Lunar and Martian Fiberglass as a Versatile Family of ISRU Value-Added Products

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Lunar Regolith consists principally of silicates, in some cases demonstrable as volcanic or impact glasses. We contend that silicon is versatile in application and should be the fundamental building block for a wide range of value-added products in a CisLunar economy. Fabrication of silicate glasses are conventional industrial processes and should be applications adaptable on the Moon and Mars. ISRU operations should yield copious masses of silicon oxide and other metal oxides which can be transformed in bulk into glass and fiberglass products. Additionally, mechanical wrapping of Silicon Webbing could prove to be more practical and durable and a lot less brittle than attempting large-scale hot glass molding of structural components. Fiberglass manufacturing increases effectiveness of prior ISRU fuel production by taking advantage of mineral benefaction and already-elevated process exit temperatures.

Contemporary Terrestrial industrial composite fiber products range from pressure vessels to lightweight sporting goods. A large number of products related to human systems support can similarly be manufactured in-situ using glass fibers and fiber fabric made from lunar silicate glass. Pressure containers, structural components, woven fiberglass fabrics, molded and machined solid objects, glass fiber and filament are each large classes of value-added fiberglass products. Pressure vessels resulting from fiberglass fabrication would be spheres and cylinders with various configurations that could apply to human support systems, along storage tanks for the very Oxygen liberated in ISRU applications. Building structures using spun glass would be similar to those currently employed by Raytheon or Scaled Composites to build composite aircraft. The anticipated tensile strength of glass made under hard vacuum is an order of magnitude greater than glass produced in atmosphere containing water vapor.

ISRU-derived spacecraft will be feasibly and affordably manufactured on the Moon, based upon fiberglass 'tankage' integrated with structured-fiberglass keels of a similar pedigree.

CNC-type programmable manufacturing can deliver state-of-the-art *flexibility of remote design and parts manufacture. These concepts suggest extensibility and evolutionary capability derived when machining fiberglass tool parts from Terrestrial design centers.*

For more exotic applications, second-generation structural components may take advantage of Silicon and Silicon-Carbide Fullerenes (Nanotubes or Nanostructures) for additional composite strength.

Initial Conditions

Lunar Regolith consists principally of silicates, in some cases demonstrable as volcanic or impact glasses. We contend that silicon is versatile in application and should be the fundamental building block for a wide range of value-added products in a CisLunar economy. There are numerous methods and types of regolith reduction, based on the objective of extracting Lunar Oxygen as half of the LH2-LO2 propellant architecture. Oxygen extraction yielding metals would be simple but for the obstacle of Silicon, which is the largest fraction (21%)[1] of the soil mass after Oxygen (45%). Silicon is the pesky stuff obstructing a clean melt of aluminum, titanium, magnesium, calcium, iron and other valuable metals, all of which would add nicely to the bottom line of the Lunar mining ledger.

The entire point of *In-Situ* Resource Utilization (ISRU) is to dramatically reduce the mass of material shipped elsewhere in space from the bottom of Earth's gravity well. The principal result of effective ISRU operations are 1) enabling long-term and continuous human presence off-planet, and 2) the creation of a CisLunar space economy sufficiently robust to accept a paid commission from Earth to jumpstart a Mission to Mars.

Immediate Applications

While we have previously enumerated a large inventory of diverse and potential Silicon applications[2,3] an economics driver had not surfaced until we investigated the conventional and future space applications of fiberglass. It would seem that Silicon-based fiberglass products may well become as ubiquitous on the Moon as Carbon-based plastic is on Earth.

Contemporary Terrestrial industrial composite fiber products range from pressure vessels to lightweight sporting goods. A large number of products related to human systems support can similarly be manufactured *in-situ* using glass fibers and fiber fabric made from Lunar silicate glass. Pressure containers, structural components, woven fiberglass fabrics, molded and machined solid objects, glass fiber and filament are each large classes of value-added fiberglass products.

Many compelling applications exist for fiber optics, braided cable, composite fiber for wrapping forms, dust filter meshes and other strand-based products.

Pressure vessels resulting from fiberglass fabrication would be spheres and cylinders of various configurations that could apply to human support systems, including storage tanks (Dewars) for the very Oxygen liberated in ISRU operations. One class of building structures using spun glass would be similar to those currently employed by Raytheon or Scaled Composites to build composite aircraft. Aerojet fabricates space-rated solid-rocket motors by wrapping fiber into a composite cylinder to contain the combustion pressures of launch. Mechanical wrapping of Silicon Webbing could prove to be more practical, versatile, durable and a lot less brittle than attempting large-scale hot glass molding of structural components.

Integrated Foundry

Fabrication of silicate glasses are conventional industrial processes and should be adaptable to the Moon and Mars, especially when integrated with other ISRU applications. Current fuel production ISRU scenarios yield partially heated masses of metal oxides as waste byproduct – a hot byproduct rich in metal oxides, including silicon, immediately useful in bulk as conventional glass products or exotic space technology.

Specialized Lunar manufacturing, in the form of fiberglass value-added products, increases the efficiency of prior ISRU fuel production by taking advantage of mineral benefaction and elevated process exit temperatures. Waste heat normally radiated to space is re-routed to industrial pallets where it continues to ramp the ore temperature toward the necessary process requirements.

This heat model allows the 60 to 70% of heat wasted by a closed-cycle alternator to be used toward industrial operations, using the more 'expensive' electrically-derived heat to close the final 25% (or less) gap toward 100% of the required energy. The electrical input generated at an efficiency in the range of 30 to 40% can be electronically servoed, permitting precise control of process temperatures.

The Production Queue

The first half of the production plant translates regolith into filament, fiber optics and fiberglass feedstock. These are stored in anticipation of orders for specific larger-scale, added-value production. This storage also serves as an 'elastic buffer' so that large volumes of material may be supplied, on short notice, from a modest plant running nonstop.

The principal stages of process flow which we currently envision at the foundry level (micro) are:

(i) Excavate or sweep, electrostatically or electromagnetically, regolith into the reactor;
(ii) Extract oxygen using Hydrogen reduction;
(iii) Blend constituent powders;
(iv) Heat to Melt;
(v) Pull glass fiber from melt;
(vi) Spool fabric and specialty filaments;
(vii) Weave fiberglass fabrics, tapes and cable;
(viii) Spool the woven glass fabrics.

One of several larger-scale production (macro) flows would be for habitats, shelters or spacecraft modules. The principal stages of process flow to convert fabric into a scaled structure are:

(i) Place bulkheads or attachment forms on a mandrel; see Figure 1;
(ii) Inflate mold form;
(iii) Wrap fabric webbing around the form/hatch assembly;
(iv) Plate inner and outer skins, laminating with CVDs.

Construction techniques for unattended manufacture of glass fiber-based structural components will be developed which will also be applicable to development on Mars. Programmable manufacturing, resembling conventional CNC automation, is capable of delivering *state-of-the-art* flexibility of remote design and parts manufacture. These concepts suggest intrinsic extensibility and evolutionary capability attained when machining second-generation tool parts from fiberglass.

Terrestrial fabrication of mating bulkheads and hatchways would minimize construction requirements for large habitats, storage and service structures. This allows for the precision machining and electronic fittings to be accomplished without immediately requiring delivery of machine shop and metal foundry capability to the Moon or Mars.

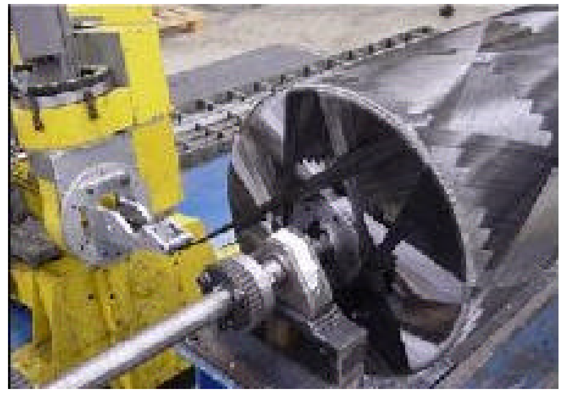

Figure 1. Wrapping a Form on a Mandrel

Adding Value Micro

The anticipated tensile strength of glass made under hard vacuum is an order of magnitude greater than glass produced in atmosphere containing water vapor[4]. This opportunity is testable and encourages experimentation on blends and alloys of the melt in conjunction with 'quenching' and other process step parameters. Doping the melt with trace minerals, such as Boron, permits fabrication of specialty glasses which have application-specific attributes such as flexibility, optical properties, *etc*. Some glasses may require that certain metals or other trace components be leached from the melt to attain the desired qualities. Use of indigenous materials in large quantities can multiply the value of 'dopant' elements hauled to the Moon or Mars.

Some of the filament output capacity will be committed to specialty glass melt. Additional strand capacity will be fragments used for reinforcing concrete, molded glass and similar products which may require some pre-alignment of the input stock.

Finer caliper fiber strands are almost entirely consumed by woven fiberglass products. Many methods exist for producing a variety of fiberglass fabrics with varying pitches, meshes, densities, porosity, *etc*.

Adding Value Macro

Diverse products for human systems support are manufactureable *in-situ* using glass fibers and fabrics. Pressure containers, structural components, woven fiberglass fabrics, molded and machined solid objects, glass fiber and filament are each large classes of value-added products. Steel I-beams typically used in building architectures may be replaced with fiberglass-based structural forms (Figure 2), offering a credible *factor of safety* by exploiting the fractional-G Lunar and Martian gravities.

Figure 2. Hyperboloids feature many fiberglass types

Two principal classes of ‘wrapped’ forms are solid core forms and hollow pressure core forms. An entire class of concrete substitutes are fabricated by wrapping woven fiberglass fabrics and specialized ‘tapes’ around a solid core, such as a rock. Another class would be pressure vessels, including Dewars, as small as a thermos bottle (Figure 3) and as large as an habitat or spacecraft fuel tank, all produced by wrapping a hollow core. The core might be deflatable and extracted for reuse.

Figure 3. An High-Pressure Fiber Bottle

These two classes of wrapped forms would be mounted on a mandrel and rotated while strands, braids, fabric strips or tapes are applied to the forms.

In addition to the wrapped-form components, cast and extruded structural parts consume vast quantities of fiber. The single obstacle to the realization of this group of components is a viable substitute for epoxy, due to the scarcity of Carbon on the Moon. One promising substitute is preplating fibers with dissimilar metals and then ‘alloy’ them together after winding. A variation is to create the wound form and then apply a metal through Chemical Vapor Deposition[5] (CVD) and plate up a metal part with integral silicon-fiber reinforcement. Many top unit systems and components will employ a variety of silicon fiberglass product types and classes.

Spiral Development at Work

As capabilities are delivered to the Lunar surface the synergisms of various industrial capabilities, inventories and feedstocks offer opportunities for an ever-expanding ‘menu’ of mission options. Imagine a quartermaster drawing inventory from a Lunar-derived ISRU warehouse on the Moon!

The shakedown of industrial development automation on the Moon will offer considerable and practical ‘lessons learned’ from an alien planetary surface which is ‘close at hand.’ This experience will provide insight into the challenges of surviving and thriving on Mars, from both the similarities to the Lunar surface as much as from the differences.

ISRU-derived spacecraft will be feasibly and affordably manufactured on the Moon, based upon fiberglass ‘tankage’ integrated with structured-fiberglass keels of a similar pedigree. For more exotic applications, second-generation structural components may take advantage of Silicon and Silicon-Carbide Fullerenes (Nanotubes) for additional com-posite strength. Silicon Fullerenes will redefine the science of applied materials, and may be blended into ‘conventional’ processes here described, especially those which may benefit from pre-aligned feedstock.

Summary

A large number of products related to human systems support, including structural members and pressure vessels, can be manufactured *in-*

situ using fiber fabric made from lunar silicate glass. An ISRU Silicon Fiberglass production effort will provide 'hands on' experience which will be transferable to the exploration of Mars and staging of a long-duration first mission. Those planning the first Mars Mission might give consideration to sending a series of missions which overlap and provide for continuous presence from the very first contact of human boots on the Martian surface.

ISRU can manufacture more than fuels: even spacecraft and communications satellites are feasibly and affordably manufactured on the Moon based on fiberglass 'tankage' integrated with structural fiberglass keels. The very ships taking us to Mars can be built of 'Moonstuff,' and the *lessons learned* will be very valuable on the Fourth Planet.

Figure 4 is a first pass compilation of fiberglass products which progresses from basic foundry outputs to integration of very sophisticated systems, vehicles, structures and tools. This will be translated into a dependency graph which shows how each component is situated in the production 'tree.' Generations of product include tooling which supplements and then gradually supercedes machine tools imported from Earth. Such a plan also indicates those capabilities which can be postponed.

Our experience with robotics and industrial automation will permit pre-positioning of an outpost with excavators and industrial pallets which generate first and second tier products from soils before the first Aldrin Cycler leaves Earth destined for Mars. Second-generation industrial facilities based on the Moon could manufacture second-generation structural components, taking advantage of Silicon Nanotubes for additional composite strength.

The next research step is to map the elements required to produce various types of glass. A similar matrix of mineral distribution on the Moon and Mars will direct mission planners to sites appropriate for specific production yields. When these efforts converge on useful results, then the production planning and tool design suggested here may commence.

Figure 4. Compilation towards a Silicon Fiber Dependency Graph

Curriculum Vitae

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A bits and bolts technologist from 'way back, Rod designs and develops products with electronics or intelligence content for the industrial world. His oil patch, avionics, mining, systems and industrial automation customers have mass-produced his designs in oil well controllers installed on five continents, avionics flying in commercial and military fleets worldwide as well as the President's Helicopter Fleet, specialized test equipment and numerous other products. These devices are often, although not exclusively, embedded controllers operating in hazardous environments.

He holds a Bachelor's degree in Math and Computer Science, having grown up with computers since the sixties. He is a VietNam-era veteran and a sometimes-current private pilot.

ENDNOTES

[1] Larry Haskin and Paul Warren, *Lunar Chemistry*.
[2] *The Development and Realization of a Silicon-60-Based Economy in CisLunar Space*. G.J. Rodriguez, *sys*RAND Corporation, Space Resources Roundtable II (2000). #7031.pdf.
[3] *SILICON: The Foundations of a CisLunar Economy*. G.J. Rodriguez, *sys*RAND Corporation, W.A. Good, ESTS Inc., AIAA 2001-4662.
[4] Traceable to John Dees' work on 'super ductility in glass' which determined that melted glass is susceptable to atmospheric water which contaminates the glass with hydroxyl ions.
[5] See www.space-mining.com for a number of Chemical Vapor Deposition (CVD) practitioners.