Sustainable in-situ resource utilization on the moon

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ABSTRACT

We propose that current in-situ resource utilization schemes based on mining of water resources on the Moon is unnecessary and unsustainable. Life support systems are capable of recycling with high efficiency. Burning of hydrogen propellant and oxygen is akin to the burning of fossil fuels. The value of in-situ resources will be in exploiting the resources that are abundant, husbanding of resources that are not and recycling as much as possible to minimise waste. We propose that a closed loop industrial ecology must be implemented with extensive recycling loops as a sustainable approach to in-situ resource utilization on the Moon. We must build in sustainability into our forays from Earth in order not to continue to make the same mistakes as we have on Earth.

1. Introduction

There are several significant lunar missions on the books despite the failure of the Google Lunar X-Prize of $40 M prize money to deliver a privately-funded rover onto the Moon and drive 0.5 km by 2018. Nevertheless, the two major competitors, Moon Express and Astrobotic, and newcomer Blue Origin are active with plans to develop lunar assets privately. More ambitiously, SpaceX has a plan to send two fee-paying tourists around the Moon using the Falcon Heavy rocket and the Dragon capsule in 2023. There are also several planned government-funded lunar missions in the near-term. NASA's efforts are focussed on the Deep Space Gateway, a space station in lunar orbit that will support astronauts to direct robotic assets on the lunar surface. Eventually, it will be expanded to include a lunar surface base, most likely at the lunar south pole. ESA's Moon Village is a human-robotic lunar infrastructure similar in concept to international Antarctic bases to meet multiple government and private sector goals (Crawford, 2017). From a purely scientific viewpoint, the development of infrastructure to support a human exploration programme can be exploited to facilitate scientific research that cannot be undertaken otherwise (Crawford, 2001). The Moon Village infrastructure would permit complex exploration activities ranging from astrobiological investigation of buried samples from Earth preserved in regolith to unique astronomical observations, especially radio telescopy from the farside. Science however will not be the driver for a Moon Village rather than strategic government and/or commercial reasons. In any case, in-situ resources (ISRU) will be essential to ensure sustainability on the Moon. The joint Russian/European Luna 27 mission purports to demonstrate ISRU techniques and bears many similarities to the recently cancelled American Lunar Resource Prospector mission

(Andrews et al., 2014). The Lunar Resource Prospector mission was based on the RESOLVE (regolith and environmental science and oxygen and lunar volatiles extraction) instrument payload which employed a neutron spectrometer and near-IR spectrometer to map the surface distribution of hydrogen in the soil, extract a 1m long core sample using a drill/auger system, heat the samples through 100–473 K to evolve core volatiles in the OVEN (oxygen and volatile extraction node) system, measure the volatile constituents using the LAVA (lunar advanced volatile analysis) system, further heat the samples through 473–1173 K in the OVEN system to extract oxygen from regolith through hydrogen reduction, and condense a water sample. The European payload will similarly comprise a drill to acquire water ice, regolith and volatiles from the subsurface to a depth of 2m and analyse them with a similar ISRU payload (a gas chromatograph-mass spectrometer).

Despite this interest in in-situ water resources – which we define as shallow ISRU in that it requires minimal processing for extraction - we view this obsession as both unsound and unsustainable. The only proposed consumable production process that can be considered renewable by virtue of its abundance is the extraction of oxygen from abundant minerals. We are concerned with deep ISRU which seeks to develop a lunar infrastructure. The first objective of deep ISRU is to provide as close to 100% supply from in-situ resources. The second objective is to construct a 100% closed cycle industrial ecology extraterrestrially. Both objectives are driven by the high cost of supply by launch from Earth. This is a statement of sustainable space exploration which is built on two pillars: (i) dematerialisation through the minimisation of material consumption, and (ii) detoxification of waste. Industrial ecology addresses detoxification of waste by converting it into resources. The IPAT equation quantifies the impact I to be minimised: I=PAT where P = population of

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industrial products produced by deep ISRU, A = cumulative resource units consumed per product produced (specific mass), T = impact per resource unit consumed (amount of waste). To reduce A requires dematerialisation and to reduce T requires detoxification. Industrial ecology seeks to reduce impact T through recycling. Industrial ecology minimises the waste of one process by feeding it as input to other processes. The Metalysis FFC Cambridge process is central to the minimisation/detoxification of waste by its yield of high purity metal without toxic reagents. It is of course highly desirable to achieve 100% closed loop recycling. A self-replication capability would enforce minimisation of A through both material and energy closure (Ellery, 2016a). Furthermore, there is a requirement in industrial ecology for cradle-to-cradle sustainability which requires recycling at end-of-life. Metal 3D printing minimises waste in the form of swarf by recycling 3D printed powder feedstock. Industrial ecology must be built into space exploration goals upfront as a fundamental design requirement rather than as an *ad hoc* afterthought, in much the same way as planetary protection procedures are built into robotic exploration missions (Debus, 2001). In the context of deep ISRU, we consider one of the most important factors is to minimise the infrastructure required to extract materials from lunar resources (first objective). Simultaneously, the material set extracted must provide full functionality for a diverse range of applications required for the construction of infrastructure such as the capacity for space manufacturing.

2. Deficiencies in current approaches

2.1. Why water?

Exploitation of local in-situ resources has high potential to reduce the mass, cost and risk of exploration missions. Current interest in lunar ISRU in order of increasing complexity is based on: (i) physical extraction of indigenous water ice directly; (ii) thermal processing of lunar volatiles to extract hydrogen; (iii) use of regolith processed into civil engineering structures, and (iv) thermochemical or electrochemical processing of lunar minerals to extract oxygen. The priority is to recover water, hydrogen and oxygen as consumables to support human occupation – water for consumption, oxygen for respiration, and oxygen/hydrogen as propellant/oxidiser. Indeed, the United Launch Alliance has imposed a commercial price of $500/kg for 1100 Mtonnes of propellant per year on the lunar surface (https://www.hou.usra.edu/, 2017). NASA has declared that it requires 100 Mtonnes of propellant per year for lunar launch vehicles (G Sanders, 2019 *private communication*). We believe that this approach is neither necessary nor sustainable for eight reasons: (i) oxygen and hydrogen requires cryogenic freezing into liquid below 90 K for O_2 and 20 K for H_2 for long-term storage (hydrogen peroxide may be directly metal-catalyzed as a monopropellant but offers only a quarter of the specific impulse of hydrogen/oxygen) unless stored in permanently shadowed craters at 40 K (suitable for passive O_2 storage only); (ii) high recycling efficiency of CELSS (closed loop environmental and life support systems) regarding water and oxygen renders the need for indigenous sources marginal, required only to replace leakage rather than as a primary supply; (iii) the use of hydrogen and oxygen as propellant/oxidiser to be combusted is wasteful of scarce resources (hydrogen in particular) akin to the burning of oil on Earth which would be better employed for the in-situ manufacture of plastics; (iv) propellant/oxidiser for surface operations can be replaced by solar-electric power sources for rovers, etc; (v) propellant/oxidiser for launch from the lunar surface can be replaced by electromagnetic launchers that can readily reach escape velocity of 1.62 m/s^2 (Kaye, 2005) supported by banks of solar-powered flywheels (Ellery, 2019a); (vi) sustainable lunar infrastructure may be effected through the use of metals and other useful materials derived as a side-effect of oxygen recovery from lunar minerals and thermal extraction of volatiles; (vii) CHONPS (carbon hydrogen oxygen nitrogen phosphorus and sulphur) constitute the most direct life-support

resources but these are (with the exception of O and to a lesser extent H) either relatively or extremely rare in the lunar environment and will require careful husbandry; (viii) the advent of sophisticated artificial intelligence techniques offers the prospects of robotic construction of a lunar industrial infrastructure without reliance on a human presence on the surface, though the Deep Space Gateway offers the prospects for direct teleoperation of robotic devices on the lunar surface from orbit. The provision of surface robotic facilities offers high prospects for surface lunar infrastructure development through ISRU. Remote teleoperation may be applied to mining operations but even short time delays effectively forbid telepresence (Lynas and Horberry, 2011). Automation offers high reliability, efficiency and accuracy compared with humans who suffer from limited vigilance – human error – but it suffers from a lack of flexibility to unanticipated problems. Furthermore, human supervisors, lacking situational awareness due to automation, become deskilled over time to deal with such events. In particular, automated alarms can induce sensory and cognitive overload to human supervisors. It will be essential therefore to engage automation of high capability – artificial intelligence – with the flexibility to deal with novel events to eliminate the requirement for human supervision. In terrestrial mining, there have been three waves of automation: (i) driverless rail transport and automated drilling; (ii) remotely operated underground ore extraction; (iii) remotely controlled load-haul machines. Today, a fourth wave of automation is occurring – the development of autonomous mapping capability in load-haul-dump vehicles, technologies that have been developed for the next-generation of planetary rovers. The chief concern is that the Deep Space Gateway will divert efforts and funds into the manned orbital elements to the detriment of the robotic surface elements of the programme. We envisage that ISRU is not necessarily tied with human missions and can be achieved robotically. Current approaches have focussed on simplicity of water extraction without consideration of the infrastructure required to support this. I would argue the complexity of attempting to extract water from the poles is just as complex as our proposed lunar industrial ecosystem, e.g. beaming reflected solar energy from vast mirrors at peaks of eternal light to solar arrays in permanently shadowed craters ~20 km away as proposed by JPL (Stoica, 2019). This is necessary to obviate the need for mining rovers to traverse the extremely rugged SPA terrain over 20 km or so distances and 11 km or so elevations between permanently shadowed craters where the resources reside and peaks of eternal light where human bases must reside. Nevertheless, the general manufacturing capabilities that we propose can support human missions in a far more robust manner – major elements of lunar infrastructure can be constructed robotically in preparation for human arrival from robotic machines to thermal and electrical power supplies for electromagnetic launchers, habitat structures, etc.

2.2. Importance of sustainability

The UN Conference on Environment and Development (1992) in Rio defined global environmental concerns and Agenda 21 called for product lifecycle assessments regarding environmental impact as a step towards sustainable development (https://sustainabledevelo). Although this referred to Earth specifically, prudence dictates that we apply such concerns to our ventures away from Earth. Product redesign must account for cradle-to-cradle lifecycle of products to implement sustainability. It has been proposed that exergy (energy available to be used to perform work) is an appropriate measure of material and energy degradation and cycling (Connelly and Koshland, 1997). Unlike energy, exergy is used up during processes involving temperature changes - it includes entropy. At thermal equilibrium, exergy is zero. Closed cycle material flows require a continuous flow of exergy to be sustainable. Open material flow collapses into a state of thermal equilibrium, i.e. unsustainable. This is a consequence of the second law of thermodynamics. Most materials, even that incorporated into products, eventually return to the environment as waste. Industrial processes can be designed to minimise

their impact on the environment. Material cycles can produce more durable products that can be upgraded and repaired later. The more materials are recycled, the less is dispersed into the environment. The industrial ecology forms a hierarchy of industrial processes in which they consume the waste products of each other without waste. The flow and transformations of industrial materials should form a metabolism within the industrial economy (Ayres et al., 1998). This industrial metabolism comprises a distributed set of physical processes that convert raw materials and energy into final products and waste using human and financial capital. This is similar to biological organisms that ingest useful material and energy to maintain their metabolic functions and also grow and procreate whilst excreting degraded waste material. They convert low entropy food into high entropy waste through the consumption of energy. However, this waste is consumed by microbes which recycle this material forming an ecosystem of inter-dependencies.

3. Lunar resources

The following summary of some of the properties of lunar regolith originates from (French et al., 1991). Lunar regolith comprises fragments of rock, minerals and glasses to a variable depth of 5–15 m in the older highlands and 3–5 m in the younger mare regions. Lunar regolith cohesion C varies from 0.1 to 1.0 kPa and friction angle ϕ varies from 30 to 50° due to the high angularity of regolith particles. Lunar regolith has a mean particle size of 40–130 μm (peaking at 60–70 μm) due to aeons of meteoritic bombardment which would pulverise a 1 kg boulder within 10 My. Lunar soil rapidly becomes increasingly dense with depth due to compaction from the aeons of micrometeoroid impacts reaching 90% densification at 30 cm depth (1.74 g/cm^3) compared with under 30% at the surface (1.58 g/cm^3). Regolith formation is based on the conflicting processes of impact fragmentation and agglutination. Micron-scale beads of pyroclastic glass are ubiquitous throughout lunar regolith comprising 10–20% by volume. Glass results from silicate melts generated from micrometeorite impacts which cement mineral grains into agglutinates. There are many different types of lunar glass which come from two types of origin – impact melting (high in siderophiles such as Fe, Ni, Co, W, Pt, etc) and tectonic (high in both Mg and Ni) sources (Delano, 1986).

Silicate minerals are the major rock-forming minerals on both Earth and the Moon. Pyroxene and feldspar are the major minerals in basalt common to both Earth and the Moon. On Earth, these include olivines and inosilicates such as pyroxenes, feldspars, quartz, micas, garnets, etc. Silicates are common on the Moon but quartz (SiO_2) is rare. Pyroxenes are inosilicate minerals ($XY(Si,Al)_2O_6$ where X = Ca, Na, Fe^{2+} and Mg, Y=Cr, Al, Fe^{3+}, Mg, Mn, Sc, Ti, V). They are silica-poor unlike amphiboles which are silica-rich so only pyroxenes are common on the Moon. Enstatite ($MgSiO_3$–$FeSiO_3$) is a pyroxene that is common in stony and iron meteorites and has been detected around stars. Feldspars are silicates that are richer in Al than pyroxenes – they form a silicate series ranging through $KAlSi_3O_8$ (orthoclase) - $NaAlSi_3O_8$ (albite) - $CaAl_2Si_2O_8$ (anorthite). Plagioclase feldspars refer to sodic and calcic feldspars. Albite is silicate-rich while anorthite is silica-poor so it is the latter that is dominant on the Moon, i.e. lunar plagioclases have lower Na content than terrestrial plagioclases while the silicate content of lunar and terrestrial plagioclase, pyroxene and olivine are similar. Olivine is a Mg–Fe silicate ((Mg^{2+},Fe^{2+})$_2SiO_4$) which forms a solution series – forsterite (Mg_2SiO_4) to fayalite (Fe_2SiO_4) – which vary in their proportions of Fe and Mg. Mg-rich olivine occurs on the Moon, Mars, meteorites, asteroids, and comets. Around 1–2% of lunar regolith comprises orthoclase feldspar and other oxides including spinels (such as pleonaste), chromite, rutile, calcium phosphate (apatite), zircon, troilite (iron sulphide) and free iron. Other minor oxide minerals include armalcolite with the general formula XYO_5 such as $Mg_{0.5}Fe_{0.5}TiO_5$. Cr is more abundant (up to 0.5%) as an impurity in lunar olivines than in terrestrial olivines so we have not targeted Cr as an extractable resource. Garnets in returned lunar samples are reckoned to be the result of contamination rather than indigenous. Common terrestrial (hydrous) minerals that are

absent on the Moon include calcite, micas/amphiboles, magnetite/haematite and most sulphides (such as copper, zinc, selenium, lead, etc) due to the lack of water.

Nanophase (np) iron Fe^0, nanometre-scale particles of Fe ~15% by weight, embedded in impact glass particles (Basu, 2005). Nanophase Fe^0 forms from the vaporization of Fe oxide minerals such as ilmenite which subsequently condensed as reduced metal globules due to the action of solar wind hydrogen: $FeO + H_2 \rightarrow Fe^0 + H_2O$. Fe^0-impregnated glasses coat many mineral grains in the lunar regolith in a 50–150 nm thick layer deposited by the condensation of impact-generated vapours. Magnetic susceptibility of lunar soil increases with decreasing grain size due to the greater fraction of nanophase Fe^0. The reflectance spectra of these grains indicate steep red slopes; reflectance spectra for ilmenite minerals by contrast are relatively flat over the visible range with a slight blue slope. Although particles <10 μm particles are readily attracted by a simple magnet, np-Fe^0 are likely to be difficult to extract because they are conducting particles insulated by dielectric glass. Because their size is less than the effective skin depth for microwave penetration, nanophase iron is crucial to facilitating bulk microwave thermal processing of lunar regolith (Taylor et al., 2005). It provides the prospect for rapid melting (1000 °C/min) at 1200 °C due to good microwave coupling at 2.45 GHz. Regolith melts over a range of temperatures 1373–1653 K due to its different constituents.

The constraints on in-situ resources on the Moon are determined by its mineral assemblage. The main minerals that can be exploited on the Moon are ilmenite ($FeTiO_3$), plagioclase feldspar anorthite ($CaAl_2Si_2O_8$), olivine (($Fe,Mg)_2SiO_4$) and pyroxene (($Fe,Mg)SiO_3$). The ancient crustal highlands representing the original crust are dominated by 70–95% anorthosite (anorthosite comprises at least 90% anorthite mineral). The more recent mare are basaltic outflows filling large impact basins primarily on the near-side and are more varied in nature with pyroxenes (both orthopyroxene and clinopyroxene), 2–20% ilmenite, 0–20% olivine and variable 10–40% plagioclase (mostly anorthite). The ilmenite fraction varies from 1 to 6% (low Ti) to >6% (high Ti). The diversity of minerals in the mare regions favour these locations for ISRU. The relative lunar elemental abundances are 45% O, 21% Si, 6–15% Fe, 5–13% Al, 8–10% Ca, 5% Mg and 6% Ti with all other minor elements – Cr, Mn, Na, K, P and S – being significantly under 1%. This suggests that it is most appropriate to exploit the more abundant O, Si, Fe, Al, Ca, Mg and Ti in lunar minerals unless ore bodies can be located. It has been declared that there are no lunar ore bodies but in fact, ore bodies do exist on the Moon but they are not indigenous. It is expected that significant quantities of meteoritic material have survived impact on the Moon. In particular, nickel-iron asteroid material may give rise to magnetic anomalies on the Moon including on the northern rim of the farside South Pole Aitken basin (remnant of a ~100 km diameter nickel-iron asteroid) (Wieczorek et al., 2012). Indeed, it may be considered that lunar sources of asteroid material are more easily exploited than those in Near-Earth Asteroid populations (Ellery et al., 2018a). These resources are suitable sources of secondary elements – reduced sources of Ni, Co, W and PGM (platinum group metals) (Bland et al., 2008) which may be localized for ready access (Yue et al., 2013). There is even the prospect of the existence of carbonaceous chondrite material on the Moon (Joy et al., 2016). Although carbon is considered highly depleted on the Moon, it is depleted by only 2 times compared with Earth soil.

KREEP-rich (potassium - rare earth elements - phosphorus) basalts are primarily located at Oceanus Procellarum and the Imbrium Basin in the northwest nearside (so-called Procellarum KREEP Terrain). There are significant differences between the abundances of rare elements associated with KREEP than on Earth (Warren and Wasson, 1979). Potassium is severely depleted on the Moon ~30 times in comparison to Earth while phosphorus is depleted by only ~2 times. Sodium is depleted compared to Earth due to the lack of albite and this sodium is restricted primarily to KREEP basalts. Hence, the amount of Na in the regolith is minimal and likely difficult to access so we regard it as an Earth-supplied ingredient. It is believed that KREEP results from urKREEP source minerals in the lunar

mantle with an average REE concentration of 1200 ppm dominated by yttrium and cerium at 300 ppm each, dropping in concentration to 3–5 ppm for europium. This is about 5 times higher than the average abundance on Earth, and indeed, over two orders of magnitude higher than on asteroids. For economic mining on Earth, concentrations of >1000 ppm are required (Castor and Hedrick, 2006), but this will not be such a constraint on the Moon where lower abundances will be tolerable. However, like on Earth, there are likely to be higher concentrations on the Moon. They can be traced through gamma ray detection due to their association with U and Th with a roughly constant ratio U/Th ~0.27 and average U concentration of ~2–5 ppm (10–20 ppm local peak). However, the challenges of extracting rare earth elements from KREEP minerals despite their high utility renders this too technologically difficult for a first generation ISRU infrastructure due to their similar physical and chemical properties (Jordens et al., 2013).

Ilmenite is the mineral with the highest concentration of solar-implanted volatiles ~50–80 ppm H, ~100–120 ppm C, ~80–100 ppm N, ~10 ppm He, etc (Table 1).

Due to gardening of the regolith over the aeons, it is expected that concentrations of volatiles are approximately constant to a depth of 2–3 m. Recovery of volatiles is through heating to 700 °C which releases almost all H, He and CO_2 but higher temperatures are required for other species such as CO (up to 1200 °C). Subsequent fractional distillation is enabled by the wide separation between condensation temperatures of molecular species – He (4.2 K), H_2 (20 K), N_2 (77 K), CO (81 K), CH_4 (109 K), CO_2 (194 K) and H_2O (373 K), It has been estimated that heating regolith from its ambient -20 °C–720 °C requires 900 J/kg/°C or 10^9 J/m^3 (Crawford, 2015) Carbon is a particularly valuable commodity but fortunately carbon is one of the more abundant volatiles (though still scarce compared to mineral inventories). The scarcity of N in lunar volatiles renders the manufacture of hydrazine (N_2H_4) and nitrogen tetroxide (N_2O_4) as unviable as propellants but small amounts of nitrogen will be required. Noble gases Ne and Ar which might be extracted as propellant for ion engines are highly rarified at <1 ppm (Kr and Xe are even rarer). ^{3}He is often touted as a nuclear fusion fuel (D+^{3}He→4He + p+18.4 MeV) – ^{3}He is very rare on Earth but D is abundant in seawater (D/H = 1.6 x 10^{-4}). ^{3}He is still rarified in lunar regolith at 4 ppb (average) up to 10 ppb (peak measured) or 20 ppb (peak estimated in mature high-Ti mare regolith) exceeding terrestrial concentrations. Assuming the highest concentration is recovered across the 2×10^6 km^2 of the high-Ti Mare Tranquillitatis and Oceanus Procellarum to a depth of 3 m, this yields a total lunar inventory of 2×10^8 kg ^{3}He. Given that nuclear fusion has yet to be commercially developed even with the much lower ignition energy DT reaction, the prospect for ^{3}He-based nuclear fusion appears remote. However, the extraction of any volatiles will also release ^{3}He – there is the thorny question of whether such scarce resources should be husbanded for future generations (which would require extreme cryogenic storage) rather than squandered as boil-off. Assuming 20 ppb ^{3}He in mature high-Ti mare basalt-derived regolith, processing of 40 m^2 at 1 m depth (3.5 m radius circle) yields 1g ^{3}He (compared with the release of 8.2 kg of carbon) while an area of 40 km^2 (3.5 km radius circle) yields a metric tonne of ^{3}He. Given the potential value and scarcity of ^{3}He reserves, it would be best reserved for future

Table 1
Concentration of solar wind-emplaced volatiles in lunar regolith (Crawford, 2015).

Volatile species	Concentration (ppm/ μg/g)	Mass/m^3 regolith (g) assuming 1660 kg/ m^3 density
H	46 ± 16	76
^{3}He	0.0042 ± 0.0034	0.007
^{4}He	14 ± 11	23
C	124 ± 45	206
N	81 ± 37	135
F	70 ± 47	116
Cl	30 ± 20	50

space nuclear fusion propulsion if cryogenic storage is feasible (at <4 K).

There exists water of hydration in minerals at all latitudes but this will be more difficult to extract than water ice. Water ice appears to reside in permanently shadowed craters at the lunar poles at temperatures ~40 K, facilitated by the fact that the sun never appears more than 1.5° above the horizon. The LCROSS (2009) impact into the Cabeus crater yielded a water concentration of 5.6 ± 2.9% by mass. Over a total area of over 31,000 km^2 of permanently shadowed area, this yields potential water deposits of 3 x 10^{12} kg. However, Chandrayaan-1 detected at least 40 shadowed craters at the north pole with a capacity for 6×10^{12} kg water ice there alone. It is nevertheless questionable how technologically accessible 40 K water ice might be - rover traverses into permanently shadowed craters and the drilling of rock-like ice present certain technological challenges. In order to provide power to the permanently shadowed regions, heliostats may be employed to reflect sunlight from peaks of eternal light into the shadowed depths – across many kilometres both vertically and horizontally. Three such heliostats can remotely heat surface ice directly or illuminate photovoltaic arrays to generate electrical energy. Water ice can be accessed through bulk heating and the capture of sublimed water vapour in cold traps within an enveloping canopy. It is unclear if there is surface ice which can be released by direct heating of loose surface regolith. Dense regolith overlying buried water ice prevents surface heat being transmitted to depth due to thermal insulation by the regolith. This requires the drilling of boreholes to depth into which heaters are inserted to access subsurface ice. However, the consumption of in-situ water to be burned as propellant/oxidizer is analogous to the burning of fossil fuels on Earth. It is not sustainable and denies those resources to future generations. Furthermore, the extraction of scarce volatiles such as carbon and nitrogen in the process of extracting water ice should be recovered – not to do so would be analogous to the burning off of natural gas during oil drilling that was normal practice on Earth, a process that wantonly wasted resources valuable to future generations. In a more extreme case, lunar ^{3}He will be released with water – while its use as fuel for nuclear fusion energy appears remote today, it must surely behove us to recover it for future generations rather than wasting it while recovering water.

4. Demandite, sustainability & lunar ecology

4.1. Demandite

There are many critical issues that we do not address in detail here such as reduced gravity, dust mitigation, radiation, etc as they are generic to all lunar activities, not just ISRU – although such issues will have to be addressed at some stage. The simplest problem is deal with is the exposed radiation environment to which carbon-backbone plastics are sensitive (replace with silicone plastics with Si–O backbones) and solid state electronics are highly sensitive (replace solid state transistors with vacuum tubes). Partial gravity represents an open problem – gravity is required to support almost all lunar operations but partial gravity is evidently preferable to microgravity exhibited in space stations. Lunar operations affected include: (a) rover traction which is partly dependent on vehicle weight according to Bekker-Wong terramechanics though this can be partially compensated through tracked chassis designs such as the elastic loop mobility system (Ellery, 2005); (b) regolith bulldozing blades for site levelling and regolith acquisition using excavators (Wilkinson and DeGennaro, 2007) such as employed by the Kapvik microrover (Qadi et al., 2012); (c) drilling to acquire subsurface raw materials which is typically dependent on weight-on-bit (though the bio-inspired drill based on the woodwasp ovipositor mechanism substantially reduces the requirement for weight-on-bit (Gao et al., 2007); (d) density separation methods of beneficiation (Avchare et al., 2014) which may require the implementation of centrifugal separators; (e) 3D printing processes which involve either material extrusion (such as fused deposition modelling but this problem has been resolved in microgravity (Snyder et al., 2013)) or powder beds (such selective laser sintering/melting)

which may be tolerant of reduced gravity or replaced with wire-based systems (such as electron beam additive manufacturing – see later).

Lunar dust is ubiquitous and pervasive and adheres to everything due to its frictional and electrostatic properties. Dust particles h ave an average aspect ratio of 0.7 and exhibit angular jagged shapes making them highly adhesive. They are levitated by solar ultraviolet radiation during the day and by solar wind flux during the night (Horanyi et al., 1998). Dust settles and adheres through van der Waal forces onto solar arrays, thermal radiators and optical surfaces. Dust mitigation techniques may be achieved through several mechanisms – vibromechanical, (electro)magnetic and electrostatic removal. Although magnetic approaches are simple (Eimer and Taylor, 2007), electrostatic approaches are favoured as the most effective (Landis and Jenkins, 2002; Calle et al., 2008; Clark et al., 2007). We have conducted successful experiments using a set of carbon nanotube/polymer composite parallel plates implementing electrostatic deflection of dust as part of an electrostatic dust curtain (Kruzelecky et al., 2011). Moving mechanical parts such as motors are particularly prone to dust invasion - rotor/stator airgap, motor alignment, brush/commutator wear, gearing friction and meshing, sheave seating, connector coupling integrity, bearings, etc. Rotary seals require fluid lubrication usually hydrocarbon oil of low viscosity and good thin film adhesion (which may be replaced by silicone oil) to minimise friction and wear while dry lubricants such as PTFE seals have high temperature and chemical stability. However, PTFE o-ring seals have been tested and found to be inadequate for high dust environments (modelled using angular silica dust) (Lauer and Allton, 1992). Magnetic fluid rotary seals can be used in a vacuum offering zero leakage (Cong and Shi, 2008). Two opposing magnets create a magnetic circuit and contain a ferrofluid, a colloidal suspension of paramagnetic particles of 10 nm diameter within a fluid (water or oil). The nanoparticles impart paramagnetic behaviour to the fluid as a whole controlled by the application of magnetic fields rendering ferrofluids ideal for rotary seals in motors. If nanophase iron could be extracted from lunar minerals and dispersed in a fluid such as silicone oil, ferrofluids could be manufactured in-situ for dust seals.

Most proposals for ISRU are concerned only with the supply of consumables such as water, oxygen and hydrogen in which other substances are either side-products or waste. This is unsustainable and will consume scarce resources unnecessarily when there are alternative solutions that do not require this because limitless solar energy is available. For instance, consumption of H_2/O_2 propellant/oxidiser can be eliminated by employing solar-powered rovers for transport (Ellery, 2016b) and electromagnetic launchers for launch (Kaye, 2005). An important aspect of sustainability is to ensure that our use of the environment does not degrade it for future generations. To build an industrial infrastructure on the Moon, we must begin with an assessment of the resources required – this is the demandite concept. We adopt the approach here of an industrial ecology comprising a series of interlocking networks of industrial ecosystems which are embedded in the natural global ecosystem (Patel, 1992). Material and energy circulate through this network to enhance self-sufficiency with respect to the natural environment. It involves tight coordination of the inter-relationships between industrial facilities to optimize the use of resources with minimal waste. This forms an internal industrial metabolism of interlocking material and energy flows. In a lunar context, it requires a near-closed loop system of process flows with integrated recycling loops to minimise waste (Ellery, 2018a). We cannot simply transport terrestrial technology to extraterrestrial environments wholesale as they require the pre-existing global infrastructure on Earth to support it. For instance, in the 1980s, computer chips were constructed from just 12 elements which had increased to 16 by the 1990s, thence to 60 elements by the latter part of the 2000s. Our approach must be to minimise the range of materials that we exploit on the Moon and minimise the support required from Earth-imported materials. One approach to our demandite is to focus on the products that we wish to manufacture on the Moon – a generic spacecraft would be one possibility. A more robust focus however is to determine how to build the means of

production rather than the product itself – indeed, this affords enormous reductions in cost by maximising leverage from the lunar environment (Ellery, 2017a). Furthermore, given that we are implementing a universal constructor, the capacity to build desired products are a side effect of this approach. A spacecraft is simply a specific variation of the more general robotic machine.

Indeed, this approach suggests that we must be able to build manufacturing facilities which we define here to be 3D printers supported by suites of robotic devices from manipulators for assembly to construction vehicles for mining. In effect, we are leveraging lunar resources to build a universal construction mechanism (Moses et al., 2014) – this production machine is a factory which comprises an assemblage of kinematic machines. In fact, self-replication is a special case of universal construction (Ellery, 2016c). The general assumption has been that ISRU must proceed in well-defined stages, though some can proceed in parallel: (i) resource site surveying – there are no ores on the Moon but there are metal-rich minerals; (ii) proof-of-concept ISRU demonstration; (iii) scalable pilot plant; (iv) full-scale production. Resource site surveying and proof-of-concept ISRU can proceed in parallel. Furthermore, in a self-replicating machine implementation, the scalable pilot plant replicates itself into full-scale production so that the two phases are merged. This considerably shortens the development time into only two phases: (i) self-replication module development; (ii) self-replication operations. The advantage that self-replication provides is that it amortises the initial capital cost of launching from Earth and delivering to the Moon the first self-replicating factory unit over subsequent generations of units leveraged in-situ on the Moon (Ellery, 2017b).

An important consideration for closing the self-replication cycle is to minimise the types of material to be mined, minimise the types of chemical processing techniques required, the types of manufacturing techniques required and minimise the amount of assembly required. A variety of chemical/electrolytic processes for lunar minerals have been explored, all offering different yields – thermal reduction by hydrogen, thermal reduction by carbon or methane, carbochlorination, molten regolith electrolysis, solid state electrolysis, vacuum/vapour phase pyrolysis and HF/H_2SO_4 acid dissolution. For example, molten regolith electrolysis at 1400–1600 °C may reduce different geological materials. Electrolysis of specific lunar minerals - anorthite ($CaAl_2Si_2O_8$), olivine (($Mg,Fe)_2SiO_4$), pyroxene ($Ca(Fe,Mg)Si_2O_6$), chromite ($FeCr_2O_4$) and ilmenite ($FeTiO_3$) – yield reduced molten material at the cathode and oxygen at the anode. Here, we adopt the Metalysis FFC process as the core chemical processing technique (Ellery et al., 2017a). For manufacturing, we adopt 3D printing as the core manufacturing process which minimises the amount of assembly required. For universal construction, we require a handful of materials derived from lunar sources, specifically to build the key components common to all kinematic machines – motors, electronics and sensors (Ellery, 2016d). Our demandite requires a minimal set of functional materials derivable from the Moon – tensile and compressive structures (wrought iron and aluminium), elastic structures (steel springs/flexures and silicone elastomers), hard structures (alumina), thermal conductors (kovar and nickel), thermal insulation (silica fiberglass), high thermal tolerance (tungsten and alumina), electrical conductors (aluminium, nickel and kovar), electrical insulation (ceramics, fused silica glass, silicone plastics and silicon steel), active vacuum tube electronics (nickel, kovar, tungsten, calcium oxide and fused silica glass), magnetic materials (cobalt-ferrite, alnico, silicon steel and permalloy), sensory transducers (aluminium resistance wire, quartz and selenium), optical structures (aluminium/nickel and fused silica glass), lubricants (silicone oil) and adhesives (silicone cement and thermite).

4.2. Industrial ecology

Hence, we are interested in mundane but widely utilitarian materials including Fe, Ni, Co, Al, Si, etc as well as potentially useful materials such as Ti metals (which would introduce Nitinol shape memory alloy into the

functional material list). On Earth, most metal ores are oxides, sulphides or silicates - sulphides are typically converted into oxides prior to oxide reduction to metal (by roasting in oxygen) followed by roasting in hydrogen to reduce the metal oxides. Similarly, some extraterrestrial minerals will require preprocessing with reagents. Furthermore, in terrestrial thermochemical processing, slag floats while the heaver metal is tapped from below – such should still occur even in low gravity fields like the Moon. For chemical processing, fluidized bed vessels are preferred as they allow continuous feeding of reagents and removal of products without moving grates or seals. Fluidised beds require small particle sizes of <0.5 mm maximum which can be imposed by physical sieving of regolith without further crushing – however, we introduce 3D printing methods which impose more stringent requirements on both particle size and size distribution which will almost certainly entail physical processing.

The lunar industrial ecology presented here requires the import of NaCl from Earth for the manufacture of silicone plastics and piezoelectric quartz from silica but it is a recycled reagent rather than consumed. Na and Cl are scarce in both lunar and asteroidal sources which could potentially impose limits on the productivity rate. Two such necessary reagents are Na_2CO_3 and HCl which are produced by calcium carbonate and nitric acid (derived from lunar volatile nitrogen) treatment of NaCl respectively. This use of NaCl bears some resemblances to proposals to use KF as an Earth-imported reagent (Landis, 2005). In this case, HF acid leaching can chemically process lunar material by dissolving regolith into fluorides. New superacids are also capable of performing difficult reactions at low temperatures, e.g. solid acid catalysts such as $HF–SbF_5$, CF_3SO_3H and FSO_3H. However, this requires continuous supply of reagents from Earth. NaCl is more stable, safer and easier to handle and process than KF. Many of the pre-processing methods presented here are employed on Earth and should require modest adaptation to the Moon.

Chlorine is liberated from NaCl as hydrochloric acid through the action of nitric acid – this requires a nitrogen source. Nitrogen is a critically scarce commodity as a lunar volatile but its use here is as a reagent so it may be recycled. Nitrogen gas is the primary volatile form of nitrogen but we require it to be in ammonia form to manufacture nitric acid. The Haber-Bosch process fixes N_2 gas with H_2 gas to yield NH_3 at high pressure 15–25 MPa and 400–500 °C over a Fe catalyst supported by CaO, SiO_2 and Al_2O_3 promoters (promoters are sourced through anorthite processing described later):

$$N_2 + 3H_2 \rightarrow 2NH_3$$
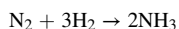
Nitric acid may be produced through the Ostwald process at 400–1000 kPa and 600–800 °C:

$$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$$
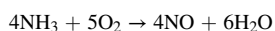
The usual Pt on Ni catalyst may be replaced with tungsten carbide on nickel (MenningChen, 2010) consistent with lunar resources. Thence,

$$2NO + O_2 \rightarrow 2NO_2$$

$$3NO_2 + H_2O \rightarrow 2HNO_3 + NO$$
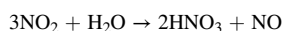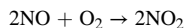
HNO_3 (gas) is required to generate HCl (gas) from NaCl (solid) yielding Chinese saltpetre $NaNO_3$ (solid):

$$NaCl + HNO_3 \rightarrow HCl + NaNO_3$$
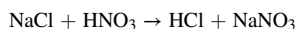
NaCl is reconstituted by processing with KCl from orthoclase processing described later:

$$KCl + NaNO_3 \rightarrow NaCl + KNO_3$$
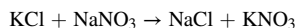
Saltpetre (potassium nitrate) is used as a catalyst for iron selenide processing as well as a stable form of potassium and nitrogen for husbanding nitrogen. Unfortunately, nitrogen volatiles are highly rarified in lunar regolith imposing a nitrogen limitation on the liberation of critical reagents.

Sodium in the form of sodium carbonate (soda ash) is manufactured from NaCl via the Solvay process through ammoniated brine:

$$NaCl + NH_3 + CO_2 + H_2O \rightarrow NaHCO_3 + NH_4Cl$$

$$2NaHCO_3 \rightarrow Na_2CO_3 + H_2O + CO_2 \text{ (calcination)}$$
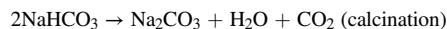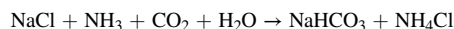
Ammonia is recycled using CaO sourced from anorthite processing and CO_2 is captured and recycled:

$$NH_4Cl + CaO \rightarrow 2NH_3 + CaCl_2 + H_2O$$
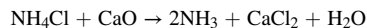
Overall reaction is given by: $2NaCl + CaCO_3 \leftrightarrow Na_2CO_3 + CaCl_2$

$CaCl_2$ is a source of Metalysis FFC process electrolyte to replenish leakage losses. Alternatively, HCl from $CaCl_2$ can be recovered for use as a recycled reagent by reacting it with water vapour above 425 °C:

$$CaCl_2 + 2H_2O \rightarrow Ca(OH)_2 + 2HCl$$
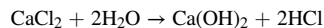
We regard slaked lime $Ca(OH)_2$ as a non-toxic waste product (though it has uses in water sewage treatment). So, slaked lime may be carbonated into calcium carbonate:

$$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$$
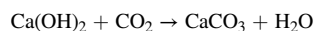
$CaCO_3$ may be calcined into CaO at 1000–1100 °C releasing CO_2 which may be recovered and recycled:

$$CaCO_3 \rightarrow CaO + CO_2 \text{ (calcination)}$$
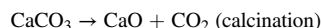
This reconstitutes CaO used for the formation of ammonia in the Solvay process. Sodium carbonate produced in the Solvay process is required for two chemical processes:

(a) the melting of silica at 2000 °C followed by seeding with Na_2SiO_3 at 350 °C and 150 MPa to grow quartz crystals as a piezoelectric sensor material – most sensor transducers including chemical sensors are derived from pressure/force/acceleration measurements enabled by piezoelectrics:

$$Na_2CO_3 + SiO_2(i) \leftrightarrow Na_2SiO_3 + CO_2$$
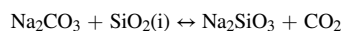
Quartz manufacture involves the growth of crystals which imposes a throughput time bottleneck of 40–80 days but very little will be required and it may be prioritised.

(b) processing of iron selenide with sodium carbonate and oxygen requires a saltpetre (KNO_3) catalyst to yield the semiconductor selenium which is photosensitive:

$$FeSe + Na_2CO_3 + 1.5O_2 \rightarrow FeO + Na_2SeO_3 + CO_2$$
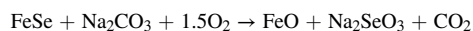
In both cases, CO_2 is recovered. The second phase requires the manufacture of H_2SO_4 from sulphur volatiles (supplemented if necessary by mineral sulphide sources especially meteoritic troilite). Sulphuric acid may be sourced from sulphur dioxide gas:

$$2SO_2 + O_2 \leftrightarrow 2SO_3$$

$$SO_3 + H_2O \rightarrow H_2SO_4$$
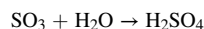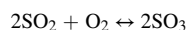
Sulphuric acid is required for the deposition of selenium from sodium selenite and the sulphuric acid is not consumed.

$$Na_2SeO_3 + H_2SO_4 \rightarrow Na_2O + H_2SO_4 + Se$$
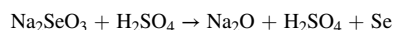
This yields the desired selenium. Recycling of the sodium may be implemented by dissolution of the sodium oxide in water to yield NaOH:

$$Na_2O + H_2O \rightarrow 2NaOH$$
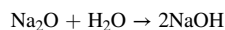
The acid/base reaction reconstitutes NaCl:

$$NaOH + HCl \rightarrow NaCl + H_2O$$
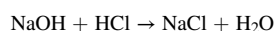
This provides the basis for the manufacture of internal sensors (piezoelectric) and external sensors (vision) that are required to support closed loop feedback control systems in robotic machines (supplemented by electromagnetic sensors).

The Moon possesses regolith volatiles including carbon that may be used as raw material for the manufacture of plastics though the scarcity of carbon suggests its careful husbandry. Polymers generally have inferior properties to metals: (i) moduli of elasticity of plastics falls in the range 10 MPa - 4 GPa compared with 50–400 GPa for metals; (ii) tensile strength of plastics is 10–100 MPa compared with up to GPa for metals; (iii) plastics have low fracture strength compared to metals; (iv) plastics have poor response to high temperatures and radiation compared with metals due to reduced tensile strength and increased ductility. Hence, metals are better suited to load-bearing, stiff structures while plastics are best employed as elastomers for applications for which there is little alternative, e.g. flexible electrical insulation of wiring. To minimise the consumption of carbon as a scarce resource, we have adopted silicone (siloxane) oils (as lubricant) and plastics (as elastomers), especially for flexible electrical insulation (such as wire sheathing) for four reasons: (i) specific hydrocarbon plastics require complex manufacturing reagents and processes; (ii) the alternating Si–O backbone of siloxanes minimises the consumption of scarce C volatiles which are incorporated only into the side chains; (iii) silicone plastic is UV-radiation resistant; (iv) silicone plastic has higher operational temperature tolerance (up to 350 °C for silicone compared with 120 °C for hydrocarbon plastic) which can be increased substantially with additives (350–500 °C). Siloxane manufacture begins with the formation of syngas from lunar volatiles methane and water at 850 °C and 4 MPa over a Ni catalyst:

$$CH_4 + H_2O \rightarrow CO + 3H_2$$
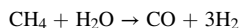
CO is also required for the carbonyl (Mond) process described later but it is not consumed. Syngas is converted to methanol (or higher alcohol) at 250 °C and 5–10 MPa over an alumina catalyst (sourced from anorthite processing):

$$CO + 2H_2 \rightarrow CH_3OH$$
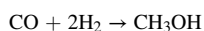
The alcohol formed determines the species of siloxane manufactured (methanol yields polydimethylsiloxane (PDMS), the simplest siloxane). Methyl chloride is formed by the action of HCl on methanol at 340 °C over an alumina catalyst:

$$CH_3OH + HCl \rightarrow CH_3Cl + H_2O$$
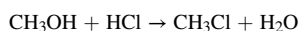
Dimethyl dichlorosilane is formed from the reaction of methyl chloride with Si at 320–370 °C and 1–5 bar in the presence of a catalyst (Rochow process):

$$2CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2$$
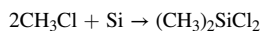
Ni can replace the more commonly used Cu catalyst in the Rochow process as copper is not available on the Moon. Intriguingly, lunar dust has been demonstrated as an effective catalyst for Fischer-Tropsch synthesis (Cabrera et al., 1976). Finally, the simplest silicone, the polydimethylsiloxane (PDMS), is formed by hydrolysis with water:

$$n(CH_3)_2SiCl_2 + nH_2O \rightarrow ((CH3)_2SiO)_n + 2nHCl$$
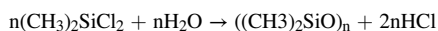
HCl is released and recycled. Hence, silicone plastics may be manufactured from lunar volatiles given a source of Cl reagent, i.e. NaCl imported from Earth. The only alternative to the consumption of carbon in silicone plastic is to convert silicone once deposited in-situ into silica by flash heating in oxygen – this burns off the carbon as CO_2 for recovery leaving silica ceramic insulation. Silica ceramic is of course brittle unlike the viscoelastic silicone – it may be remarked that carbon volatiles are by far the most common lunar volatile with the exception of hydrogen. Thin <1000 μm PDMS membranes ~1 m in size have been 3D printed with features sizes ~0.1 μm using direct laser printing (Low et al., 2017). This

has potential for coating of in-situ produced aluminium solar sails rather than mylar.

A suite of metals is required to perform a variety of functions from structural to electrical, magnetic and thermal processes. These hearth-based processes require elevated temperatures suggesting that the dominant form of energy required for ISRU is thermal. This would imply that solar concentrators such as Fresnel lenses and mirrors will dominate the required energy supply. Chemical reduction of metal oxide minerals implies the use of a chemical reducing agent such as hydrogen (hydrogen reduction) or carbon compounds such as carbon monoxide or methane (carbothermal reduction). It is energetically easier to release oxygen from Fe oxide than most other metal oxides. Fe is also the most widely used metal on Earth by virtue of its versatility of alloys. Ilmenite occurs in concentrations of 10–25% by weight in Fe-rich mare basalts and contains 31.6% Ti and 36.8% Fe. The most commonly proposed lunar ISRU technique is thermal reduction of the common lunar mare mineral ilmenite at 1000 °C using hydrogen (from electrolysed water) in a fluidised bed:

$$FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$$
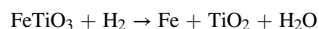
Increasing the temperature to the melting point of Fe ~1600 °C releases Fe by liquation. Water must be electrolysed into its constituents:

$$H_2O \rightarrow H_2 + \frac{1}{2}O_2 \text{ by electrolysis}$$
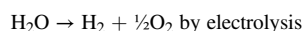
The hydrogen is recycled while oxygen may be used to convert iron into ferrite for magnets ($Fe_2O_3/Fe_2O_3.CoO$):

$$2Fe + 1.5O_2 \rightarrow Fe_2O_3/Fe_2O_3.CoO$$
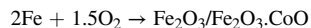
$Fe_2O_3.CoO$ is also magnetostrictive. FeO occurs in fractions up to 20% in lunar glass – it may be oxidised into Fe_2O_3 by roasting at 600 °C. Magnetite (Fe_3O_4) may be formed by heating haematite (Fe_2O_3) to 1400 °C. This may be used in a ferrofluid when suspended in water with silicone surfactant (Hill, 2002). Titanium dioxide (TiO_2) nanomaterials have been proposed as electrodes for water-splitting in photosynthetic photovoltaics (Chen and Mao, 2007) but this represents a major challenge for lunar application. However, Ti may be recovered from rutile (TiO_2) through the Metalysis FFC process. Ti with Ni offers the potential for manufacturing the shape memory alloy NiTi (nitinol) which has a transition temperature of $A_s = 95$ °C and applied stress of 800 MPa at 2–3% strain. This potentially introduces versatile options for distributed actuation in large structures (Lynch et al., 2016; Ellery, 2015). Steel alloy typically comprises up to 2.1% C with a minimum melting temperature of 1130–1315 °C - the addition of carbon reduces its melting point for ease of casting. Higher than 2.1% C is cast iron – cast iron has a melting point of 1375 °C. Hence, the addition of carbon is not essential and wrought iron on the Moon would not be subjected to rusting. Stainless steel comprises a minimum of 11% Cr (usually with Ni) to resist corrosion through the formation of a thin passive chromium oxide layer – this is also not required in most extraterrestrial environments such as the Moon. Although wrought iron is an effective structural material, there are a number of steel alloys that offer functional capabilities with low carbon content – tool steel (Fe–W alloy) for cutting tools such as milling heads, silicon steel (up to 3% Si) for electromagnets and motor cores, kovar (Fe–Ni–Co–Si alloy) for high temperature electrical wiring, permalloy (Fe–Ni alloy) for magnetic shielding and ferrite for permanent magnets ($CoFe_2O_4$). Si is a constituent in magnetically soft silicon steel for use in electric motor cores - this introduces the possibility of manufacturing electric motors in-situ. Steel alloy manufacture requires a range of alloying materials, primarily from the significant nickel-iron meteorite deposits on the Moon (Ellery et al., 2018a) (Table 1). For instance, kovar, a fernico alloy of Fe, Ni and Co can replace glass-compatible copper conductors) with the Ni and Co sourced from NiFe asteroidal material located at certain lunar crater rims.

Most meteorites are comprised of minerals based on eight major elements – oxygen, silicon, magnesium, iron, aluminium, calcium, sodium

and potassium – and several minor elements – sulphur, chromium, phosphorus, carbon and titanium. The commonest minerals are pyroxene (especially enstatite in stony meteorites), olivine (especially fayalite except in E chondrites), plagioclase feldspar (especially anorthite with albite being rare), kamacite (NiFe metal) and taenite (NiFe metal) with lower incidences of troilite (FeS), schreibersite (FeNi)$_3$P and cohenite (Fe,Ni)$_3$C. Chondritic meteorites generally comprise 10–30% native metal but metallic asteroids comprise up to 99% ferrous metal alloy. Silicate minerals – pyroxenes, olivines and feldspars – are dominant in stony meteorites. Chromite FeCr$_2$O$_4$ is the commonest metal oxide in ordinary chondrites. The alloy additives to steel – nickel, cobalt, tungsten and selenium - may be sourced from in-situ nickel-iron meteorite material detectable as magnetic anomalies associated with impact craters. Nickel-iron meteorites comprise primarily of kamacite/taenite Fe–Ni metal alloy with significant amounts of cobalt and microparticle inclusions of tungsten. Kamacite (4–7.5% Ni) and taenite (27–65% Ni) are ferromagnetic NiFe alloys contaminated with ~0.5% Co constituting the major constituent in nickel-iron meteorites. The metals are in a free metal state of Fe–Ni–Co alloy with W micro-inclusions and troilite (FeS) contaminants. Direct melting of metal alloy will yield sub-optimal composition of ferrous steel enriched in nickel, cobalt and other minor metals. The major metals Fe–Ni–Co may be purified through different carbonyl (Mond) processes under mild conditions with a S catalyst. This involves heating the metal alloy to up to 260 °C under pressure in the presence of CO gas to form gaseous metal carbonyls that can be fractionally distilled to separate the different metals (Mond process). The carbonyl process has different processing conditions for purifying different metals. For Ni, this requires reacting CO with an S catalyst at 40–80 °C and 1 bar to form nickel carbonyl gas which is then reversed at 230 °C and 60 bar while Fe purification requires different conditions:

Fe(CO)$_5$ ↔ 5CO + Fe (175 °C/100 bar)

Ni(CO)$_4$ ↔ 4CO + Ni (55 °C/1 bar)

Co$_2$(CO)$_8$ ↔ 8CO + 2Co (150 °C/35 bar)
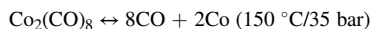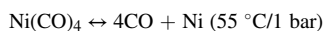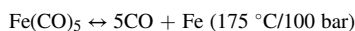
Co may be extracted similarly through the carbonyl process but under different conditions. Alternatively, Co may be extracted by roasting with S in oxygen to convert cobalt into cobalt sulphate which is soluble in water. Co may then be extracted electrolytically. In all cases, CO may be derived from lunar volatiles and should be recycled (it is not consumed). The S catalyst can be derived from troilite (FeS) which is an accessory mineral in almost all meteorites including NiFe meteorites often associated with pentlandite (Fe,Ni)$_9$S$_8$ and graphite. The release of the sulphur catalyst involves roasting troilite in oxygen to release sulphur dioxide gas which is then mixed with hydrogen sulphide gas at 750–1100 °C over an alumina catalyst (Claus process):

4FeS + 7O$_2$ → 2Fe$_2$O$_3$ + 4SO$_2$

SO$_2$ + H$_2$S → 3S + H$_2$O
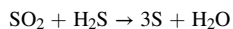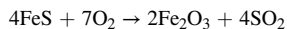
Meteoritic NiFe alloys are also enriched in W microparticle inclusions at a concentration of 0.1–5 μg/g. Following grinding into particles, the high density of W at 19.3 lends itself to extraction from the residue of the Mond process by density. Separation of particle mixtures by specific density may be achieved through centrifugal separation into concentrate and gangue. In a hydrocyclone, a wet feed slurry enters a cyclone tangentially. Centrifugal forces force heavier particles down a decreasing conical diameter while fine particles remain in the upper cylindrical diameter. The low concentration of tungsten highlights the criticality of this material but it is required only for the tips of tooling (tool steel) and especially as the thermionic cathodic material for vacuum tube heating elements. Ceramic-metal (cermet) composites offer high thermal tolerance and may be formed from tungsten and alumina powder. Selenium is found in association with troilite with an S/Se ratio of ~2450 in meteorites making it rare. However, it is required only for photosensitive

applications. Mastery of the carbonyl (Mond) process on the Moon provides a field demonstration of asteroid mining techniques in a more benign environment (0.166g rather than milli-g gravity).

Alumina reduced to pure Al offers several multirole capabilities: (i) structural metal; (ii) electrical wiring; (iii) reflective surfaces including solar sails; (vi) high performance AlNiCo (8–12% Al, 15–16% Ni, 5–24% Co, up to 6% Cu, up to 1% Ti and the rest being Fe) permanent magnets (though some loss in strength is expected with the omission of Cu); (v) thermite welding with iron oxide. The addition of Al to the manifest of metals also permits the manufacture of AlNiCo for magnetically hard materials. Aluminium metal - useful for both lightweight structural purposes and electrically conductive wiring - is difficult to extract from the ubiquitous anorthite and requires pre-processing methods to yield alumina (which is also difficult to reduce) which itself has use as a refractory material in solar furnaces as well as a catalyst. Although bauxite on Earth is the primary Al ore, anorthite has been used commercially as a source of Al using a lime-soda process which yields alumina:

CaAl$_2$Si$_2$O$_8$ + 3CaCO$_3$ + Na$_2$CO$_3$ → 2NaAlO$_2$ + 2Ca$_2$SiO$_4$ + 4CO$_2$
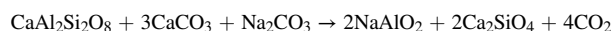
A further series of processes are required to yield Al$_2$O$_3$ rendering this too complex for lunar application. Fluidised bed carbochlorination of anorthite at 770 °C is another approach:

CaO + Al$_2$O$_3$ + 2SiO$_2$ + 8C + 8Cl$_2$ → CaCl$_2$ + 8CO +2SiCl$_4$ + 2AlCl$_3$
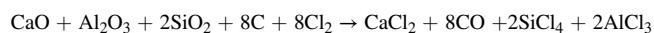
Lunar highland mineral anorthite (CaAl$_2$Si$_2$O$_8$) may be processed in two ways to yield different products. The first pathway involves carbothermal reduction at 1650–1860 °C for 3 h to yield CaO used for thermionic cathode coatings, Al$_2$O$_3$ as either feedstock for the FFC Cambridge process for reduction to aluminium metal or as a hardy ceramic (such as refractory crucible linings) and silicon metal for silicon steel alloying:

CaAl$_2$Si$_2$O$_8$ + 4C → 4CO + CaO + Al$_2$O$_3$ + 2Si

Quicklime (CaO) is an alkali earth metal oxide coating applied to tungsten in vacuum tubes to reduce its work function. It is required in only small amounts. The CO may be recovered and recycled. Excess CaO may be converted into slaked lime Ca(OH)$_2$:

CaO + H$_2$O → Ca(OH)$_2$
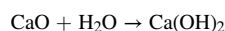
This has potential uses in cement production. Alternatively, excess CaO may be reduced to Ca metal through the Metalysis FFC process which is often proposed as an electrical conductor in vacuum – although its conductivity by mass is superior to both copper and aluminium due to its low density, it is not superior than either by volume. Hence, we favour aluminium as the electrical conductor of choice.

The second pathway for anorthite involves artificial weathering using HCl to yield a different set of products including silica (rather than Si metal) for the production of fused silica glass. Glass particles are abundant in all lunar regolith with variable colour and refractive indices (low-refractive index, lighter glasses with high Al content in the highlands and higher refractive index, darker glasses with high Fe and Ti content in the mare regions). Glasses often form agglutinates (25–30% of lunar regolith) comprising fragmented mineral grains in a glass matrix formed from impact melts during micrometeoroid impacts. Melting regolith with rapid cooling forms glass but such glass would be of poor quality. Natural lunar glass is also unsuited to engineering applications. Foamed glass may be formed for primary structure or glass/optical fibres for composite reinforcement. Electrospinning is an efficient method of fibre production applicable to any soluble fibre. Glass fibre has a versatility of uses – glass wool for thermal insulation, high strength/weight ratio for tensile applications, low coefficient of thermal expansion and high electrical insulation, and optical applications such as fibre-optics. Glass may be melted in a furnace, rapidly cooled and extruded or drawn mechanically by winders through a metal bushing forming reinforcing glass fibres. Cooled molten regolith from 1450 to 1600 °C may also form such glass

fibres (Tucker et al., 2006). If the glass fibres are drawn through a polyamide or silicone solution, they form an opaque coating to form optical fibres. Glass wool offers a much lower thermal conductivity ~0.04 W/m$^\circ$C than silica glass at 2 W/m$^\circ$C. For optical applications, glass requires transparency. Note that soda ash (Na_2CO_3) and potash (K_2CO_3) is used as inputs for making soda lime glass. Soda lime glass (71–73% SiO_2, 12–14% Na_2O and 10–12% CaO) with its low melting point of 1000 $^\circ$C for ease of casting cannot be made on the Moon due to the paucity of Na and imported Na from NaCl must be recycled rather than consumed. Borosilicate glass (pyrex) with its higher melting temperature of 1650 $^\circ$C is commonly used for chemical vessels for its inertness, durability and heat tolerance. However, borosilicate glass is infeasible because B_2O_3 is scarce on the Moon. The melting point of borosilicate glass is close to that of fused silica (pure SiO_2) with its melting point of ~1700 $^\circ$C. Aluminosilicate glass (52–60% SiO_2, 15–25% Al_2O_3, 12% MgO, 5–15% CaO, 4% B_2O_3, 1% NaO and 1% other oxides) has a melting temperature of 1130–1350 $^\circ$C and may be approximated by lunar anorthosite (anorthite, pyroxene, olivine and ilmenite) especially anorthite ($CaAl_2Si_2O_8$) plus MgO less the minor constituents (Landis, 2007). Acid leaching can remove undesirable components from the lunar soil. Aluminosilicate glass is potentially reactive to oxygen-rich fire (only to be problematic in oxidation reactions). However, the moderate to high FeO content in indigenously derived glass causes glass darkening which is undesirable for transparency so it would have to be removed. This may be accomplished through purification of silica to which the other components may be added in the required proportions rather than forming glass from anorthite. However, we assume that fused silica glass is manufactured and exploited as it offers predictable properties and high transparency for optics. Silica – which is rare on the Moon - is highly desirable for the formation of fused silica glass for optical components, as feedstock for the FFC Cambridge process to yield silicon for electrical steel alloy and as a thermal insulation in fibre form. SiO_2 may yield fused silica glass through simple heating at 1550 $^\circ$C while the anhydrous conditions of the Moon generate higher tensile strength glass than on Earth.

Hydrolysis is a common weathering process on Earth in which water as a weak acid (carbonic acid due to dissolved carbon dioxide) can react with silicate minerals. Hydrolysis may be implemented artificially using stronger acids such as HCl. This eliminates the involvement of carbon, so we propose the action of hot HCl on anorthite which is readily dissolved in mineral acid through acid leaching (Veldhuyzen, 1995):

$$CaAl_2Si_2O_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + 2SiO_2$$
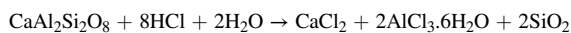
Silica is precipitated while $CaCl_2$ and $AlCl_3$ remain in solution and must be precipitated separately through heating. The only waste is $CaCl_2$ which re-supplies leakage losses in the FFC Cambridge process universal electrolyte but the rest can be recycled into HCl and CaO as outlined earlier. Aluminium choride hexahydrate may be heated to 100 $^\circ$C to yield HCl which may be recycled yielding $Al(OH)_3$:

$$2AlCl_3.6H_2O \rightarrow Al(OH)_3 + 3HCl + 3H_2O$$
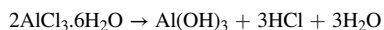
Hydrochloric acid and water are recycled. Precipitated aluminum hydroxide may be in turn heated to 400 $^\circ$C yielding alumina (calcination is another pathway to alumina):

$$2Al(OH)_3 \rightarrow Al_2O_3 + 3H_2O$$

Filtration and washing yields silica purity in excess of 99%. Alumina has highly desirable properties including high thermal tolerance and high hardness that lend itself to the lining of thermal crucibles. Alumina may also be subject to the Metalysis FFC process to yield elemental aluminium as (a) an electrically conducting material; (b) a structural material; (c) high thermal conductivity material of 200 W/m$^\circ$C (half that of copper) suitable for thermal straps; (d) solar sail coating; (e) a component of strong AlNiCo hard magnets. Aluminium can also be used for joining. Since electronegativity corresponds to a reverse reactivity

series, metals can displace any metal lower in the reactivity series, e.g. $2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$. This is the basis for the thermite reaction that is used for welding steel or iron together using Al powder. Aluminium is a particularly desirable metal for its diverse applications as a lightweight structural material, as electrically conducting wiring, as thermally conductive straps and as a metal joining agent.
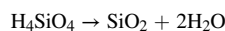
Natural weathering on Earth offers insights into how further lunar minerals might be processed substituting strong HCl for weak H_2CO_3 as a form of artificial weathering. Chemical weathering of aluminosilicates such as feldspar involves hydrolysis by weak carbonic acid (carbon dioxide dissolved in rainwater) forming the clay mineral kaolinite and silicic acid from which silica can be precipitated:

$$2KAlSi_3O_8 + 2H_2CO_3 + 9H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 4H_4SiO_4 + 2K^+ + 2HCO^{3-}$$
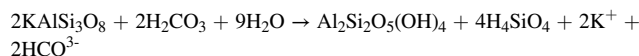
Similarly, artificial chemical weathering of orthoclase with hot HCl yields silicic acid and the clay mineral illite:

$$3KAlSi_3O_8 + 2HCl + 12H_2O \rightarrow KAl_3Si_3O_{10}(OH)_2 + 6H_4SiO_4 + 2KCl$$

Silica can be precipitated from silicic acid:

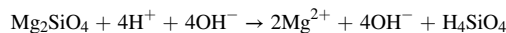$$H_4SiO_4 \rightarrow SiO_2 + 2H_2O$$

From silica, both fused silica glass and quartz can be manufactured. Illite can be further weathered into the clay mineral kaolinite which has multiple uses such as porcelain, cement and mineral wool (for thermal insulation and hydroponics):

$$2KAl_3Si_3O_{10}(OH)_2 + 2HCl + 3H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2KCl$$
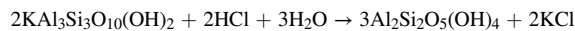
NaCl can be reconstituted from KCl using $NaNO_3$ as described earlier. Olivine may be subjected to carbothermal reduction at 2000 $^\circ$C to yield Si and MgO. Alternatively, weathering of olivine is possible due to the instability of olivine in hot water which is why olivine is rare terrestrially:
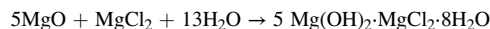
$$Mg_2SiO_4 + 4H^+ + 4OH^- \rightarrow 2Mg^{2+} + 4OH^- + H_4SiO_4$$

Both olivine end members yield useful materials including SiO_2 ceramic:

$$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3SiO_2 + 2H_2O$$

$$Mg_2SiO_4 + 4H_2O \rightarrow 2MgO + SiO_2 + 4H_2O$$
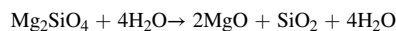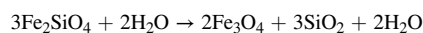
Fayalite yields magnetite (ferrite) and silica while forsterite yields magnesia and silica – the Moon's olivine is dominated by forsterite. MgO which can be reduced directly using the FFC Cambridge process to yield magnesium metal - however, we do not recommend extracting magnesium metal from the oxide as it has a tendency to outgas in a vacuum despite its potential utility in ultralightweight structures. Alternatively, some MgO can be further reacted with HCl to yield $MgCl_2$:

$$MgO + HCl \rightarrow MgCl_2 + H_2O$$
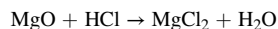
Dissolved $MgCl_2$ salt in water mixed with MgO yields Sorel cement:

$$5MgO + MgCl_2 + 13H_2O \rightarrow 5 Mg(OH)_2 \cdot MgCl_2 \cdot 8H_2O$$

Sorel cement consumes chlorine so it would not be suitable as part of a self-sustained industrial ecology but has been proposed as binder for 3D printing regolith in the D-shape process (Cesaretti et al., 2014). My group has already 3D printed casts in Sorel cement for casting different materials including sintered metal-impregnated clays (which are produced by artificial weathering of pyroxene and orthoclase) and other binders using our commercial universal extruder [*unpublished results*]. We do not require Mg metal and other silicates yield silica. Hence, the processing of olivine is not required.

On Earth, clinopyroxenes (e.g. augite and diopside) are more abundant than orthopyroxenes which are associated with olivine –

orthopyroxenes weather hydrothermally much more rapidly than clinopyroxenes so clinopyroxenes are more common on Earth. Clinopyroxenes are also more abundant on the Moon such as Ca-rich augite but not due to weathering. Lunar augite may be artificially weathered to yield Ca montmorillonite, soluble silica and insoluble iron oxide:

$$Ca(Fe,Al)Si_2O_6 + HCl + H_2O \rightarrow Ca_{0.33}(Al)_2(Si_4O_{10})(OH)_2.nH_2O + H_4SiO_4 + CaCl_2 + Fe(OH)_3$$
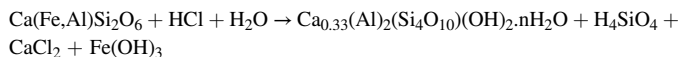
Montmorillonite is an expanding clay unlike illite and kaolinite. Montmorillonite is the primary ingredient in bentonite which has multiple uses: (i) viscous agent in drilling mud; (ii) binder in sand casting - green sand is sand mixed 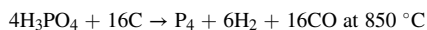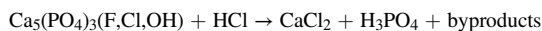with bentonite clay and water; (iii) absorbent material (montmorillonite and kaolinite) in Fuller's earth cleaning agent; (iv) feldspar and kaolinite may be supplemented by bentonite to form pottery. We consider the utility of clay to be marginal unless deep drilling is implemented (by default, we assume that raw materials is accessed on the surface through open-cast mining). Similarly, meteoritic enstatite may be rapidly artificially weathered:

$$Mg_2Si_2O_6 + HCl + H_2O \rightarrow Mg_3Si_4O_{10}(OH)_2 + H_4SiO_4 + MgCl_2.nH_2O$$
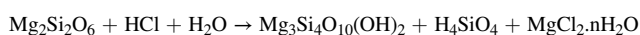
This yields talc, silica and magnesium chloride. Talc is a waste product that can potentially be used as a dry solid lubricant but its utility is again marginal. Tungsten disulphide is more appropriate as a dry lubricant that has higher temperature tolerance than the more widespread molybdenum disulphide – tungsten disulphide is manufactured by depositing sulphur onto a tungsten substrate and heating at 300–400 °C. We discard processing of clinopyroxenes as unnecessary.

There are further processes that may be explored. Acid leaching with dilute HCl can also release most of the rare earth elements from KREEP deposits (Ellery et al., 2018b) but we do not address this further. However, in passing, we may propose that P may be extracted from the mineral apatite (calcium phosphate $Ca_5(PO_4)_3(F,Cl,OH)$) by warm HCl leaching:

$$Ca_5(PO_4)_3(F,Cl,OH) + HCl \rightarrow CaCl_2 + H_3PO_4 + byproducts$$

$$4H_3PO_4 + 16C \rightarrow P_4 + 6H_2 + 16CO \text{ at } 850 °C$$

Aluminium and phosphorus are potential p- and n-type dopants for solar grade silicon for the manufacture of silicon solar cells. However, apatite is relatively scarce on the Moon and control of dopant diffusion requires exacting manufacturing conditions. This completes our inventory of lunar material processing of all major lunar minerals. It appears that processing of olivine and pyroxenes are superfluous to the lunar industrial ecology which requires only volatiles, ilmenite, anorthite and orthoclase and imported NaCl as raw materials. Mindful of the need to employ sustainable approaches to ISRU (Ellery, 2018a), this lunar industrial ecology can support a complete infrastructure with recycling loops and minimal waste (Ellery et al., 2018c).

4.3. Universal processor

Direct magma electrolysis of regolith is highly energy-intensive as it requires a molten state for the minerals (1300–1700 °C) to generate oxygen at the anode and yields mongrel alloys including Fe–Si at the cathode and molten silicate ceramic. Although silicate ceramics may be used for structures, mongrel alloys yield uncontrolled performance depending on the specific composition of the original mineral. This is the reason for employing chemical pre-processing to yield more predictable and controllable materials. Our industrial ecology scheme exploits the capabilities of the Metalysis FFC (Fray Farthing Chen) process that reduces any solid oxide (such as rutile, alumina, silica, etc) into near-pure metal using a $CaCl_2$ electrolyte to yield iron, titanium, aluminium, etc from pre-processed lunar minerals (Ellery et al., 2017b). It is a general electrolytic mineral reduction process which exhibits a solid-state mineral oxide cathode and a graphite anode at 900–1100 °C. Maximum

benefit is obtained by pre-processing of complex minerals into simple oxides to yield elemental metals. The FFC process can reduce any oxide into near-pure metal releasing O_2. However, the graphite anode is corroded by oxygen, forming CO/CO_2. We have avoided the use of carbon compounds as consumed product and as consumed reagent (in the case of sodium carbonate in quartz production and selenium extraction, carbon is recycled from recovered CO_2) because carbon volatiles in the lunar regolith are scarce. This places a premium on recovering carbon: for example, we may recover graphite anodes that are eroded as CO/CO_2 during oxygen production in the Metalysis FFC process. First, any CO in the CO/CO_2 mix formed by the liberation of oxygen at the graphite anode can be oxidised fully:

$$CO + 0.5O_2 \rightarrow CO_2$$
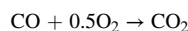
The CO_2 can be recycled through the Sabatier reaction at 300 °C over an Ni catalyst (sourced from nickel-iron meteorites):

$$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$$
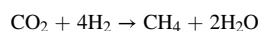
Methane can then be pyrolytically cracked at 1400 °C to yield elemental carbon for graphite anode reconstitution:

$$CH_4 \rightarrow C + 2H_2$$
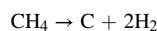
This illustrates that the Sabatier reaction which is often proposed for the conversion of Martian atmosphere CO_2 into CH_4 fuel (Ellery and Muscatello, 2017) can be field tested rigorously on the moon. The American Mars 2020 rover will carry the MOXIE experiment to demonstrate the Sabatier process of extracting CH_4 and O_2 from the CO_2 Martian atmosphere and H_2 extracted from water. In the Metalysis FFC process, the sintered solid cathode, initially a metal oxide is converted into sintered pure metal with >99% purity which may be crushed and used directly as powder feedstock for selective laser sintering – this was demonstrated with rutile reduced to Ti metal by Metalysis (Ellery et al., 2017b). The lunar ecology yields the demandite from which we can manufacture a wide variety of functional capabilities using lunar resources.

5. 3D printing techniques

5.1. Universal construction by 3D printing

The introduction of rapid prototyping technology allows us to progress beyond the supply of consumables to the construction of complex objects using processed materials with layered construction. The products of the lunar ecology constitute feedstock for 3D printing which provides a general-purpose manufacturing technique without the waste inherent in more traditional subtractive techniques. 3D printing involves a suite of manufacturing technologies premised on the construction of 3D parts additively layer-by-layer rather than subtractively such as turning or milling. It permits complex geometries to be generated and reduces the requirement for joining and assembly while almost completely eliminating material waste. Just as significantly, it can be used to create positive or negative moulds from which casts can be made for mass production to overcome the seriality of 3D printing. Stereolithography (SLA) was the first 3D printing technique developed by Charles Hull in 1985. SLA is based on a liquid photopolymer which hardens when exposed to UV light. A vertically-actuated platform is immersed in a vat of photopolymer such that only a very thin layer of liquid covers the surface. A UV laser is scanned over the surface in a specific pattern curing the photopolymer in the desired shape. The platform is lowered until the same thickness of liquid photopolymer is above the previous solid layer. Hence, the UV laser builds the 3D part layer-by-layer. This technique offers very high tolerances and good surface finish but it is limited to photopolymers. Fused deposition modelling (FDM) involves extrusion of a melted thermoplastic fed by a wire into a heating chamber. Extrusion is by a nozzle through which liquid thermoplastic is deposited onto a

platform. The nozzle traces out a pattern which hardens. The platform is depressed and another layer added by the nozzle. It is limited to thermoplastics though additives can be included. Laminated object manufacturing (LOM) uses adhesive-backed sheets (of paper, plastic, ceramic, composite, metals, etc) lain on top of each other using a heated roller, each layer being cut by laser into the required pattern once it has been laid. This technique requires prior forming of the layers and adhesive. Powdered metal may be sintered into a wide variety of structures through additive manufacturing. Selective laser sintering/melting (SLS/M) involves the use of a laser to thermally sinter or melt a powder bed of metal, ceramic or polymer onto a platform. The laser beam scans the pattern which fuses or melts the powder into a solid layer. The sintering temperature (900–1300 °C) can be considerably below the melting temperature (1600 °C) of a metal (in this case, iron/steel) favouring a low cooling rate. The platform is depressed with another powder layer lain over the top of the previous layer and the process repeated. The unfused powder acts as temporary support. Laser energy absorption rate is directly proportional to electrical resistivity so insulators tend to require more energy for processing. LENS (laser engineered shaping) is variation in which powder is fed directly into the laser beam and melts the particles onto a platform. SLS/SLM has become the most popular technique but electron beam additive manufacturing (EBAM) which replaces the laser with an electron beam offers certain advantages including greater efficiency for lunar application (Taminger and Hafley, 2006). SLS/M does introduce residual stresses in the 3D part due to shrinkage of each layer on cooling which may be alleviated by heating the chamber to reduce temperature gradients (Mercelis and Kruth, 2006). The chief problem with all 3D printing is that it yields poor finish, often exhibiting a staircase effect requiring post-processing. Nevertheless, metals may be 3D printed directly from metal feedstock into a variety of useful machines such as propellant/oxidant tanks, mining structures, manufacturing and assembly machines. The RepRap 3D printer is an FDM device that prints in thermoplastic (Jones et al., 2011) (ABS and PLA being most common though there exist universal extruder parts that can print in more diverse materials with low melting points). Its unique capability is that it can print many of its own plastic parts, representing the first step towards self-replication capability.

To complete the self-replication process, RepRap would need to be able to 3D print its structural metal bars (which would be enabled through metal printing capability), its electric motor drives, its electronics boards and its computer programs. In addition, it would need to self-assemble (a capability afforded by mechatronic capabilities (Zykov et al., 2005)) and include its own power system, and its raw material-to-feedstock processing within its self-replication scheme. We hypothesise that it suffices to 3D print electric motors, vacuum tubes and piezoelectric/selenium sensors to prove universal construction. A universal kit of parts had been proposed as a universal construction system with a view to enable self-assembly with standard connections of robotic machines and habitats from in-situ resources with self-replication capacity (Howe, 2006). We have been making some progress in 3D printing DC electric motors (Ellery, 2018b) and demonstrating them as part of a 3D printed self-assembling system of actuated panels (Ellery and Elaskri, 2019) as a significant step towards the realization of a universal constructor. We have also indicated how these universal construction properties may be exploited to construct entire lunar bases and their interior configuration (Ellery, 2019b).

5.2. Electromagnetic launchers

If a DC electric motor were rolled out into a linear motor, we have the basis for an electromagnetic launcher. As we stated earlier, electromagnetic launchers can exploit abundant supplies of solar energy on the Moon rather than consuming scarce resource of H_2/O_2. Furthermore, the complexity of launch pad construction including logistics is arguably no less than that involved in electromagnetic launcher construction. There are two types of electromagnetic launcher – railgun and coilgun - capable

of launching payloads at high speeds beyond lunar escape velocity *in vacuo* (Schroeder et al., 1989). In the railgun, the armature current is delivered to the armature through a sliding contact with parallel rails. A perpendicular magnetic field from external coils provides the driving force. In the coilgun, there is no contact as the ring current is maintained by magnetic induction between mutually coupled coils on the barrel and projectile respectively. The driving magnetic field is generated by a series of coils that are energized successively. The coilgun is a linear electric motor comprising a series of stator coils which accelerates an armature. The coil type design is superior in eliminating contact wear but requires very high switching voltages. The railgun has limits on its performance but this may be enhanced by introducing additional complexities such as additional rails and use of a helical coil armature but the sliding contact remains (Engel and Timpson, 2015). The coilgun is in general preferable. Muzzle velocity is given by:

$$v = \left(\frac{2\gamma c T \varepsilon \mu_0 \sigma l}{r^2 \rho^2} \right)^{1/3}$$

where γ = electrical conductivity, c = specific heat per unit volume, T = temperature, ε = geometric factor<0.5, μ = magnetic permeability, $\sigma = \frac{B^2}{\varepsilon \mu_0}$ = maximum armature stress, B = magnetic flux density, r = ratio of projectile-to-armature mass, ρ = armature mass density, l = barrel length. Hence, the launch velocity is critically dependent on coil electrical conductivity, armature stresses and magnetic flux density which will be determined by the 3D printing quality of coils, magnets and structural robustness of the armature. A detailed exposition on electromagnetic launchers in a different context is given in (Ellery and Howe, 2018). Lunar escape velocity is achievable in a modest-sized electromagnetic launcher depending on the acceleration permitted – higher acceleration permits shorter length.

6. Conclusions

ISRU is an actively developing field ranging from the supply of consumables to human missions through the full spectrum to colonisation of the Moon through leveraging of an industrial infrastructure. Of particular importance, 3D printing is a recent technological development that promises to transform ISRU capabilities, culminating in the possibility of self-replicating machines. Although we have not considered the overall architecture of a self-replicating machine here, there have been several proposals of such (Chirikjian et al., 2002). This capability would transform lunar exploration and development, opening a number of hitherto implausible mission concepts. The potential for lunar exploitation is potentially enormous including the provision of solar power satellites manufactured from lunar resources and launched into high Earth orbit by electromagnetic launcher to provide scalable clean energy to Earth (Ellery, 2018c).

Declaration of competing interest

There is no conflict of interest.

CRediT authorship contribution statement

Alex Ellery: Writing - original draft, Writing - review & editing.

Appendix A. Supplementary data

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