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Geophysiological Treatment of an Ailing Earth from Space: Self-replication Technology Is Essential

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Abstract: Current approaches to climate change mitigation are insufficient to solve the problem of climate change. In analogy to medical practice, we submit that baseload clean energy sources are required (antibiotic) together with geoengineering (analgesic). We have highlighted space technology as offering these solutions—solar power satellites in geostationary orbit around Earth and space-based solar shields at the L1 Sun-Earth Lagrange point. The chief hurdle is the high cost of launching assets into space. We propose to eliminate this cost barrier by implementing self-replication technology based on 3D printing techniques applied to material resources on the Moon. This eliminates the launch cost problem. We have been making progress in developing the underlying capabilities that will realise self-replication technology. The ability to 3D print electric motors and electronics is key to the construction of robotic machines from lunar material. This work will be described. If self-replication technology can be implemented even in a simple way it opens the possibility of exponential growth in productive capacity on the Moon. Constellations of both solar power satellites and solar shield modules—our treatment of choice—become feasible at very low cost.

Keywords: Geoengineering, Solar Shield, Solar Energy, Solar Power Satellites, Geophysiology

Introduction

The Paris Agreement (2015) of the UN Framework Convention on Climate Change recommended that global warming should be limited to 1.5–2.0°C. A 1.5°C limit correlates to a 50% probability of sea level rise of 1.5 m by 2100; a 2.0°C limit correlates to a 50% probability of sea level rise of 2.7m by 2100. In 2015, global CO_2 concentrations passed 400 ppm—it is expected that once it reaches 450 ppm by around 2030, significant climatic effects will occur. Many consider the 450 ppm scenario assumption that global temperature rise will be limited to 2°C to be erroneous and dangerous. Current global warming has reached 0.6–0.9°C above pre-industrial levels, but yet to come are the effects of thermal inertia of the Earth's oceans which are expected to impose a further 0.8–1.25°C temperature rise over 40–60 years even if no further greenhouse gas emissions were forthcoming. This assessment excludes the effects of methane and nitrogen oxide greenhouse gases and reduced aerosol cooling due to diminishing coal burning. Despite the Paris Agreement, there is little evidence of abatement of greenhouse gas emissions, and, indeed, its lower limit has already been effectively surpassed. This means that further global warming will be inevitable and continue to worsen, the effects of which can be combatted only through geoengineering. There are several approaches to geoengineering, most of which involve solar radiation management, the current favourites of which are marine cloud brightening and stratospheric aerosols. Carbon dioxide removal techniques include ocean fertilization and carbon air capture amongst others. Solar radiation management offers more rapid effects than gradual CO_2 removal. Usually, space-based geoengineering through a solar shield at the Sun-Earth L1 point is considered too technologically challenging to be entertained seriously, but it offers significant advantages:

1. it involves no direct chemical interaction with the Earth's atmosphere;
2. it is implementable in structured phases;
3. it is fully controllable, modulatable, and reversible.

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Geoengineering is not a sustainable solution to global climate change as it does not tackle the underlying accumulation of atmospheric CO_2. For this, clean energy sources are required such as solar power and wind energy. The current projected global energy mix for 2030 (assuming a 40–50% energy increase from 2010) comprises 25–30% oil, 20–30% coal, 20–30% natural gas, 5–10% nuclear sources, and 10–20% renewable sources, i.e. 60–90% fossil fuels (Pyke 2012). Natural gas combustion, by halving greenhouse gas emissions compared to coal burning, is commonly touted as a transitional energy source—this is a mythical concept as it still contributes to greenhouse gas accumulation, albeit at a slower rate. Renewable resources are dominated by solar photovoltaic and wind energy generation—nuclear energy, although promising as a clean energy source, presents severe political challenges. The expandability of renewable sources presents certain difficulties, particularly regarding power load matching due to the intermittency of supply. Most demand occurs during the daytime during both summer and winter, but solar energy generated is limited to noon-centred daytime near the summer equator while wind is restricted to windy sites with highest output during spring/autumn at night. Renewable sources must often be supplemented for peak load supply, commonly through natural gas burning which offers rapid response to demand. The nail in the coffin for renewable resides in their poor areal efficiencies ~2–10 W/m^2 imposing high real estate requirements potentially encroaching on other activities such as agriculture, urban growth, or plain human distaste (MacKay 2009). A corollary of this is that there are no terrestrial renewable energy schemes suitable for general global baseload power supply. There is, however, a non-terrestrial solution—solar power satellites which offer an areal power density of 230 W/m^2 to Earth for a baseload power supply with zero greenhouse gas emissions.

It appears then that we should treat the Earth as a geophysiological system in which climate change constitutes a geophysiological disease. In medicine, diseases are often treated systematically to combat the disease symptoms and their underlying aetiology. An analgesic provides short-term pain relief in treating the symptoms; an antibiotic destroys the causative agents—bacteria—that yield the symptoms over a sustained treatment duration. The geophysiological system of the Earth may be treated similarly with an integrated treatment regimen—geoengineering offers a short-term treatment of global warming symptoms combined with sustained clean energy sources to eliminate greenhouse gas emissions. This approach negates the argument that climate intervention through geoengineering detracts from climate mitigation via clean energy. Human activities are reaching the limits of Earth's capacity to return to its natural state (Lovelock 2011). Furthermore, the exploitation of the space environment allows us to supplement the limits imposed by our finite Earth through exploitation of resources off-Earth. Indeed, this may be the first sign that humanity has outgrown its cradle and must garner resources (in this case, energy) from outer space.

Space-based Geoengineering—The Analgesic

Geoengineering has been proposed as a necessary emergency stop-gap to prevent global warming from spiralling out of control (Keith and Dowlatabadi 1992). Geoengineering approaches to climate change intervention are unpopular and are regarded with suspicion, however. Notwithstanding this, there are two main approaches to geoengineering to alter the Earth's thermal balance:

1. removal of CO_2 from the atmosphere to be sequestered safely;
2. reduce solar radiation to Earth by reducing the solar flux to Earth or by increasing Earth's albedo.

Lenton and Vaughan (2009) suggest that, of all the various schemes proposed, only space-based geoengineering and stratospheric aerosols are capable of providing sufficient uniformity of greenhouse warming intervention with scalability to global application while the other geoengineering approaches require deployment in combination to gain global-scale effects. Of these, space-based approaches are regarded as technologically unworkable and enormously costly, but they are fully controllable and reversible. Many geoengineering schemes require significant investment of energy and materials but only space-based approaches offer the prospect of exploiting space resources to minimize the use of Earth resources. Space-based geoengineering using solar shields (sunshades) accomplishes much the same thing as sulphate particles injected into the stratosphere in reducing the solar constant but without polluting the Earth's atmosphere and potentially endangering the Earth's biosphere. Solar shields involve the manipulation of only a single parameter—incident solar flux to Earth—and do not involve any chemical intervention with the Earth's environment. Solar shields are therefore subject to fewer side effects and these are potentially more predictable than in other approaches.

The first concept for space-based geoengineering involved a large glass Fresnel lens emplaced at the Lagrangian point at L1 between the Earth and the Sun at 1.5 Mkm from Earth (Early 1989). At L1, a reduction of solar flux to the Earth by 2% requires a shield of 2000 km diameter and 10 μm thick massing up to 100 Mtonnes (McInnes 2002). This would effectively counteract the 2^{o}C greenhouse warming predicted by CO_2 doubling for 2050. The shield lens refracts light rather than reflecting it to minimise solar photon perturbations. Given that global warming is increasing over time, it may be necessary to incrementally increase the size of the solar shield accordingly. A more recent suggestion involves launching from Earth 1.6×10^{13} small glass refractive disks of 60 cm diameter to near L1 centred at 185 Mkm from Earth forming an elongated cloud with an elliptical diameter of 6200 x 7200 km and thickness of 100,000 km (Angel 2006). Each 5 μm thick disk would be embedded into a larger reflecting heliogyro solar sail that modulates radiation pressure through tilting. Each disk has a mass of 1.2 g totalling 19.2 Mtonnes for the cloud. It was envisaged that the disks would be launched up high altitude mountains by 20 x 2 km long electromagnetic railguns firing a 1 tonne stick of 800,000 disks every 5 minutes for 10 years. At today's launch costs, this would amount to $400 T. Each stack would deploy to L1 from GTO using solar-powered ion propulsion using 150 kg of Ar fuel to deliver the required Δv of 1 km/s.

Our approach is to eliminate the launch problem entirely by exploring the possibility of utilising extraterrestrial material for robotic construction. This is in-situ resource utilisation (ISRU). The processing of lunar in-situ resources is explored as a technological lever to enable low-cost approaches to space-based geoengineering in the construction of the solar shield enabled by 3D printing technology. Our approach involves the manufacture of 2.8×10^{9} Fresnel lenses of 1.2 m diameter that form a 2000 km disk with active station-keeping at L1. These would be manufactured from in-situ resources on the Moon thereby circumventing launch costs from Earth—the cost of launch at ~$20,000/kg to low Earth orbit renders the launch of any significant mass prohibitively expensive. Even SpaceX with its Falcon Heavy launcher and the proposed single-stage-to-orbit launchers such as the Skylon spaceplane estimated to reduce launch costs to ~$2000/kg do little to change the prohibitive economics.

Solar Power Satellites—The Antibiotic

The ultimate clean renewable energy source is the Sun, and this provides the basis for solar power generation on Earth. However, a considerable amount of solar energy is absorbed by the atmosphere; it requires clear skies for maximum efficacy and operates only during daylight. From space, a solar flux of 1360 W/m^2 is incident on the Earth's atmosphere, around 1000 W/m^2 of which reaches the Earth's surface. On the Earth's surface near the equator, 5–7 full-sun hours per day may be generated from a flat solar panel depending on the time of year. The addition of east-west tracking can increase this to 9 hours per day—north-south tracking adds little additional coverage as the cosine projection for a maximum of 23.5^{o} is 0.92. This generates an average integrated areal solar energy density of around 65 W/m^2.

Solar power satellites (SPS) offer the potential for a highly scalable, uninterrupted, clean source of baseload power to replace fossil fuels to dominate the global energy mix. It was originally proposed as a very large structure (Glaser 1968). Each SPS satellite comprises three main parts:

1. a large area solar energy collector nominally comprising panels of photovoltaic cells to convert sunlight into electrical energy—total area of typically ~10 km2
2. a dc-to-microwave converter comprising semiconductor or microwave tube converters, e.g. klystrons or magnetrons
3. a transmitting microwave antenna to transmit ~GHz microwaves to ground rectenna arrays via slotted waveguides—total area of typically ~1–10 km2 central peak

The SPS solar panel is covered with photovoltaic cells to convert incident solar energy into electrical energy which is then converted to microwave energy for transmission to Earth. The solar array is connected to the transmitter antenna via a motorised rotary joint to ensure that the solar panel points to the Sun and the transmit antenna points to Earth at all times. The antenna elements may be parabolic, slot, or dipole antennas. A microwave tube such as a magnetron, klystron, or travelling wave tube performs electrical dc to radiofrequency with an efficiency of 50–70%. Capturing solar energy in space requires retransmitting it through the Earth's atmosphere in a form that minimizes attenuation. Wireless power transmission through the Earth's atmosphere may be implemented at microwave or optical electromagnetic frequencies. The use of lasers offers advantages in reducing aperture sizes but they are severely compromised by cloud cover and rain. The high efficiency of microwave energy generation favours microwave energy transmission. The most commonly proposed frequency of transmission is 2.45 GHz, the same as in microwave ovens, and is unaffected by cloud cover or rainfall.

The 1979 NASA Reference System comprised a constellation of 60 x 250 tonne SPS spacecraft in geostationary equatorial orbit (GEO) delivering a total of 300 GW of electrical energy at the spacecraft (assuming around 15% efficiency). Each SPS solar panel collection area of 50 km^2 would span 10 km long by 5 km wide. A 1 km diameter array of 100 x 10 W parabolic transmitting antennas per square metre (100 million antennas in total with 0.75λ antenna spacing) transmits at 2.45 GHz to a 10 x 13 km receiving antenna (rectenna) on the ground. For the ground rectenna, a slotted waveguide antenna offers high aperture efficiency >95% making it favourable over monopole, dipole, microstrip patch, and parabolic dish antennas. A transmitted 1.44 GW from each transmitter at 87% efficiency yields 1.25 GW at the rectenna. It is transmitted to give a received peak intensity of 230 W/m^2 (23 mW/cm^2) at the rectenna centre with a 10 dB Gaussian amplitude taper away from the centre of the rectenna array.

More recent developments exploit higher efficiency components but also adopt a more modular approach. The NASA Sun Tower incorporates Fresnel lens concentrators for higher efficiency electrical power generation and ESA's Sail Tower incorporates a solar sail propulsion system for efficient station-keeping. The SPS-alpha concept incorporates robotic assembly of its thin-film reflector heliostat modules into an integrated satellite system (Mankins 2012). Japan's SPS developments have proceeded the furthest (Sasaki 2014). The JAXA SPS 2000 design adopts a fully distributed formation flying system. The JAXA1 SPS version involves a 2 km x 2 km square solar panel with photovoltaic cells on one side and microwave slotted radiators on the other. JAXA2 employs a freeflying configuration of two mirror arrays that beam light onto an intervening panel mounted with photovoltaic panels on both sides. SPS, despite their promise as a clean energy source, have been relegated out of consideration due to their enormous cost and technological challenge. It has been suggested that for SPS to become economically feasible, launch costs must decrease from their current $20,000/kg to low Earth orbit (LEO) to <$200/kg. Even with the advent of single-stage-to-orbit launchers which propose launch costs dropping to $2,000/kg, this will not be realized. Yet, the advantages of SPS are many. Solar energy generated in space is unattenuated by atmospheric absorption, cloud-cover, rainfall, day-night cycling, or seasonal variations. Assuming a modern photovoltaic conversion efficiency of 20%, an output power density of over 270 W/m^2 is available to Earth even without the use of solar concentrators. SPS provide five times as much integrated energy as the best terrestrial locations uninterrupted all day, every day.

The conversion of microwave energy into direct current on the ground is achieved by arrays of rectennas (rectifying antennas). Diffraction of the microwave beam generates an angular spread given by:

$$\frac{d_t}{d_r} \approx R\lambda \; (= 3.6\text{x}10^7 \times 0.122 = 4.4\text{x}10^6) \qquad (1)$$

where d_t = transmitter diameter, d_r = receiver diameter, R = separation range, λ = microwave wavelength. It is easier to construct a large ground rectenna with a small space transmitter antenna. A large rectenna array—slotted waveguides are most commonly adopted for structural simplicity—is required to receive and rectify microwave energy into direct current on the ground. The rectenna comprises an antenna, a low pass input filter, a rectifying diode (most commonly a Schottky diode for their low power losses and high switching speeds), and a smoothing filter. Rf-to-dc conversion efficiency is typically 85–90% at 2.45 GHz. It requires no terrestrial power source. Furthermore, microwaves are not dangerous at low power levels—230 W/m^2 is considered safe for humans and birds (Pignolet et al. 2001).

Rather than implementing large structures, our approach is to exploit a highly modular architecture of a distributed formation of 2.9 x 10^{11} 1m^2 SPS micro-satellites in constellation at geostationary equatorial orbit (GEO) to generate the 20 TW of energy required on Earth. Given a GEO ring at 36,000 km altitude with a perimeter of 2.65 x 10^8 m, this would effectively require a geostationary band 1.1 km wide representing a challenge for formation flying. This would subtend an angle that is an order of magnitude smaller than the resolution of the human eye, so would not be visible to the naked eye. Each satellite comprises a 1 m^2 cross section Fresnel lens concentrator for thermionic energy conversion for which we have conservatively assumed thermionic energy conversion efficiency of 10% and microwave conversion/transmission efficiency of 50%. Collectively, they may be phased to direct their microwave energy to any specified locations on the Earth's surface.

In-Situ Resource Utilisation—Beyond the Finite Earth

The chief limitation to SPS and solar shield concepts is the prohibitive costs of launch from Earth. This does not account for the manufacturing resources required on Earth to realise such hardware. To obviate this, we suggest that such machines could be manufactured in space. In-situ resource utilization (ISRU) concerns the extraction and use of indigenous materials derived from extraterrestrial locations, in this case the Moon, as feedstock for further processing. The forthcoming Resource Prospector Mission (2020) to the Moon will be a technological demonstrator to demonstrate the extraction of lunar oxygen, impregnated volatiles, and iron from the lunar regolith, particularly from the lunar mineral ilmenite. Ilmenite (Apollo 12 sample) is composed of 52–54% TiO_2, 45% FeO, 0.3–04% Al_2O_3, 0.2–0.4% Cr_2O_3, 0.1–0.4% MgO, and 0.3–0.4% MnO. Resource Prospector will employ a rover mounted with a drill to access subsurface regolith samples and will be processing the regolith directly. Alternatively, a more sophisticated rover could employ a scoop to access surface regolith, subject the regolith to comminution by motor-driven crushing, and electromagnetic beneficiation to acquire the ilmenite fraction. The 30 kg Kapvik micro-rover with its scoop would be suited to the task of surface regolith acquisition (Figure 1) (Setterfield et al. 2014).

Figure 1: Kapvik Micro-rover at the Canadian Space Agency Mars Yard
Source: Ellery 2014

Volatiles impregnated into the lunar regolith by solar wind constitute 96% H_2 (~120 ppm), almost 4% He, and trace amounts of H_2O, CO, CO_2, CH_4, N_2, NH_3, H_2S, SO_2, and noble gases such as Ar. These gases are preferentially absorbed onto small particles of the ilmenite ($FeTiO_3$) mineral that is abundant in the lunar maria. Ilmenite grains heated to 700°C will release 90% of the volatiles; if heated to 900°C, sulphur compounds H_2S and SO_2 are also released completing the release of the entire volatile fraction. The volatiles can be separated out through condensation in a fractional distillation column: He at 4.2 K, H_2 at 20 K, N_2 at 77 K, CO at 81 K, CH_4 at 109 K, CO_2 at 194 K, and H_2O at 373 K. Of specific interest are the carbon compounds but they are scarce on the Moon. Silicone plastics of the form $(R_2SiO)_n$ have O-Si-O backbones, reducing the carbon consumption inherent in hydrocarbon plastics—they are versatile, highly heat resistant, radiation resistant, and may be used for flexible electrical insulation. They may be manufactured from syngas and silicate minerals. Silicones may be formed into arrays of elastomer-based whiskers offering the possibility of tactile sensing (N'Guyen et al. 2009). Silicone plastics may serve as precursors to ceramics in which silicone is converted to silica by flame combustion in oxygen (Nariswama 2010):

$$SiO_xC_y + (1 - x + 2y)O_2 \rightarrow SiO_2 + yCO_2$$

This provides a mechanism for 3D printing silica ceramic without involving the extreme temperatures of direct sintering of ceramics while the CO_2 is recovered (thereby conserving carbon resources). Silica from silicate minerals may be formed into high purity fused silica glass at 1700–2000°C for optical components such as lenses. Precision glass moulding offers the prospect for complex lens geometries such as Fresnel lenses or other optical components without grinding or polishing. Precision glass moulding begins with a near-spherical glass blank inserted into a 3D-printed precision mould of steel and heated to the working temperature between the transition temperature and glass softening temperature. The mould is closed and compressed under a controlled force. The glass is slowly cooled and removed from the mould. Convex shapes such as Fresnel lenses are readily moulded with surface roughness <3 µm. Silica may also be purified into quartz which is piezoelectric and serves two functions—the basis for force sensing and a radiofrequency oscillator in a simple Pierce circuit.

RPM will demonstrate hydrogen reduction of ilmenite to extract oxygen at 900–1100°C within a reaction chamber for 1–3 hours:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$
$$2H_2O \rightarrow 2H_2 + O_2$$

Hydrogen is recycled and oxygen recovered. Although RPM will not recover Fe or rutile (TiO_2), Fe is a highly versatile material for an iron-based industrial infrastructure: (i) wrought iron is near-pure Fe that is tough and malleable for tensile structures; (ii) cast iron with 2–4% C and 1–2% Si is a more brittle structural material for compressive structures; (iii) ferrotungsten tool steel with <2% C with 9–18% tungsten is hard, resistant to abrasion, and resistant to the dulling of cutting edges; (iv) fernico is a family of iron alloys that include Ni and Co for high electrical conductivity with a thermal coefficient of expansion that matches that of glass—an example is kovar alloy with 53% Fe, 29% Ni, 17% Co, 0.2% Si, and <0.01% C with a high electrical and thermal conductivity used for electrical connections through glass seals such as those found in vacuum tubes; (v) invar with 64% Ni and 36% Fe also has low thermal expansion; (vi) ferrosilicon (silicon electrical steel) with up to 3% Si and 97% Fe is highly electrically resistive and used in magnetically soft iron cores of motors and transformers. Rather than introducing the complexity of extracting Ti from titania (TiO_2) residue (which could be accomplished through the FFC Cambridge process [Ellery et al. 2017] which also enables the extraction of aluminium and magnesium from anorthite with some preprocessing), it may be extruded into fibres for thermal insulation or fibre-reinforced composites. Certain materials such as Ni, Co, and W are scarce on the Moon and require access to Ni-Fe asteroidal material. Distortions in the lunar gravity field (mascons) indicate buried metal asteroid material such as at the rim of the South Pole Aitken Basin. Nickel-iron asteroids constitute a Ni source often with Co contaminant—both Co and Ni may be extracted magnetically. Purification may be implemented through the Mond process. Asteroidal NiFe alloys are often enriched in tungsten microparticle inclusions—tungsten's very high density of 19.3 times that of water presents a simple means for its separation from other elements.

One of the most important considerations for a self-replicator is material and component closure (von Tiesenhausen and Darbro 1980)—simplicity is the key which is most appropriately implemented through a minimal set of materials to be extracted. The iron-based technology described fulfills this requirement (there is no requirement to extract aluminium, titanium, copper, chromium, etc.). Based on the large economy of scale approach characteristic of Earth's industrial complex, around 10,000 tonnes of equipment would need to be delivered to the Moon to build an industrial infrastructure of sufficient capacity to build SPS, be it implemented as a small number of large structures or a large number of small structures. This would still be prohibitive ~\$1T. An alternative is to discard the large economy of scale approach by implementing large numbers of modular small-scale factories on the Moon which can be launched incrementally. This does not solve the problem however as the delivery of large numbers of small units compared with small numbers of large factories makes little difference to the total launch mass required. The key, however, is to implement a small-scale factory similar to a biological cell—a self-replicating machine deployed onto the Moon can build copies of itself to exponentially expand its productive capacity in-situ from a single unit. In this fashion, extraterrestrial materials can be exploited at diminishing cost. An example of such an approach was the Chirikjian-Sukathorn lunar factory concept, a self-replicating machine concept of 5 tonnes comprising two robots with a payload (comprising two manipulators, a bulldozer shovel, and material grinder/separator) with a total mass of 1500 kg plus a 1000 kg furnace and 2,500 kg of solar array to cover 100 m^2 area (Chirikjian et al. 2002). Hence, this approach requires a mass delivery to the Moon ~\$1B, three orders of magnitude less than the large economy of scale approach. The Chirikjian-Suthakorn demonstration was based on Lego Mindstorms kits comprising a system of robots capable of assembling component modules into replicated robots.

Though simple in scope and considering only self-assembly aspects, this was a significant practical demonstration.

Self-replication Technology—Lessons from Life

Similarities in the fundamental technologies of the solar shield and solar power satellites, particularly the trend toward distributed formations of large numbers of simpler units over complex, monolithic spacecraft offer advantages of greater service availability. However, such large numbers will require enormous productive capacity. The power of self-replication technology lies precisely in its enormous productive capacity in which millions of spacecraft units could be constructed in parallel. This exponentially increasing productive capacity may be quantified thus (Ellery 2017):

$$P = \sum_{i=1}^{n} (1+r)^i \qquad (2)$$

where r = number of offspring per generation and n = number of generations. Assuming two offspring per generation, 13 generations yield a population of over 2 million self-reproducing machines—this reduces the specific cost of production to ~$1/kg—while 20 generations yield a population of almost 5 billion such machines with a negligible specific cost of production per kg. If each generation of machines takes 6 months to construct, 2 million factories may be constructed within 6.5 years growing to 5 billion factories within 10 years. Self-replication of these production facilities on the Moon will enable mass production of spacecraft units for SPS and/or solar shield in parallel from in-situ local resources. The potential of self-replicating factories is too powerful to ignore.

We postulate that 3D printing effectively constitutes universal construction—an hitherto theoretical concept (von Neumann and Burks 1966). A universal constructor is a machine that can manufacture any machine (a construction version of a Turing machine) given the appropriate program, energy, and raw materials. If the program describes itself, the universal constructor will build a copy of itself, i.e. a universal constructor is also a self-replicating machine. Advances in 3D printing technology suggest that 3D printing can implement self-replication. The RepRap 3D printer is an example of a prototype partially self-replicating machine—it can print its own plastic parts (Figure 2).

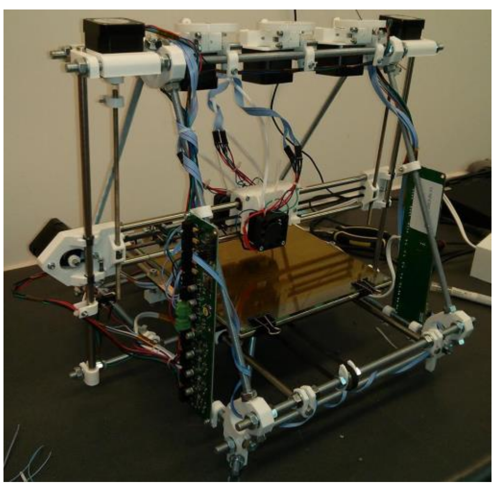

Figure 2: Basic Structure of the RepRap 3D Printer
Source: Ellery 2016

RepRap uses fused deposition modelling (FDM) which can print a variety of plastics including, with modification, silicone plastics. Additive manufacturing (or more colloquially, 3D printing) is one of the most versatile modes of manufacturing. Indeed, 3D printers can construct physical configurations that are unachievable by other means of manufacturing. If RepRap were able to print its metal bars, joiners, motors, electronics, and be able to self-assemble, it would effectively constitute a self-replicating machine. However, there are 3D printers that can print in metals as a further step toward self-replication. Selective laser sintering/melting (SLS/M) is a versatile technique in that it can print many different materials including metals, plastics, and ceramics using laser sintering or melting. Electron beam freeform fabrication (EBF3) may be used to print metals only (Kaminger et al. 2006). In this case, an electron gun, a variation on the vacuum tube, generates a magnetically controlled electron beam to melt metals at a work surface. A similar technology—electric discharge machining (EDM)—adopts a pulse voltage discharge between the electrode tool and the workpiece to remove some material—in a way, it is the inverse of EBF3 offering a subtractive manufacturing to complement additive manufacturing. EDM is a versatile method of manufacturing complex 3D microstructures with cavities and contours such as tooling and involute gear teeth (Reynaerts et al. 1998).

We envisage constructing a versatile 3D printer system from the lunar materials defined earlier using an identical parent 3D printer system. All 3D printers are effectively Cartesian robots constituting a work platform and a printing head that move in 3D relative to each other, driven by motors. The key elements that we are developing are 3D-printable electric motors—the electric motor system is an integrated unit comprising actuator, control electronics, and sensors. Our corollary is that if an electric motor *system* can be 3D printed, the 3D printer constitutes a universal constructor capable of self-replication. In general, given that a machine is a specific geometry of motors, this enables construction of any motorised device. Assembly may be performed by robotic manipulators or wrists that are constructed from motors configured serially or in the Cartesian configuration of the 3D printer. Hence, a three degree of freedom wrist can be mounted to replace the printing head of a 3D printer to perform assembly. Motorised tools that constitute a typical fabrication laboratory are kinematic configurations of motors—lathes, milling machines, drill presses, bending presses, compression presses, extruders, centrifugal ball mills, etc. Robotic mining machines can similarly be constructed from motors—robotic manipulators and robotic rovers such as excavators, loaders, haul-dump trucks, drills, or any combination thereof such as load-haul-dump trucks, JCBs, etc. This is a form of reconfigurability where robotic motorized modules can be assembled into different configurations for different tasks (Lipson and Malone 2001). The application of such reconfigurability has considerable implications for rapid response manufacturing (Chen 2001).

3D Printed Magnetics as the Key to Self-replication

We have concentrated on the development of 3D-printable mechatronic components, i.e., electric actuators, electronics, and sensors. These are the key components in any type of robot mechanism, be it a 3D printer, robotic manipulator, rover vehicles, further manufacturing machines, etc. In particular, we are focused on 3D printing two components to demonstrate that 3D printing constitutes an universal construction mechanism—electric motors and magnetrons, both magnetic devices.

A DC electric motor comprises three major components:

1. magnetically soft rotor core which must have high magnetic permeability to support large magnetic fields, low magnetic coercivity for low magnetic hysteresis, and high electric permittivity to resist the formation of eddy currents;
2. electrically conductive armature coils to invoke electromagnetic properties to the magnetically soft rotor;
3. permanent magnet stator with high magnetic permeability.

For 3D printing, this presents a complex set of materials configured into a complex assembly that operates as a singular functional unit—the generation of mechanical torque. We have concentrated on the rotor core as this imposes several material properties that require the employment of multiple materials—a matrix of insulating material, nominally plastic or ceramic, into which are embedded iron (preferably silicon steel) particles. Following a number of precursor prototypes, we have successfully manufactured rotors by 3D printing 50% iron particles (by mass) in a polyactic acid (PLA) matrix through fused deposition manufacturing and powder metallurgy processed 50% silicon steel particles (by volume) in a PLA matrix (Figure 3).

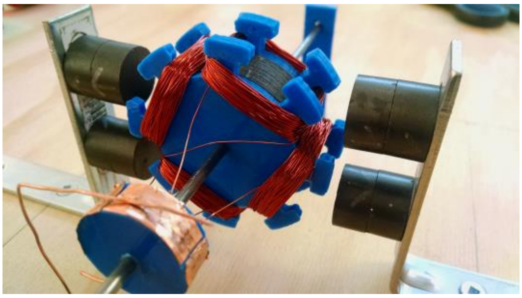

Figure 3a: Rotor Core of 3D-printed Iron Particles in PLA
Source: Ellery 2017

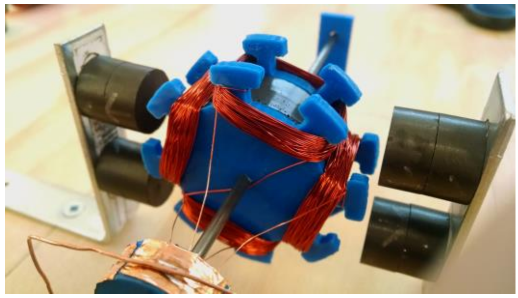

Figure 3b: Rotor core of Powder Metallurgy Processed Silicon Steel Particles in PLA
Source: Ellery 2017

Furthermore, we have successfully devised a means to photolithographically print wire coils into a wiring pattern that we have tested in a pancake motor configuration (Figure 4).

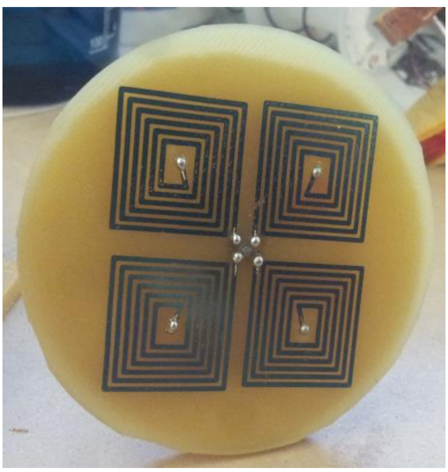

Figure 4a: Lithographically-printed Wiring Pattern
Source: Ellery 2017

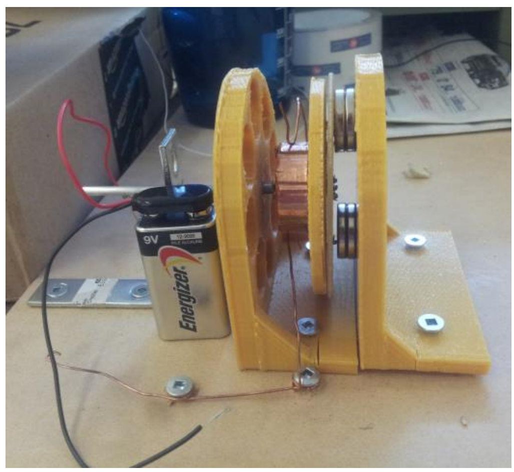

Figure 4b: Tested in a Pancake Motor
Source: Ellery 2017

We are currently working on integrating the multiple layers of the wiring pattern with a different approach to 3D printing the rotor by adopting thin slices of silicon steel and PLA. We attempted 3D printing of a magnetically soft electromagnetic stator using 3D-printed iron particles in PLA but even with 900 turns of wire, the magnetic field generated was negligible (Figure 5). An attempt with selective laser sintered (SLM) magnetically soft steel yielded only 3G of magnetic field—far short of the 10–20 G required to torque the rotor.

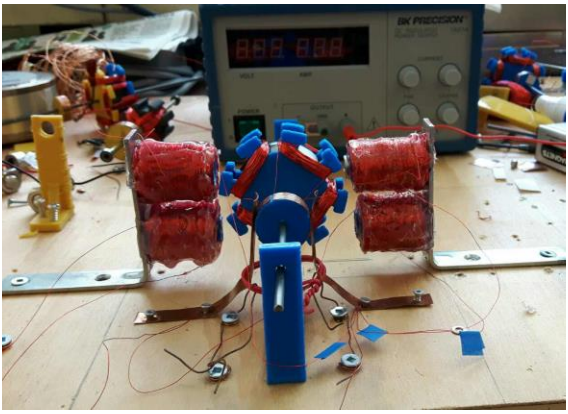

Figure 5a: 3D-printed Stator of Fe Embedded in PLA
Source: Ellery 2017

Figure 5b: 3D-printed Stator of Soft Magnetic Steel
Source: Ellery 2017

The poor magnetic flux generated from 3D-printed soft magnets suggest that we should focus on 3D printing hard magnets—ferrites, alnico, and rare earth magnets. This is currently being explored using both selective laser melting and electron beam freeform fabrication. The initial goal is to complete the entire assembly—rotor, coils, and stators—to form the first fully 3D-printed electric motor. However, it will be important to reduce the assembly required for a 3D-printed electric motor. This will require 3D printing to print multiple materials simultaneously on the same work platform. We have begun to explore this aspect by building a prototype 3D printer mounted with three heads on a single work platform—a plastic extruder head for silicone plastic extrusion, a molten aluminum printing mechanism, and a milling head for accurate finishing after deposition. We have successfully demonstrated the deposition of molten aluminium alloy (heated by a solar Fresnel lens) onto silicone plastic as a first step toward multi-material handling for integrated 3D printing (Figure 6).

Figure 6: Molten Aluminum Deposited Directly onto Silicone Plastic
Source: Ellery 2017

With regard to 3D printing electronics, rather than attempting to apply 3D printing to solid state electronics, lunar material availability suggests the adoption of vacuum tubes for active electronics (Ellery 2016). We are in the process of developing a 3D-printable vacuum tube and we are concentrating on a magnetron, a large-scale vacuum tube that incorporates magnets (it is also one of the main components of the SPS). In general, vacuum tube-based dc-to-rf microwave generators are superior in performance to monolithic microwave integrated circuits for both higher output power and superior efficiencies. Vacuum tube approaches for microwave transmission include magnetrons, klystrons, and travelling wave tube amplifiers. Magnetrons comprise a hot cathode (electron gun) emitting thermionic electrons accelerated by a voltage of ~10+ keV applied across the anode and cathode and an external magnetic field focusses the electron beam (Figure 7).

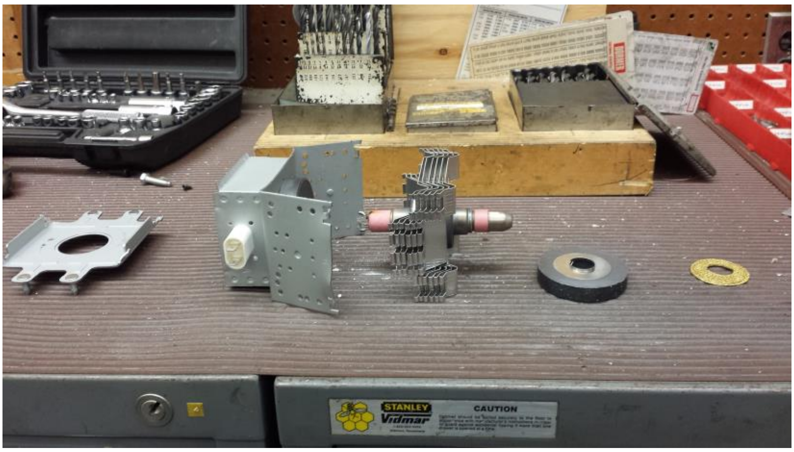

Figure 7: Configuration of a Microwave Oven Magnetron
Source: Ellery 2017

It exploits E x B interaction generated by the passage of emitted electrons through a magnetic field. The cavity magnetron has a central hot cathode running through the magnetron from which electrons are emitted. Around the rim of the central chamber are cylindrical resonant cavities, the dimensions of which determine the resonant frequency. Permanent horseshoe magnets enclose both the central anode and the outer cylindrical anode and generate a field parallel to the long axis of the magnetron. The curvature of the electron path is controlled by varying the electric potential between the electrodes. At a critical magnetic field, electrons just reach the anode offering triode behaviour and generate cyclotron radio waves due to electrons cycling between the cathode and anode. In the resonant cavity magnetron, oscillation is generated by physical shaping of the anode, rather than through control of electric circuits or magnetic fields. Between the cathode and the surrounding holes are resonating slots. Our first analysis was to analyse the materials constituting the different parts of the magnetron—the cooling fins were of a standard aluminium alloy, the electrical wiring and resonating cavity was standard copper alloy, the cathode was tantalum-based, the permanent magnet was a rare earth alloy, and the main chassis was magnetic steel. Apart from the main chassis (for which non-magnetic steel was expected), these were as expected and could be replaced with lunar analogue materials. We are about to embark on a metal 3D-printing programme to demonstrate 3D printing of the magnetron.

The next stage will be to 3D print the metal components of the electric motor and the magnetron, with particular interest in 3D printing the magnetic components. The possibility of tailoring magnetic properties offers the potential for integrated magnets and magnets with novel geometries and designs.

Electrical Power on the Side

It has become increasingly common to employ Fresnel lenses or parabolic mirrors as concentrators to enhance photovoltaic cell performance (Hebraken et al. 2001). Such concentrators may be used to power a solar furnace—in-situ resource utilization requires significant amounts of thermal energy. A lunar solar furnace comprises a tungsten or alumina crucible onto which parabolic mirrors or Fresnel lenses concentrate solar power generating 1600°C or 2700°C respectively. For mirrors, metals in general have high reflectivity (Spisz et al. 1969): steel can be polished to create ~75% reflectivity, nickel offers higher reflectivity ~80–85% while aluminium offers the best performance with 90–92% reflectivity. A parabolic mirror with a 2 m diameter and focal length of 0.85 m generates a solar illumination of 2 kW projecting an average flux of 15 MW/m^2 over an area 0.01 m diameter sufficient to melt refractory metal oxides. The solar furnace is capable of sintering regolith, smelting metal-containing minerals and/or vacuum pyrolysis. Optical concentrators offer the prospect for direct thermal processing of materials rather using inefficiently generated electrical energy.

Most spacecraft are powered with arrays of photovoltaic cells to convert sunlight into electrical power. Thermionic power conversion into electrical energy is based on vacuum tube-based devices and does not involve any mobile machinery nor any fluid handling. The anode must be kept cool to avoid back-emission of electrons. The anode electrodes are typically Ni with a work function of 5.0 eV or Pt with a work function of 5.36 eV, the former being available from lunar resources. The higher the cathode temperature >1200°C, the higher is the thermal efficiency. Efficiencies of 20% are typical of Russian nuclear reactor thermionic conversion with T_C = 1650°C and T_A = 650°C (Gyftopoulos and Hatsopoulos 1963). The cathode is typically tungsten, tantalum, or molybdenum—tungsten is most common and offers superior performance. Tungsten must be heated to 2200 K to yield an output current density of 25 mA/cm^2; an output of 1 A/cm^2 requires a temperature of 2600 K. Higher conversion efficiency of ~40% is enabled by shaping the electric potential applied through the thermionic converter (Meir et al. 2013). A positive gate electrode is inserted between the emitter and collector electrodes to create a potential trough. This trough accelerates electrons from the emitter but decelerates them toward the collector. An applied magnetic field guides electrons through holes in the gate electrode to enhance output current, similar to an ion engine. Alternatively, photon-enhanced thermionic emission (PETE) combines photovoltaic and thermionic conversion in a single process to yield higher efficiencies (Schwede et al. 2010). Hence, the vacuum tube provides the basis for moderately efficient electrical energy generation.

Manufacture of Spacecraft Modules

Once the self-replicating factories have reached their final desired population, they may be programmed to construct spacecraft modules, be they solar shield or solar power satellite modules. Once constructed, the spacecraft modules may be launched into lunar orbit by electromagnetic launchers thereby minimizing the consumption of fuel (though hydrogen and oxygen resources are in abundance on the Moon). Buckets with launch adaptors for restraining each spacecraft module may be accelerated to launch speeds. From the Moon, an electromagnetic launcher must launch into L1 transfer orbit at 3 km/s—this is easily within reach of modest electromagnetic launchers compared with 12 km/s required to launch from Earth. On the Moon, a 15 km long track can provide 30g continuous acceleration using 2T superconducting magnets for the 3 km/s escape velocity. Alignment and precision are the critical requirements to ensure accurate rendezvous targeting. Large amounts of electrical energy must be stored for release during launches—flywheels are currently used at the JET Torus for high-power densities and the ability to supply high power over short release times—flywheels are high speed motorized wheels that act as mechanical batteries.

For in-space propulsion, solar sails are the system of choice as they involve no fuel. Thin films of steel or Ni or Al may be deposited either onto silicone polymer sheets or accumulated into metal foils. Electron beam physical vapour deposition is a form of physical vapour deposition of thin films through energetic electron bombardment (~20 kV) of a target material by an electron gun into a vapour. Sputter deposition is a form of physical vapour deposition for depositing thin films. Sputtering sources involve magnetrons to generate high electric and magnetic fields to confine a plasma. An inert gas such as Ar (that exists in lunar regolith in small quantities) yields more plasma for a higher deposition rate. Sputtered atoms are neutral and unaffected by the magnetic field. For a pure iron film sail with a density of $\rho = 7.87 \times 10^6$ g/m^3, the minimum thickness for a solar sail is 12 μm. All other subsystems of the spacecraft—structure, mechanisms, attitude control, power generation/storage, thermal control, command and data handling, and communications—are all derivable from the self-replication capability. Wrought iron and/or aluminium may be used for the primary and secondary structures—wrought iron is ideal for load-bearing with high temperature tolerance. 3D printing offers greater flexibility in structural design such as isogrid and monolithic truss designs. Attitude control may employ reaction wheels, momentum wheels, or control moment gyroscopes driven by the electric motors. Station-keeping in large constellations may be implemented through a number of coordination techniques such as potential fields, neural fields, flocking algorithms, etc. (McQuade et al. 2003). Thermal control may be based on passive systems such as thermally conductive straps of fernico or aluminium, thermal insulation with glass and titania fibres, radiators of polished steel/nickel/aluminium, or active methods that rely on resistance wire heaters and electric motors such as louvres, etc. Data handling and communications may be implemented through a combination of vacuum tube–based analogue circuits, analogue-based logic circuits, and neural network circuits. Magnetrons are essentially vacuum tube devices. Power generation in space may be similar to that employed on the lunar surface. Similarly, Fresnel lenses may be implemented in space as solar concentrators as on the lunar surface.

Conclusions

We have considered the value of adopting a space-based approach to climate change intervention and mitigation as a form of geophysiological treatment as analgesic and antibiotic respectively. We suggest that its attraction is symptomatic that we are exceeding Earth's capacity to support an accelerating demand of its finite resources. We must begin to utilize extraterrestrial resources—on the Moon—in order to leverage solar energy supply to Earth and to implement global cooling as a response to global warming. The only way to leverage these extraterrestrial resources at low cost is to implement a robotic self-replication capability. We suggest that 3D printing offers an universal construction mechanism suitable for self-replication. We have outlined an effective plan to achieve this by initially demonstrating aspects of 3D printing of electric motors and vacuum tubes. We have not encountered any fundamental showstoppers at this early stage and demonstrated the basic feasibility of self-replicating machines—the devil will be in the details, of course. Self-replication technology will open up enormous possibilities for providing additional options for combating climate change whilst meeting growing demands for global energy.

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