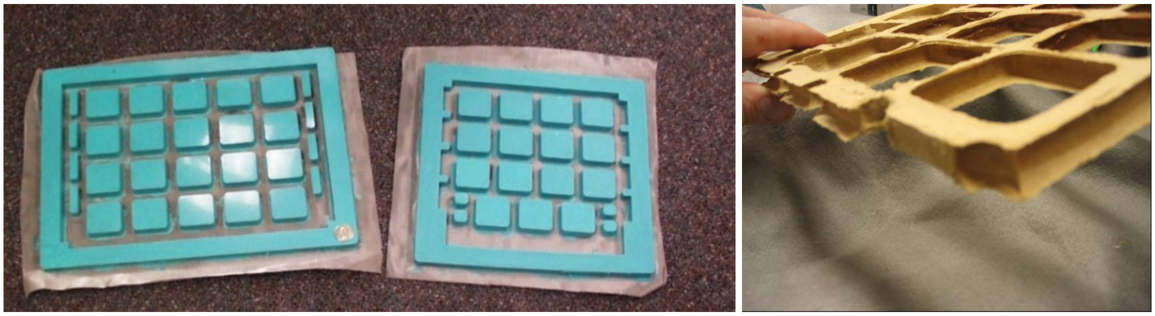

Figure 4. Silicon molds for forming three dimensional panel elements from wheat fiber. Design provides compaction in three dimensions as shown in the fiber grid.

IV. NASA Supported Agricultural Fiber Work

NASA has evaluated a number of plant species for use in Advanced Life Support Systems[13]. The top plant candidates for use in an ALS include the cereals wheat and rice, white potatoes and sweet potatoes (starch), and beans, soybeans, and peanuts (protein). These species all have fibers that may be useful. If food production is not a consideration, fiber crops such as kenaf, flax, or ramie could also be grown. NASA, through the Small Business Innovative Research (SBIR) program, has funded some investigations into using plant fibers for making items that would be useful in space habitations.

Tuskegee University has developed paper from inedible white potato, peanut, and soybean plant residues for use in Advanced Life Support Systems[24]. Potential uses investigated include use as a medium for inoculum of bioreactors, and to possibly replace general paper materials (e.g. toweling). Tuskegee University also conducted tests for using paper materials fabricated from inedible materials of sweet potatoes to support seeds in hydroponics.

Orbital Technologies Corporation (now Sierra Space) was funded by NASA for a multiyear project with the USDA Forest Products Laboratory (FPL) to investigate the use of wheat straw for the fabrication of plant support materials, such as plant plugs (Figure 5) and root shoot barriers for potential use in ALS crop production facilities[25]. These plants also provide materials (e.g. starch) that can be used as recyclable binders in structural fiber components. The purpose of this research was to develop the processes and knowledge required to fabricate plant support structures such as plant plugs, root/shoot barriers, and plant restraints or "fencing" from inedible plant biomass, and to determine the feasibility of utilizing these structures in ALS systems. These structures are a challenge as the goal was to provide plant supports that maintain structural integrity in a wet environment for an entire crop cycle without the use of additives that could impede the recycling process in an ALS system. Research carried out included characterizing fiber sources, optimizing plant plug fabrication, developing and testing root/shoot barriers and plant restraints from pressed wheat fiber (Figure 5), and evaluating the impact of this technology on ALS system resources.

Figure 5. (L>R) Lettuce growth on root/shoot interface formed from heat pressed wheat fiber, wheat and squash seedlings in medium density plant plugs formed from wheat straw.

It was demonstrated during these tests that seed plugs from inedible plant biomass are capable of maintaining integrity in wet environments for the duration of one crop cycle without binders or coatings. It was also demonstrated that structural items like root/shoot barriers and plant fencing could be fabricated from formed fibers without using additives. These structures were able to function for a full crop cycle. Multiple recycling passes with formed fiber materials resulted in some decrease in average fiber size, but did not impact the ability of the fiber to be remade into new structures.

V. Mars Habitat Biomanufacturing Issues

Primary factors that will impact the feasibility of implementing biomanufacturing in a Mars habitat will be mass, power, volume, and crew time. While most of the myriad of non-metal materials needed in a planetary habitat could be produced by biomanufacturing on site, it might be more efficient to transport some items or materials from Earth in their finished state rather than send the equipment and supplies necessary to make them on site. Relevant trade studies will need to be done during the planning of any large scale Mars base. Prior to implementing biomanufacturing, significant development of synthetic biology systems, bioregenerative life support systems, and more traditional fabrication and processing techniques will be required. Some goals include developing manufacturing techniques that use flexible, multiuse tooling and equipment to produce a variety of products (e.g. 3D printing, chemical synthesis systems). Significantly, safety (flammability, high pressure, moving components) and health (particulates, VOCs) issues for all selected processes need to be understood and risks mitigated appropriately. It will also be important to develop logistics with a mind toward how materials provided in vehicles (packaging etc) will be of benefit to the overall manufacturing system at the destination (e.g. using packaging that when discarded can become a component in biocomposite materials). Safe and highly reliable storage for propagules of the necessary biological organisms need to be developed and tested. It will also be important to identify critical habitat needs early in the mission design process as this may enable development of new biomanufacturing processes to provide those items.

Protocols need to be developed to smoothly integrate biomanufacturing activities to minimize any adverse impact on biobased life support processes. Biomanufacturing protocols developed for terrestrial applications should function in Mars 1/3g, but need to be evaluated for any problems or reduced functionality due to reduced gravity and atmospheric pressures. Conversely, hardware designed for these processes should take advantage of the reduced structural needs due to low gravity to reduce system mass. Designs will need to be as volume and power efficient as possible. Automation of mechanical, organism culture, and chemical processes will also have significant benefits in reducing crew loads and should be implemented where possible.

The means to obtain planetary resources (e.g. CO_2) will need to be well understood and tested, and equipment to extract these materials will need to be at a high TRL. It is also important to verify that extraction techniques are sized to accommodate demands of planetary resource inputs needed by the full complement of biomanufacturing processes.

VI. Conclusion

We believe a system using in situ resources as a feedstock to be cycled through a bioregenerative life support system to produce a broad variety of raw fabrication materials will make possible more advanced planetary-base concepts[26], enabling radical improvements in long-duration mission mass, performance, and cost. This includes the manufacture of structural materials from fibers using processes such as extrusion, compression molding, weaving, or other methods to make useful items. More exotic materials can be produced through synthetic biology techniques using genetically modified or synthetic organisms to make materials (that could not otherwise be effectively produced in a remote setting) that can be processed through biorefining (extraction, separation and purification) techniques before being processed using more traditional manufacturing techniques. On-site biomanufacturing and biorefining may enable much more extensive planetary base designs than would be considered possible through standard mission architectures. Processes related to generation of plant products (both genetically altered and naturally occurring), processing of diverse waste streams, and many manufacturing, processing and fabrication technologies, have been used commercially or have been demonstrated in the laboratory to some extent. To date the use of life support systems as a tool to provide a manufacturing base in a remote, hostile environment with only limited available resources has been relatively unexplored.

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