Natural Feedstocks for Fabrication of Spare Parts = Sustainability for Planetary Missions. B. L. Cooper[1] and D. S. McKay[2], [1]Cooper Research (League City TX U.S.A., bcooper108@gmail.com), [2]NASA Lyndon B. Johnson Space Center, Houston Texas U.S.A. (david.s.mckay@nasa.gov).

Abstract: Sustainability of a human settlement on another planetary surface requires the ability to fabricate parts on a one-up basis using computer-aided-design (CAD) instructions. This may be done with additive fabrication (laser sintering) in which feedstock is derived from local materials. Size fractionation of planetary regolith is required in order to obtain particles of a useful diameter for the laser-sintering process. Newly-developed room-temperature masers (collimated microwave beams) can replace lasers in the additive fabrication process, increasing efficiency of the system.

Microwave sintering of lunar soil: Scientists announced the amazing capability of microwave energy to melt lunar regolith in 2004 [1]. Various uses for this property were considered, including microwave sintering of the lunar surface to create landing pads, berms, and roads [2].

Additive Manufacturing: More recently, additive manufacturing techniques have gained widespread popularity, and kits are now available for home users to perform additive manufacturing on a hobby basis [3]. Extrusion techniques (Figure 1) are the simplest of these, the most robust of which [4] has been shown capable of creating near-finished forms of stainless steel, which can be sintered after formation to create objects with densities of 90% volume fraction and tensile strength of up to 35% of the strength of CNC-derived components [5].

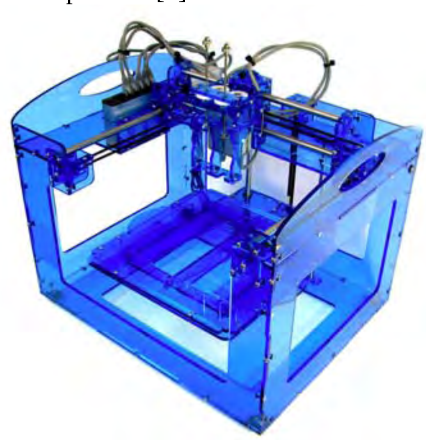

Figure 1. Fab@Home model 2 is an extrusion-type additive manufacturing device. It can use several types of feedstock from polymers to chocolate; kit price ~$2000.

A more complex process, laser sintering, has also come into widespread use [6, 7]. In this process, layers of powder are added sequentially to a bed of material, and the laser is computer-directed to melt or sinter each layer so as to build up a completed object.

Both of these processes have potential for use on the Moon or Mars to manufacture replacement parts, spares, and many other useful items during an extended stay on another planet. However, a recent breakthrough in maser technology offers the possibility to replace laser sintering with maser sintering, which would be very effective in sintering soils with sufficient metallic content.

Masers: Masers, the precursor to lasers, were developed in the 1950s [8]. A maser amplifies molecular radiation rather than visible light, and the resulting electromagnetic output is in the range of microwaves. Maser-operated radar has no thermal noise, allowing a very weak echo to be received. During the early 1960s, the Jet Propulsion Laboratory developed a maser to provide ultra-low-noise amplification of S-band microwave signals received from deep space probes. This maser used hydrogen to chill the amplifier down to a temperature of four degrees kelvin [9].

Until recently, masers have been used only for specialized applications, due to the extreme conditions related to their operation. Atomic and free-electron masers require vacuum chambers and pumping; and solid-state masers, although they excel as low-noise amplifiers and are occasionally incorporated in ultrastable oscillators, typically require cryogenic refrigeration [10].

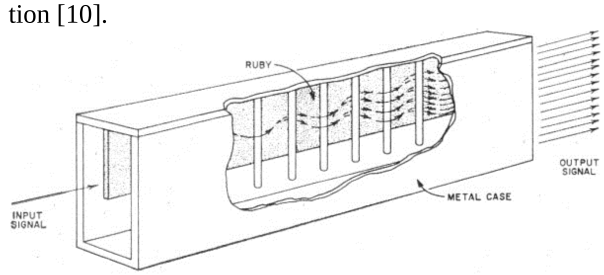

Figure 2. Schematic of how a maser operates. The cutaway view shows how the input signal weaves in and out of the row of pins next to the strip of ruby; each time the signal goes around a pin, additional energy is radiated. resulting in increased amplification.

By 1965, most of the organizations and specialized personnel that had developed maser technology had moved on to the optical spectrum and lasers. Developments after 1965 were mostly concerned with deep-space communications, radio astronomy, or high-precision instrumentation.

Current Research: In August of 2012, the first room-temperature maser was announced [10, 11]. This breakthrough makes it possible to merge the advantages of microwave sintering of lunar soil with the additive manufacturing techniques that are based on lasers. By exchanging the lasers for masers, a very effective system can be made for manufacturing items from lunar soil. The microwave energy couples with lunar soil because of the nanophase iron which is separated by a dielectric layer of silica glass [1]. Asteroids are expected to have less nanophase iron than on the Moon because the solar wind, and presently it is not known if any soils on Mars have nanophase iron.

Feedstock Preparation: Additive manufacturing via laser sintering requires a feedstock powder of small size. Sintered metal objects have been built with an extursion-type 3D printer, in which the feedstock particles had a diameter of 12 micrometers [5]. We have developed an apparatus, based on gas flow, for dry-size-sorting of particles producing a ~ 2 micrometer-feedstock directly from a friable regolith on the moon, Mars, or other planetary bodies. Designs for planetary regolith pneumatic mining, coring, and transport have been tested in low gravity and partial vacuum and show outstanding performance. The addition of our dry size-sorter would produce a single integrated pneumatic system capable of producing a ~ 2 micrometer size powder directly from a regolith which would in turn enable the operation of an end-to-end additive laser or maser manufacturing system.

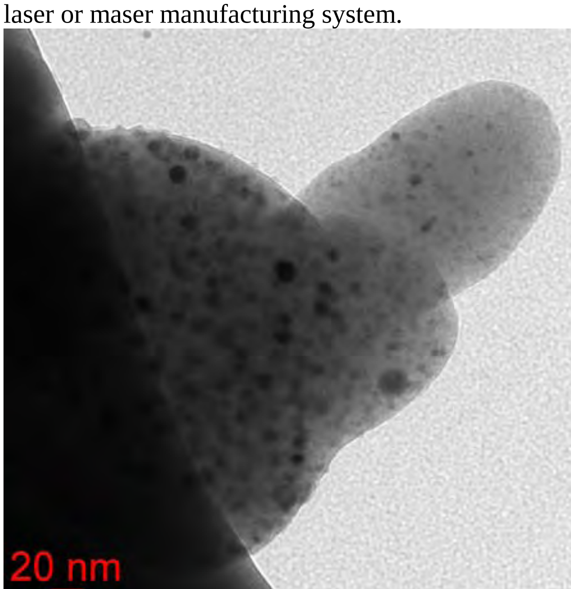

Figure 3. Nano-phase iron (np-Fe^0) blebs (black and dark gray spots) in a backscattered scanning electron micrograph of Apollo 14 soil 14003,96.

In order to perform a high-fidelity test of additive manufacturing with regolith simulants, simulants must be modified to include sub-micrometer Fe^0 particles, which have been shown to be a common component of lunar soil (Figure 3) and are also expected to be present in asteroids [12]. Such np-Fe^0-rich silica glasses have been produced by [13] and [14]. These can be used to study the effect of maser sintering. Masers are expected to be more effective than lasers on soil with np-Fe^0 content because of the interaction between the microwave radiation and the iron particles [1]. However, both may work.

Demonstration of the usefulness of planetary feedstock of proper size for both laser- and maser-sintered additive manufacturing will be a major step forward for "living off the land" on other Solar System bodies.

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