Using Fabricators to Reduce Space Transportation Costs

Dr. David S. McKay, Assistant Chief for Exploration and Technology
Lyndon B. Johnson Space Center, Houston, Texas

Hubert P. Davis, President
Davis Aerospace Company, Canyon Lake, Texas

Dr. Marshall Burns, President
Ennex Fabrication Technologies, Los Angeles

Abstract

Ever since the Apollo landings, one of the primary barriers to more ambitious space projects has been the exorbitant cost of lifting equipment and construction components off of the Earth. Fabricators offer an intriguing solution by allowing for the use of native materials on the Moon, Mars, or other destinations in the production of tool and building parts. This paper discusses

- The kinds of objects that can be practically made in this fashion,
- Fabricator processes suitable for extraterrestrial environments,
- Raw materials available, and
- The impact of this use of technology on the cost of space projects.

Introduction

When the European settlers came to America, they brought their hammers, axes, saws, and barrels of nails. With these tools and materials they built cabins, barns, and forts. They did not, however, bring wood, the most important construction material they would need, because they knew they would find plenty of timber at their new home site. In fact, in many cases they had to get to work cutting down trees not only to provide lumber for construction but also to provide clear land to plant crops.

When we go to the Moon, Mars, and the Asteroids, we know we will not find any trees or wood. But we will find plenty of other construction and industrial materials, such as iron, aluminum, and magnesium, from which we can build shelters, factories, and machinery. The presence of these materials could save us the expense of launching steel beams and aluminum habitat shells, except for one major problem. What will stand as the modern analog of the settlers' hammers, axes, and saws? What tools can we take with us to turn celestial rocks and dust into walls and girders?

Until recently, this was a "Catch-22" situation. We need refineries and foundries to process raw ore into building materials. But refineries and foundries are large, heavy facilities that consume voluminous materials in their own construction. So how can a lunar or other celestial settlement be bootstrapped out of the indigenous soil?

The answer may lie in additive fabricators. A fabricator[1] (or *fabber*) is an ultra-modern machine that *makes things automatically.* Fabricators use raw materials and computer data to generate three-dimensional, solid objects you can hold in your hands, submit to testing, or assemble into working mechanisms. They are being used by manufacturers around the world for low-volume production, prototyping, and mold mastering. They are also used by scientists and

[1] For more background on fabricators, see *Automated Fabrication—Improving Productivity in Manufacturing* by Marshall Burns, Prentice Hall, 1993, ISBN 0-13-119462-3.

surgeons for solid imaging, and by a few modern artists for innovative computerized sculpture. Manufacturers report enormous productivity gains from using fabricators.

As the quality and speed of fabricator output steadily improves, we are gradually moving toward a time when these machines will be able to participate in the construction of large structures and make parts to be incorporated into working machinery. The ability of several processes to work with metals may allow the launch of one or a small number of fabricators to spawn the construction of an entire colony.

This paper investigates several of the issues important to evaluating the opportunity to reduce transportation costs by using fabricators for on-site generation of machine parts and construction components. The important issues are:

- **Items to be made.** What can we expect to practically make in space using the kinds of fabricators discussed here?
- **Suitable fab processes.** What fabrication processes are suitable for operation in a space environment?
- **Raw materials.** What materials are readily available in space for fabricator feedstock, and what is their suitability for the candidate processes?
- **Benefits.** How will the ability to make these items on-site affect the cost of future space projects?

The investigation of these issues cannot be done uniformly for all off-Earth locations. Each celestial body has differences in the composition of its surface materials, and in environmental factors, such as gravity, temperature, radiation, etc. Furthermore, space-based fabricators are not limited to operation on the surface of a celestial body, but could also include orbiting facilities. The cost of lifting raw materials off of small bodies like the Moon is very much smaller than for Earth. Thus, in cases where there are advantages for operating a fabrication process in the microgravity available in orbit, this also becomes a candidate location.

What Shall We Make?

There are some definite rules about when a project is appropriate for a fabricator. These rules do not apply in the same way off the face of the Earth. One of the rules is that you don't use a fabricator when the job can be done more economically by another process, such as casting or extrusion. However, this rule is stated in a context that assumes that there are foundries, extrusion presses, and other typical manufacturing equipment within shipping distance. None of this equipment currently exists in space, and transporting it would be very expensive. Therefore we may find it practical to use fabricators, at least in the initial stages, to make blocks, bars, beams, rails, and other simple shapes that one would not consider running in an Earthbound fabricator.

With a fabricator, the opportunity arises to make changes to designs that would otherwise not be practical. For example, if a construction project calls for an arrangement of posts and beams, one would normally, on Earth, order them in standard shapes and lengths and then cut them on-site to the required lengths and weld them into the needed configuration. The individual sections of all the posts and beams are all identical because it is more economical to order them that way. But if each section is being created individually in a fabricator, this allows the engineers to apply special characteristics to individual components. For example, one might want to design flanges or other connection hardware directly into specific sections of individual posts and beams. With well designed connection hardware fabricated as integral to the construction elements, one may be able to design buildings as "erector sets" ready for assembly, without the need for the crew to perform any specialized tasks, such as welding or drilling of bolt holes.

Another novel design might apply in making bricks. Two problems with making bricks in a fabricator on Earth would be the time it takes to solidify their large bulk and the cost of the fabricator raw material. But again, those problems may be eliminated by the differences of the extraterrestrial situation. First, the raw materials for the fabrication processes anticipated may be essentially free and abundant, like timber was to the American settlers. Second, it may not be necessary to solidify the entire bulk of the bricks. Subject to the engineering requirements of the construction project, it may be sufficient to solidify only an exterior shell of the brick, which would then contain the remaining mass of unconsolidated raw material inside. Such a brick would provide just as much radiation shielding as a fully solid brick, yet take much less time to fabricate.

A fabricator provides the opportunity to transform a mundane brick into a functional construction element. On Earth, bricks are simple rectangular blocks because that makes them easy to cast. But, like the posts and beams discussed above, bricks in a fabricator could be made with connection hardware that could reduce or eliminate the need for mortar. Moreover, bricks could be designed with internal channels or external mounting brackets for ductwork, wiring, lighting elements, hazard detectors, and other functional subsystems.

For vehicles, it is not likely that we would use fabricators right away to make highly complex systems, such as engines and brakes. However, many other vehicle parts could be practically made on-site, such as frame members, body panels, axles, and wheels. Also, when problems occur with engine and brake systems, a fabricator could be used to make replacement parts.

In an unfamiliar space environment, unanticipated situations will arise constantly to challenge the crew. When constructing an outpost from Earth-supplied components, the crew would have to meet those challenges by "making do" with whatever is at hand. But with a fabricator, the crew can respond to challenges by inventing and fabricating new tools and new kinds of construction elements at will. The inventive designs may come from the space crew itself, or the designs may be conceived by the support crew on Earth and transmitted to the outpost for local fabrication there.

Given these considerations, one might expect the items made in a space-based fabricator to include

- Construction elements, such as posts, beams, and bricks, individually designed for mating to neighbors and provision of appropriate functionality.
- Conduits for plumbing, air management, and space radiators.
- Fixtures and fittings, such as brackets, joints, etc.
- Large vehicle elements, such as frame members and wheels, as well as replacement parts for complex vehicle systems, such as engines and brakes.
- Hand tools, such as mallets and wrenches, as well as parts and fittings for power tools, including bases for heavy machinery.
- Structural and functional elements of technology projects, such as solar power collectors, telescopes, transmitters, etc.

An immediate concern that arises in considering the use of fabricators to make such items is the quality of fabrication. Today's fabricators do not yet match the physical properties available from more mature manufacturing processes, such as investment casting and bulk sintering. And even if Earthbound fabricators do become developed to the point of competing adequately on the basis of material properties, space-based fabricators will still be experimental devices that cannot promise matching properties because they will be working with foreign materials and subject to a different environment in terms of gravity, atmosphere, radiation, etc. However, in considering this issue, one must be careful not to apply the extraordinary quality standards normally used in space projects today. One must recall that the primary reason for these lofty standards is that there is generally no opportunity to replace components that malfunction in space. This fundamental assumption is negated by the introduction of fabricators to the supply system. Thus, while one does not want to take any chances with the safety of building construction or hand-held tools, in general it will be acceptable to apply ordinary, Earth-like quality standards to items made in space-based fabricators.

Suitability of Processes for Space-Based Fabrication

Fabricators today are categorized as either <u>subtractive</u> or <u>additive</u>, depending on whether they work by carving away material from a solid block (CNC machining) or by building up the desired object from an amorphous material. Since subtractive fabricators require billets or other bulk stock as raw material, they are not considered here, and we focus on strictly additive processes.

There are three basic categories of additive fabrication technologies: aimed deposition, selective sintering, and selective curing. These are briefly described in the following subsections, along with comments on their use in space.

Selective sintering

In selective sintering, a powder is caused to melt in specific locations, and the melted powder then fuses into a contiguous solid, which builds up the shape of the desired object. Although most fully developed for use with thermoplastics, there has been successful study of its application to metal and ceramic powders. There are three approaches to achieving sintering of a metallic or ceramic feedstock:

- Using a very high-energy beam to achieve sufficient heating to directly melt a standard, high-melting-point metal or ceramic.[2]
- Using a beam of moderate energy with a low-melting-point alloy or a mixture that includes a low-melting-point component.[3]
- Using a metal or ceramic powder either with a polymer coating or with a polymer component mixed into the powder. The selective sintering process then actually operates on the polymer coating or component in order to form a "green body" which is later subjected to bulk heating to burn out the polymer and cause direct fusing of the metal.[4]

On Earth, the energy beam is generally supplied by a laser, although electron beams have also been proposed. In space, an excellent source of thermal energy is likely to be concentrated sunlight.

Selective sintering is a promising technique for near-term testing of space applications. This is because some success has been demonstrated in applications to metals already, and because raw metal and ceramic powders are available on the Moon (see *Raw Material* below). Any of the three approaches listed above may be used. For polymer-coated powders, the polymer would need to be supplied from Earth, but the mass of polymer consumed would be small compared to the mass of metal fabricated, so the goal of reduced transportation costs would be accomplished.

Aimed deposition

In aimed deposition, a stream of material is aimed at specific locations on the growing object to build it up. The material may be deposited in the form of droplets or in a continuous bead. A number of projects have studied application of this technique to metals.[5] It may be suitable for use in space, using feedstocks melted in a solar-heated crucible. This is a promising technique, which could emerge as the method of choice for fabricating in metals. However, the application of the technology to metals is quite immature. Many issues need to be resolved in Earthbound development before it is practical to test this technique for space applications.

Another idea which would fall into this category is Pegna's technique for fabricating in concrete.[6] Pegna selectively deposits Portland cement on successive layers of sand and initiates a bonding reaction in each layer by wetting with steam. A more efficient use of water would have to be developed for this be practical for use in space.

---

[2] An example of the use of a high-energy beam, although not with a powder feedstock, is in *Electron beam solid freeform fabrication of metal parts* by V. R. Davé, J. E. Matz, and T. W. Eagar in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 64..71.

[3] *Accuracy and mechanical behavior of metal parts produced by lasersintering* by T. Pintat, M. Greul, M. Greulich, and C. Wilkening in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 72..9.

[4] *Selective Laser Sintering and Fused Deposition Modeling processes for functional ceramic parts* by E. Alair Griffin and Scott McMillin in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 25..30.

Effect of processing parameters in SLS of metal-polymer powers by B. Badrinarayan and J. W. Barlow in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 55..63.

Free form fabrication of high strength metal components and dies by C. C. Bampton and R. Burkett in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 342..5.

Effect of particle size on SLS and post-processing of alumina with polymer binders by P. Kamatchi Subramanian, J. W. Barlow, and H. L. Marcus in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 346..52.

[5] *Thermal design parameters critical to the development of solid freeform fabrication of structural materials with controlled nano-liter droplets* by Melissa Orme and Changzheng Huang in *Solid Freeform Fabrication Proceedings*, September 1995, p 88..95.

"Incremental fabrication" builds directly in metal by Marshall Burns in *Rapid Prototyping Report*, January 1992.

[6] *Application of cementitious bulk materials to site processed solid freeform construction* by Joseph Pegna in *Solid Freeform Fabrication Proceedings*, University of Texas, September 1995, page 39..45.

Formulations and applications of lunar concrete have been extensively studied by William Agosto and colleagues at NASA.[7]

Selective curing

In selective curing, a liquid resin is caused to cure (harden) in specific locations to grow the desired object. The Earth-based version of this, using organic photopolymers, is not practical for space applications because of the absence of organic base materials. However, the abundance of silicon on the Moon may offer the basis of a whole new industry in silicon-based polymers. Today's *silicones* are polymers with an alternating silicon-oxygen backbone. They can be made into photopolymers, but currently this is done by hanging organic functional groups on the inorganic backbone. It is possible that we will see fully inorganic photopolymers in the future, or polymer resins that are subject to another form of selective curing, such as thermal or voltaic. If such materials do become available, it will be interesting to consider their use in fabricators on the Moon or other silicon-rich environments.

Process Schematics

Fig. 1 illustrates a selection of possible schemes for space-based fabricators. The techniques illustrated fall into the categories of sintering (a and d) and droplet deposition (b and c). All of these particular techniques use heating as part of the process, which in the illustrations is supplied by an integrated solar collector. The advantages of this source of heating, as well as an alternative, are discussed below.

The system in Fig. 1(a) is essentially equivalent to the sintering fabricators made by DTM (Austin, Texas) and EOS (Munich, Germany), except that the process heat is supplied by focused sunlight instead of by a laser beam. Such a device works as follows. A platform is provided on which to build the desired object. Successive layers of raw powder are deposited from a hopper on top of each other, with the entire cake of powder layers resting on the platform. The platform is mechanized for vertical motion, and is lowered by the thickness of one layer each time a new layer of powder is deposited. In this way, the top surface of the powder cake is maintained at a constant level. The platform and powder cake are enclosed in a chamber which is maintained at an elevated temperature at which the powder is not hot enough to fuse, but does not need a great deal of additional heat to bring it up to a temperature at which it will fuse. Each time a new layer of powder is deposited, a beam of concentrated sunlight from a solar collector is scanned across it to raise selected regions of the layer to the fusing temperature. Where the solar beam strikes, the grains of powder melt momentarily and fuse to each other and to the underlying layer. The beam is controlled by data from a CAD design of the object to be built; the regions of powder which are scanned in each layer of powder make up one cross section of the desired object. After each cross section is formed in this way, the platform is lowered, another layer of raw powder is deposited, and the process is repeated until the complete object is formed.

Fig. 1(b) and (c) show two methods of aimed deposition. The technique in Fig. 1(c) deposits molten droplets of material, very much like the fabricators made by BPM, Sanders, and 3D Systems today. Fig. 1(b) shows an alternative technique which is being studied with lasers at national research laboratories in both Germany and the United States.[8] Here, instead of melting the material in a crucible, a stream of powder is aimed at the correct locations and the falling powder is melted in mid-stream. This process may offer significant advantages in the fabricated material properties at the cost of the increased mechanical complexity needed to synchronize the scanning of the light beam and the powder deposition stream.

Fig. 1(d) shows a variation on the sintering process suggested to us by Kenneth J. Hayworth of Ennex Fabrication Technologies. In today's commercial fabricators, the fabrication chamber is bound by walls that limit the size of

---

[7] *Lunar cements/concretes for orbital structures* by William N. Agosto, John H. Wickman, and Eric James in *Engineering, Construction, and Operations in Space IV* (Proceedings of Space '94, Albuquerque, February 26 .. March 3, 1994), American Society of Civil Engineers, New York, 1994, page 157..68.

[8] *Approaches to prototyping of metallic parts* by W. König, T. Celiker, and H.-J. Herfurth in *Proceedings of the 2nd European Conference on Rapid Prototyping and Manufacturing*, University of Nottingham, July 1993, page 303..16.

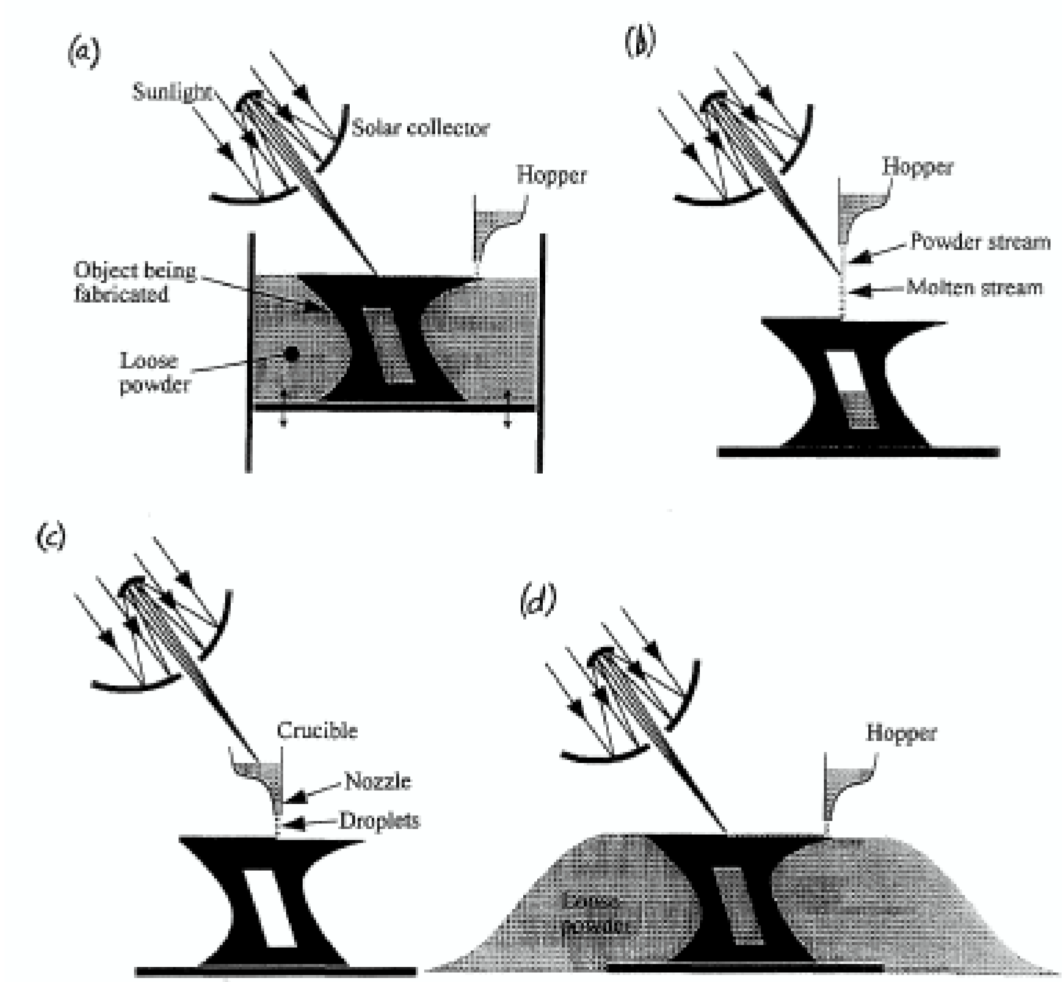

Fig. 1. **Schematics of four heat-based fabricator systems** using focused sunlight as the source of process heat. Those shown are adapted from processes currently used on Earth, (a) selective sintering of powder deposited on a descending bed, (b) melting in place of an aimed powder stream, (c) deposition of molten droplets, and (d) selective sintering with an uncontained powder bed. See the text for a more detailed description of each system.

Note a conspicuous difference among the techniques is in the residual material in unprocessed regions. Sintering leaves loose powder in cavities not scanned by the heating beam, as seen in (a) and (d). Droplet deposition, as in (c), is able to leave hollow cavities, although the formation of horizontal ceilings as in this illustration may be problematic. Melting of a deposited powder stream, as in (b), is the most flexible, able to fill void regions with loose material from the hopper or leave them partially or completely empty.

objects that can be built. The purpose of the chamber is not only to contain the loose powder, but also to provide an inert, unperturbed environment. On the Moon, where there is essentially no atmosphere, an inert, unperturbed environment is available without an enclosed chamber. With containment of the loose powder by a built-up embankment, it may not be necessary to work in a chamber at all. This would simplify and reduce the mass of the equipment needed for a lunar sinterer by eliminating the walls of the chamber as well as the elevator device needed to move the build platform within these walls.

Solar heating

All of the processes illustrated in Fig. 1 use heating as part of the fabrication process, and show this heat provided by a solar collector integrated into the fabricator. The use of a solar collector has several advantages over a laser.

First, a solar collector has a much longer life than a laser, and does not need to be recharged or replaced on a regular basis as a laser does. Second, although a modest amount of electricity would be needed to power the controls of the solar collector, thermal power is provided freely by sunlight, whereas a laser requires electricity for thermal power as well as for controls.

Taking up these advantages, NASA has already been studying the provision of a solar-collector utility for use by various materials processing experiments on the Moon.[9] This communal solar collector would use optical waveguides to provide concentrated sunlight to the equipment needing it. Thus, the first lunar sinterer might not need to include its own solar collector, but may be able to plug into a waveguide from the communal system instead.

One important advantage of providing the concentrated sunlight through an optical waveguide is that it allows the main part of the fabricator to be physically separated from the solar collector. Even if the fabricator uses its own, dedicated solar collector, this would allow the collector to be located in a place of constant sunlight while the main part of the fabricator is located in constant shade, where thermal regulation would be easier to provide by space radiation. An example of a pair of such locations would be in the vicinity of the crater near the lunar South Pole studied recently by the Clementine probe. There are highlands at the rim of this crater which are constantly bathed in sunlight throughout the month-long lunar "day," while other regions inside the crater are continuously shadowed. An optical waveguide a few kilometers long could connect a solar connector at the rim with a fabricator below for potentially non-stop operation.

Raw Material

The raw material available for local supply to a fabricator depends on the particular celestial body on which it is located, as well as the specific region of that body at which it is placed. For simplicity, we will limit most of the following discussion here to the body which is the most studied, our Moon. Mars appears to be largely similar to the Moon in composition, but with some important differences. The asteroids, on the other hand, offer a variety of compositions, including some with carbon-based compounds. The availability of carbon will be very important when more is know about it and the means are available to travel to it.

The lunar surface[10] is composed largely of minerals and glasses, mostly oxides of silicon, aluminum, iron, calcium, magnesium, and titanium. Eons of meteorite impact have pulverized a great deal of this material into a fine powder with grains mostly in the range of ten to 100 microns. Three of the schemes suggested in Fig. 1 require powdered feedstock (a, b, and d), and these processes will naturally benefit from this abundant, naturally available powder.

One of the important challenges in working with this lunar soil is separation of the constituent materials into usable fabricator feedstock. There is some debate over the use of magnetic separation of iron particles from the soil. While some experts contend this should be feasible, others point out that such a process will result in a greater concentration of ferrous agglutinates (shock-melted, fused soil particles).

Another intriguing potential source of metallic iron is the reduction of mineral oxides.[11] This process has been extensively studied as a method of generating free oxygen, a commodity of obviously great value. NASA's prime candidate for oxygen extraction is pyroclastic glass (volcanic ash from early lunar eruptions). Tests of this lunar material have yielded the greatest free oxygen with byproducts of silicates and iron metal. Unfortunately the solid

---

[9] *Optical waveguide solar energy system for lunar material processing* by Takashi Nakamura, Constance L. Senior, James M. Shoji, and Robert D. Waldron in *Engineering, Construction, and Operations in Space IV* (Proceedings of Space '94, Albuquerque, February 26 .. March 3, 1994), American Society of Civil Engineers, New York, 1994, page 1266..77.

[10] *Mineralogical and chemical properties of the lunar regolith* by David S. McKay and Douglas W. Ming in *Lunar base agriculture: Soils for plant growth*, ASA-CSSA-SSSA, Madison, WI, 1989, page 45..68.

[11] *Lunar oxygen production—A maturing technology* by Carlton C. Allen, Gary G. Bond, and David S. McKay in *Engineering, Construction, and Operations in Space IV* (Proceedings of Space '94, Albuquerque, February 26 .. March 3, 1994), American Society of Civil Engineers, New York, 1994, page 1157..66.

byproducts are intimately mixed and it is a subject of debate whether the iron component may be economically separated in a useful form.

If obtaining reasonably pure metallic feedstock remains difficult, useful properties may still be obtained from fabrication processes performed directly on pyroclastic glass or other raw mineral stock. A glassy material may offer a reasonable softening temperature to allow for sintering, and with enough bulk to overcome brittleness may be a suitable material for containers and low-impact tools and construction elements.

Benefits

It is difficult to estimate the cost of transporting goods from Earth to another celestial body when there is no working transportation system available for the job. Estimates for the Moon range from \$7,000 to \$30,000 per kilogram and even possibly much higher, depending on whose scenario one has faith in. At these costs, the ability of fabricators to eliminate the transportation of a great deal of necessary equipment and construction elements will be a tremendous boon to any extensive space mission.

Perhaps more important than a quantitative dollar savings is the fact that one or more on-site fabricators would allow crew members to respond to emergencies and devise situational inventions which could make the difference between failed and successful missions. Also, if the fabricators were placed in advance and operated remotely for a period of time, the crew could arrive at a site which is already supplied with the tools and components needed to get to work on the objectives of the mission.

Next Steps

The way to begin evaluating whether space fabricators are workable is to test the concept with physical experiments. These experiments should be performed by robotic operation on the lunar surface after first confirming their feasibility in Earthbound tests. NASA has identified several terrestrial materials that simulate the properties of various lunar soils. One good simulant, called JSC-1, is available in large quantities, has the grain size distribution of actual lunar soils, and yields metallic iron as a byproduct of oxygen extraction.[12] We recommend that NASA engage in a program to design a lunar-surface apparatus, which would be built and first operated on Earth using JSC-1 or another lunar simulant. This would provide a low-risk way to prove out the concept and advance it in stages to actual implementation in future space missions. Coordinating these experiments with others on oxygen production and optical waveguides (as well as possibly solar wind gas extraction) may providing opportunities for sharing resources and lowering cost and launch mass.

Conclusion

As a commercial technology, additive fabricators are less than a decade old on Earth. The various methods are undergoing very rapid refinement and improvement. These methods present new possibilities for building up objects from celestially available materials. This new capability will allow explorers to venture forth with fabricators to build their homesteads and their industrial facilities. It has long been recognized that machines with such capability would be necessary to really make space settlement feasible, just as the European settlers needed their saws and hammers to begin building a home in America from native timber. It may be that fabricators will be the breakthrough that finally cracks the barrier to space habitation.

[12] *JSC-1: A new lunar soil simulant* by David S. McKay, James, L. Carter, Walter W. Boles, Carlton C. Allen, and Judith H. Allton in *Engineering, Construction, and Operations in Space IV* (Proceedings of Space '94, Albuquerque, February 26 .. March 3, 1994), American Society of Civil Engineers, New York, 1994, page 857..66.