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REVIEW

Leveraging in situ resources for lunar base construction

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Abstract: We explore the limits of in situ resource utilization (ISRU) on the Moon to maximize living off the land by building lunar bases from in situ material. We adopt the philosophy of indigenous peoples who excelled in sustainability. We are interested in leveraging lunar resources to manufacture an entire lunar base in such a fashion that is fully sustainable and minimizes supplies required from Earth. A range of metals, ceramics and volatiles can be extracted from lunar minerals to support construction of a lunar base that include structure, piping and electrical distribution systems. To 3D print a lunar base, we must 3D print the load-bearing structure, electrical distribution system, water-based heating system, drinking water system, air system and orbital transport system from in situ resources. We also address the manufacture of the interior of the lunar base from local resources. The majority of systems constituting a lunar base can be manufactured from in situ resources.

Key words: lunar base, in situ resource utilization, sustainable space exploration, additive manufacturing.

Résumé : Nous explorons les limites de l'utilisation des ressources in situ (URIS) sur la Lune pour maximiser la vie sur la Lune en construisant des bases lunaires à partir de matériaux in situ. Nous adoptons la philosophie des peuples autochtones qui ont excellé en matière de durabilité. Nous sommes intéressés à tirer parti des ressources lunaires pour fabriquer une base lunaire entière d'une manière totalement durable et qu'elle minimise les approvisionnements requis de la Terre. Une gamme de métaux, céramiques et composants volatils peuvent être extraits des minéraux lunaires pour soutenir la construction d'une base lunaire qui comprend la structure, la tuyauterie et le système de distribution électrique. Pour imprimer en 3D une base lunaire, nous devons imprimer en 3D la structure portante, le système de distribution électrique, le système de chauffage à l'eau, le système d'eau potable, le système d'air et le système de transport orbital à partir de ressources in situ. Nous abordons également la fabrication de l'intérieur de la base lunaire à partir de ressources locales. La majorité des systèmes constituant une base lunaire peuvent être fabriqués à partir de ressources in situ. [Traduit par la Rédaction]

Mots-clés : base lunaire, utilisation in situ des ressources, exploration spatiale durable, fabrication additive.

1. Introduction

Everyone is going to the Moon. The Chinese Chang'e programme is a vigorous lunar exploration programme (https://en.wikipedia.org/wiki/Chinese_Lunar_Exploration_Program) – Chang'e 4 landed on the lunar farside and hosted a small garden of seedlings that germinated on the Moon; Change'e 5 recently returned almost 2 kg of lunar samples to Earth from the 1.2–2.0 By old Oceanus Procellarum region to enable calibration of solar system ages based on cratering densities; Chang'e 6 will be another sample return mission in 2023 followed by Chang'e 7 and then Change'e 8 scheduled for 2027 which will operate a 3D printer to demonstrate use of lunar regolith as a structural material. Clearly, the Chinese programme is focussed on lunar base development for human habitation. Currently, the US Lunar Gateway is also envisaged to be supported by a lunar surface habitat, a lunar mobile habitat, and a lunar terrain vehicle for deployment at the lunar south pole. Beyond this, the Moon Village is an open concept to build a complete infrastructure comprising several lunar bases of perhaps 100 personnel devoted to different tasks operated by different institutions. For a sustained presence on the Moon, we need to emplace a space infrastructure which itself is premised on leveraging local resources as far as possible. We consider the lunar base as the central component of the Moon Village and explore the degree to which it might be leveraged from local resources. Fabrication of assets using in situ resources on the Moon is an extension of the goal of eliminating in-space spares and reducing re-supply from Earth. The lunar base is also an essential precursor to a Mars base to mitigate the risks of the latter (Mendell 1991). Long duration missions require infrastructure with the ability to self-repair to yield 100% reliability (Murphy et al. 2009) — this implies that reliability is enhanced if in situ resource utilization (ISRU) can be leveraged to the maximum extent, i.e., as close to 100% as is feasible. Our concern is to leverage lunar bases/habitats from in situ resources beyond the supply of water to robotically build the entire habitat from in situ resources in preparation for human occupancy. Once productive assets are emplaced on the Moon, the private sector may exploit these assets in the pursuit of commerce — private space companies have flourished recently including SpaceX, Blue Origin, Virgin Galactic, and Moon Express. Although it is fruitless to speculate on the course of such future entrepreneurship, several possible applications come to mind such as the manufacture of solar power satellites (Ellery 2016) and space-based geoengineering (Ellery 2017) from lunar resources that circumvent the high costs of launch from Earth.

2. Lunar environment

The lunar environment imposes reduced gravity loading, high radiation and micrometeorite flux, a pervasive and abrasive dust problem, severe high-low temperature excursions, a high pressure-differential between interior and exterior lunar base environments, and material outgassing due to vacuum. The daytime temperature

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on the Moon reaches up to 400 K dropping to under 120 K at night (40 K in permanently shadowed craters). Internal heat flow to the subsurface during the lunar day ranges from 0.016 to 0.021 W/m^2; during the lunar night, heat loss is by thermal emittance from the regolith to deep space.

Lunar dust is a ubiquitous problem on the Moon due to high particle angularity imparting high abrasiveness on seals, optical surfaces, thermal surfaces and, for human missions, deleterious physiological effects. Fine-grained lunar dust is levitated by solar ultraviolet radiation during the day and by solar wind flux at night (Horanyi et al. 1998). Lunar regolith has increasing abundances of agglutinate glasses and nanophase metallic iron content with decreasing size (Gaussian average size is 3.0 μm) (Liu and Taylor 2008). Nanophase iron Fe^0 in lunar regolith appear as ~10 nm diameter inclusions within glasses produced by microtektite bombardment of the lunar surface (Keller and Clemett 2001). This nanophase iron significantly increases the oxidative reactivity of regolith due to the production of hydroxyl radicals through Fenton reactions with iron oxides (Wallace et al. 2010). There are a significant number of particles <2.5 μm which are regarded as toxic to the respiratory system. One way to minimize dust elevation is to implement transport via cable tracks supported at height above the ground by luffing masts (Benaroya et al. 2002). Dust mitigation to prevent settling of dust and their adhesion by van der Waal forces onto solar arrays, thermal radiators and optical surfaces may be achieved through several mechanisms, including vibromechanical, (electro)magnetic, and electrostatic removal. Although magnetic approaches are simple (Eimer and Taylor 2007), electrostatic are favoured as the most effective (Landis and Jenkins 2002; Calle et al. 2008; Clark et al. 2007). Seals such as gaskets may be used to eliminate leakage across mechanical barriers which can also provide dynamic spring action. Mechanical seals include double-shielded ball bearings, dust cups, brush/felt seals, z-seals, lip seals (e.g., s-lip), dust wipers, and o-ring seals (variants include v-rings, and t-rings). Most seals squeeze out voids under compression and, for pressure applications, the seal transmits external pressure radially. Seals constructed from silicone elastomer are appropriate for static applications. To account for thermal expansion, a rule of thumb is that the seal should be over-sized by 10% of its shrunken volume. PTFE dry seals are resistant to temperature excursions; however, composite seals comprise an elastomeric ring with a rigid PTFE working face. However, PTFE o-ring seals have been tested and found to be inadequate for high dust environments (Lauer and Allton 1992).

Lunar dust is also a significant problem for mechanical components such as motors and gears used on rovers, manipulators, drills, and manufacturing machines. Rotor/stator airgap, motor alignment, brush/commutator wear, gearing friction and meshing, sheave seating, connector coupling integrity, bearings and motor temperature are all detrimentally affected by dust contamination. Rotary seals are used for sealing between moving parts. While static seals rely on solid-solid contact, rotary seals require fluid lubrication such as silicone oil to minimize friction and wear. Magnetic fluid rotary seals can be used in vacuum and low pressures offering zero leakage for fluid sealing (Cong and Shi 2008). Two opposing magnets create a magnetic circuit and contain a ferrofluid. Ferrofluids are colloidal suspensions of paramagnetic particles of 10 nm diameter within a fluid which imparts paramagnetic behaviour to the fluid as a whole. The application of magnetic fields allows control of such fluids which can be used to seal two regions. This makes them ideal for rotary seals in motors. Nanophase iron may potentially provide the basis for ferrofluidic seals but this has yet to be explored. It is a potential resource for dust mitigation in motorized systems using magnetic seals (Kruzelecky et al. 2010).

Although lunar bases are currently to be emplaced at lunar poles at peaks of eternal light (with >75% sunlight time) for adjacent access to water ice in permanently shaded craters, access to minerals and volatiles will be required for maximum ISRU leverage (Staehle et al. 1993). Lunar lava tubes offer attractive sites for habitat locations affording natural protection; for example, there is a 50 m diameter skylight in a 100 m diameter lava tube 90 m deep in the Marius Hills at 303°E-14°N (Blamont (2014). It is plausible that such lava tubes may also be repositories of water ice. However, the currently favoured location for a lunar base is on the rim of the Shackleton crater within the South Pole Aitken Basin.

3. Varieties of lunar habitat

The lunar habitat's internal space provides a pressurized and filtered atmosphere with controlled temperature and humidity for its astronaut inhabitants at a minimum. Reduction of the internal habitat pressure requires an increase in oxygen concentration to maintain its partial pressure — 0.5–0.7 bar requires 25–30% oxygen. There are several approaches to the structure of a lunar base (Benaroya 2002): (*i*) spacecraft-type metal structure; (*ii*) inflatable structure; (*iii*) truss-based structure; (*iv*) fused regolith/basalt/concrete structure; (*v*) tensegrity-based structure; (*vi*) hybrid structure. A thin metal (nominally, aluminium) enclosure is simple but offers little shielding — typical spacecraft shielding is approximately 5 g/cm^2 Al but ISS offers 20 g/cm^2 in several locations due to passive shielding offered by payload racks. The latter is effective against proton penetration with energies under 100–200 MeV. This is adequate for a storm shelter against short duration solar proton events. For much heavier and energetic galactic cosmic rays, lightweight passive shielding with high hydrogen content such as polyethylene or water layer provides around 80% exposed dose reduction. Active magnetic dipolar shielding has been proposed to deflect incident particle radiation; however, the high magnetic fields require superconducting magnets which are impractical (Durante 2014). Aluminium shells are difficult to expand in size unless they are of modular design. Lunar bases should implement separate but interconnected pressurized compartments with sealable hatches at both ends to prevent catastrophic leakage of the entire base. Modules must include sleeping quarters (preferably individual), a galley, a communal wardroom, washing/heads facilities, a fabrication workshop, one or more scientific laboratories and stowage facilities. An inflatable structure is a lightweight fibre composite membrane but it is vulnerable to puncture. Hence, an inflatable structure forms the inner membrane of the habitat around which both stiffening and shielding structure is required. A truss-manufacturing facility has been suggested for in-space deployment which may be adapted for planetary deployment (Garibotti et al. 1980) — it is constructed from and produces a truss-based assembly necessary for large rigid structures. Geodetic tubular beams are constructed from rod feedstock simplifying manufacture while affording maximum flexibility of design. Truss and tensegrity structures require internal layers as they are open. A hybrid structure might include several elements such as an inflatable structure enclosed in a tensegrity frame covered in an outer layer of regolith.

It is typically envisaged that lunar base development will evolve through at least three phases. The first stage in the construction of planetary habitats may be in the delivery of one or more prefabricated modules that must be aligned either by crane or through mobility. Habitat designs tend to follow the modular tube designs of space stations the size and shape of which are determined by the launch fairing generating homogeneous but dull and sterile spaces. Minimum ceiling height is 3.5 m to accommodate ventilation shafts under reduced gravity. Mobile habitats (mobitats) may employ wheeled, tracked or legged locomotion but are limited to approximately 10 tonnes maximum — legs are capable of traversing rough terrain but suffer from control complexity issues compared with wheels and tracks (Cohen 2004).

The second stage may involve the erection of inflatable membranes requiring a degree of construction effort. Inflatables are typically constructed from fibre-reinforced polymer composites to provide tensile support offering compact storage with low specific mass of 3 kg/m^2. They are employed to form the sealed inner frame of a spherical, cylindrical or toroidal habitat.

The inner surface comprises a Mylar gas barrier surrounded by a tensile membrane of multilayer Vectran textile with Nomex for impact protection or Kevlar cloth. Around this, multilayer thermal insulation is sandwiched by an outer protective layer. An inflatable habitat has a structure from inside to outside comprising (Jablonski and Ogden 2008): (*i*) woven fabric for acoustic damping, (*ii*) inflatable multilayer polymer, (*iii*) multilayer thermal insulation, (*iv*) bladder layers for flame and puncture resistance, (*v*) impact protection fabric. A double-skin fabric membrane structure sandwiching a structural foam of polyurethane impregnated with gas has been proposed (Chow and Lin 1989). An inner inflatable wall based on structural tubes forming arched structures may provide a temporary scaffold during construction of the outer wall to keep the structure within the angle of repose of the regolith. Pressurized inflatables require a gas to inflate them — the only local in situ source of gas is oxygen (which is flammable) and water vapour (which requires elevated temperatures up to 120 °C). High temperatures can be tolerated if the hydrocarbon polymer is replaced by temperature tolerant silicone elastomer. Although inflatables are readily transported, they can deflate with disastrous consequences (though rigidized inflatables do not suffer this problem) (Benaroya 2002). Alternatively, erectable habitats from flat-packs using motorized rigid panels can autonomously self-assemble into polyhedral shapes (Ellery and Elaskri 2019) — such rigid panels may be constructed from local resources such as aluminium or cast basalt tiles. A hybrid approach involves an inflatable habitat with rigid segments; the habitat is inflated, whereas the rigid components must self-deploy and lock into position. The polymers of inflatable structures cannot readily be manufactured in situ, rendering inflatable habitats unsuitable for an in situ constructed lunar base.

The third stage involves the exploitation of in situ resources, initially for the construction of habitats and then incorporating construction machines themselves. We seek to leapfrog this phased approach directly to the third stage, a prospect provided by maximizing leverage of in situ resources that we address later.

NASA recommends a habitation volume of 20 m^3/person for short stays of several months, but long-term habitation requires 120 m^3/person. A floor depth of 4 m provides 3.0–3.5 m of height space (3.0 m is standard ceiling height), i.e., 30 m^2 of floor space/person. These requirements increase for bioregenerative life support; food production requires a further 15–40 m^2/person (nominally 20 m^2), waste-water recycling requires a further 3–5 m^2/person and oxygen production requires a further 6–10 m^2/person, i.e., a further 25–55 m^2/person. Most lunar bases are designed for 6–12 persons. With fewer restrictions on size compared with a space station, a planetary habitat can offer 120 m^2 per person to permit privacy and greater functional versatility of activities. There are several architectural network configurations of connected modular volumes — radial, ring, linear and gridded sets of modular volumes connected by tunnels — which control circulation through connecting modules, each module being dedicated to a specific function (Porter and Bradley 2016). A common shape for modules is a dodecahedral shape for rigid aluminium segments and spheres and cylinders of polymer skins for inflatable segments. The radial configuration requires several doors per module; the ring configuration requires two doors per module; the linear configuration requires only one door per module. The radial configuration offers direct paths that bypass other modules such as private quarters.

It is envisaged that lunar bases will not be isolated but will cluster to form a community of bases — the Moon Village. Roadways accommodate controlled traffic of physical material to and from a lunar base and between different lunar bases of the Moon Village. The Moon Village must be compact to minimize inter-base transport. Three types of costs are associated with the transport of goods that affect the relative merits of local in situ resource access and centralized mining: (*i*) haul costs which quantify the cost of haulage due to energy consumption during transport; (*ii*) overhead costs which quantify the cost of terminal equipment at that location; (*iii*) transfer costs which are costs of cargo transport required for support activities. It is desirable to reduce distances to minimize energy consumption and transfer costs such as access to energy and water supplies for ore processing. On Earth, transport by rail offers a balance between the low initial capital cost but increasing consumption cost of road transport with distance compared with high initial cost of cargo handling but insensitivity to distance of ocean transport. Rail requires some initial cargo handling facilities but the rise in cost with distance is modest favouring rail as a compromise. Modular metal rail segments may be laid and then welded together — thermite involves the exothermic reaction between powdered fuel (Al or Mg) and an oxidizer (silicon oxide or iron oxide) all of which can be recovered from in situ resources, e.g., $Fe_2O_3 + 2Al \rightarrow 2Fe + Al_2O_3$. The Zipf inverse distance law quantifies the volume of material N as inversely proportional to the distance D travelled:

$$N = \frac{k}{D} \tag{1}$$

A more sophisticated gravitational model declares that distance travelled is dependent on the strength of attraction imposed by additional factors such as terrain relief and obstacles.

$$N = k\frac{(w_i p_i - w_j p_j)}{d_{ij}^a} \tag{2}$$

where p_i = demand at location i, p_j = demand at location j, d_{ij} = distance between locations i and j, a = exponent of distance that determines the sharpness of attraction, $w_{i,j}$ = weighting factors that quantify other factors such as relief, and obstacles. This can be modelled readily by a potential field representation implemented on rover platforms, e.g., Frazier et al. (2014).

4. In situ compressive engineering materials

We first consider the primary structure of a lunar base as this comprises the dominant mass of the lunar base. Traditional universal civil engineering materials include stone, brick, lime, cement, sand, cement/lime/mud mortar, concrete, metals (steel, aluminium, copper) and glass. Plastic has been widely used as a substitute for many materials — one of the simplest plastics to manufacture is Bakelite, a synthetic phenol formaldehyde thermosetting resin formed through a condensation reaction of phenol with formaldehyde in the presence of HCl or NH_3 catalyst. It may be cast or moulded into heat-resistant non-electrically conducting shapes. The paucity of carbon on the Moon renders the manufacture of carbon chain plastics unsuitable unless they are recycled; thermosetting is difficult to recycle unlike thermoplastics. We wish to avoid the use of wood, plastic, organic paints, varnishes, and binders. In space, materials must exhibit low outgassing in vacuum which eliminates many plastics and adhesives, such as polyethylene, polyvinyl chloride, polytetrafluoroethylene, nylon, acrylics, and some metals, such as zinc, magnesium and most solders and some brazing alloys. Hydrocarbon plastics degrade when exposed to radiation and (or) temperatures exceeding 120 °C rendering them unsuitable for deployment on the Moon. Although polyethylene $(C_2H_4)_n$ is widely used as sealant and epoxy, these roles can be undertaken by silicones which have high radiation and temperature tolerance due to their silicate backbones. Appropriate in situ materials include steels, aluminium, titanium, nickel, tungsten, silicone plastics and ceramic substitutes for plastics such as alumina, porcelain, and glass. Our lunar industrial ecology produces the ceramics silica, alumina and rutile from lunar minerals and bulk metals aluminium and iron and associated alloying metals. We refer to the lunar industrial ecology in Appendix A that schematizes the basic raw materials extractable from the Moon.

Different options are available for the construction of primary structures from lunar material for lunar bases and other civil engineering erections. These include loose regolith, sintered regolith, cast basalt, glass/glass fibre reinforced composites, metals such as aluminium and various concretes, the most promising of which are cast regolith and lunar glass (Happel 1993). All these materials can be subjected to variants of 3D printing techniques. Concrete comprises aggregate, sand and binder - the binder (cement) is traditionally calcium silicate which, when water is added, hardens. The cement mixer was adopted for NASA's Precursor ISRU Lunar Oxygen Testbed (PILOT) to mix and heat the regolith in a tumbling reactor. Alternatively, an internal auger can stir the regolith without reliance on gravity. Terrestrial Portland cement is manufactured by roasting limestone or chalk ($CaCO_3$) and aluminosilicate clay in a kiln at 1450 °C to form clinker — a mixture of quicklime (CaO) with oxides of silicon, iron, and aluminium. The cooled clinker is combined with gypsum (which causes the cement to set) and powdered. The cement powder forms a paste when mixed with water to which sand and gravel are added to form concrete. It hardens through hydration reactions over time to form a matrix of calcium silicate hydrate. This yields large amounts of CO_2 ($CaCO_3 \rightarrow CaO + CO_2$) from the limestone accounting for 5% of all GHG emissions (Amato 2013). The furnace is also typically powered through fossil fuel combustion yielding further CO_2 emissions.

Sulphur concrete has been proposed as a lunar alternative to Portland cement with rapid setting to within 70%–80% of ultimate compressive strength within 24 h without the use of water. Sulphur cement has higher compressive strength than Portland cement. Sulphur concrete uses 12%–22% sulphur as a thermoplastic binder which is melted at 119 °C and mixed with any type of aggregate and then hardens. Sulphur concrete can be recycled by heating to 120 °C to melt the sulphur as there is no chemical reaction between the binder and its other components. A lunar version of sulphur concrete would be a mixture of 65% regolith with 35% sulphur which can tolerate sub-zero temperatures (Gracia and Casanova 1998). Unfortunately, sulphur has a low average concentration of 0.16–0.27% in high-Ti mare basalt (average 715 ± 216 μg/g), mostly in the form of troilite (FeS) typically associated with ilmenite; significant regolith must be processed to yield sufficient sulphur for large-scale concrete structures. Heating troilite in oxygen to 1100–1300 °C releases 80%–95% of its sulphur as SO_2 leaving magnetite (Fe_3O_4) (Vaniman et al. 1992). There are rare sulphide minerals as small grains in lunar regolith such as chalcopyrite ($CuFeS_2$), pentlandite ($(Fe,Ni)_9S_8$) and sphalerite ((Zn,Fe)Si) but these will be difficult to process. There are very small amounts sulphurous volatiles (H_2S and SO_2) in the regolith, and the Claus reaction of H_2S and SO_2 yields sulphur and water. Asteroidal resources however are more promising with achondrites offering a low concentration of under 1% of FeS-based sulphur rising to 5%–6% in some carbonaceous chondrites but can reach as high as 15%. Sulphur's melting point at ~120 °C prevents its use in environments where such temperatures are exceeded such as the lunar equatorial surface where its use would be marginal (temperature range +123 °C to −220 °C). Furthermore, the low ambient pressure ~10^{-10} Pa on the lunar surface renders sulphur prone to sublimation (Grugel 2008). Mass evaporation rate Γ may be estimated through the Hertz-Knudsen equation:

$$\Gamma = \alpha_v \sqrt{\frac{m}{2\pi RT}}(P_0 - P) \qquad (3)$$

where α_v = evaporation coefficient = 1 for sulphur (assumption consistent with values for metals and metal oxides), m = atomic mass = 32.06 for sulphur, R = gas constant, T = absolute temperature, P_0 = partial pressure of gas in equilibrium with its solid, and P = ambient pressure. At room temperature, sulphur sublimation rates yield a 5-year timescale to erode a 1 cm deep layer in sulphur concrete, sufficient to impose an integrity hazard and this will increase substantially with increased temperature. Thermal cycling between –190 °C and 20 °C yields an 80% loss in compressive strength of sulphur concrete due to differences in thermal expansion of sulphur and silicate. Indeed, sulphur concrete is limited to temperatures below 96 °C to due to its phase transition at 96 °C causing a 7% volume change that would cause cracking. We conclude that sulphur concrete is not practical because: (*i*) sulphur is not particularly common on the Moon compared with calcium and water; (*ii*) intolerance of upper lunar temperatures (up to 125 °C) and thermal cycling. Water appears to have greater abundance in polar regions than sulphur sources suggesting that more traditional Portland-type cements may be more practical.

Several other potential lunar cements are possible subject to minor constraints (Wilhelm and Curbach 2014; Ishikawa et al. 1992) — lunar pyroxene and plagioclase feldspar are sources of quicklime (CaO) (Mueller et al. 2016). "Lunarcrete" may be formed from melted individual minerals CaO, SiO_2, and Al_2O_3 at 3000 K and quenched and mixed with water. Portland lunarcrete would comprise 60%–69% CaO (nominally 64% CaO which could be sourced from high calcium anorthite with up to 19% CaO), 20%–24% SiO_2 (sourced from anorthite and (or) orthoclase), 3%–4% Al_2O_3 (sourced from anorthite) and 2%–4% Fe_2O_3 (sourced from ilmenite) mixed with in situ water which may be cast and cured under pressurized conditions to prevent water evaporation (Lin 1987). Concrete typically provides a compression strength of 30–40 MPa after a month of setting time. Rather than wet mix cement which is water-intensive (25%–40% water in Portland cement), injecting steam into dry cement (dry mix/steam injection) at 180–200 °C and elevated pressure for 18 h reduces the required water to a water/cement ratio of 15%–25%. It gives a compression strength of 70 MPa. Glass fibres or metal rebar may be incorporated into concrete as reinforcement to increase its mechanical strength. If 1% polyethylene imported from Earth were added to concrete, its radiation shielding effectiveness would be dramatically enhanced.

An alternative lunarcrete comprises 90% regolith with 10% thermoplastic (polyethylene) binder by mass which may be cast in moulds and heated to 230 °C for 5 h to cure into bricks with a strength of 12.6–12.9 MPa (Lee et al. 2015). This requires plastic binder to be transported from Earth as well as being unsuitable due to its tendency to outgassing. A geopolymer binder (aluminosilica activated by a solution of sodium silicate and sodium hydroxide) with 98% lunar regolith may be used to manufacture structural panels for radiation shielding and thermal insulation with a strength of 16–37 MPa (Montes et al. 2015). NaCl is already required to be transported from Earth as a recycled reagent for the lunar industrial ecology (Appendix A), but its use as a consumer product, concrete, is wasteful of a valuable material. It is best reserved as recycled reagents. Metals such as aluminium can be melted to which lunar regolith can be added to form a composite of 30%–40% aluminium with a compressive strength of 13.8 MPa. We propose that kaolinite clay may be employed as a wet binder with water resembling its use in terrestrial Portland cement. Kaolinite is a waste product of artificial weathering of orthoclase with HCl acid to yield silica in the lunar industrial ecology (Appendix A). However, the processing complexity of cement and its poor bulk structural performance suggest that it may be employed as a joining material. Alternatively, mortar is a paste used to bind bricks, and the simplest mortar is sun-dried clay. Kaolinite ($Al_2Si_2O_5(OH)_4$) is a clay produced through chemical weathering of aluminium silicates such as lunar feldspar (Appendix A). Ultimately, binding might be eliminated altogether, e.g., the Armadillo Vault is a 15 m diameter dome constructed from 400 limestone slabs without any adhesive.

Solar sintering of regolith eliminates the requirement for polymer, salt or clay binders. Sintering requires lower temperatures under the melting point to partially melt the powdered material followed by slow cooling to a solid. Compression pressure is required to reduce porosity and shrinkage. Regolith can be sintered into bricks at 1100 °C; sintered regolith has a high compression strength and mixing metal particles into regolith during sintering increases its tensile strength. A sintered regolith outer shell reinforced with ribs acts as a micrometeorite and radiation shield and offers good thermal insulation properties enhanced with a vacuum layer formed by the ribs. The vacuum gap insulates against conductive and convective heat losses. Sintering may be implemented by solar concentrators or microwave processing at 1000–1100 °C just below regolith melting temperatures. Microwave sintering exploits the ubiquity of nanophase iron in regolith that acts as thermal nuclei to rapidly melt it at 1200–1500 °C. Microwave sintering offers stronger binding than solar concentrator sintering. Regolith sintering may be extended to the surrounding terrain in the vicinity of the base comprising foundation and roadways to mitigate against dust generation. Sintering regolith with 15% steel powder yields a compressive strength of 55 MPa. Microwave-sintered bricks may be formed from nanophase iron-impregnated lunar regolith in an alumina crucible placed directly into a microwave cavity (Thiebaut and Cowley 2019). Refractory bricks may be manufactured through a geothermite reaction involving 33% aluminium powder mixed with 67% lunar regolith (incorporating mineral oxides silica, alumina and spinel) (Faierson et al. 2010). Refractory bricks also may be manufactured by mixing metal oxide particles with 5%–15% organic binder such as glycerol, clay/water or sulphur which is subsequently burned out. Automated robotic manipulation of large construction bricks is required for construction of structures. Self-assembly will require that bricks incorporate their own actuation and computing capabilities or that an external manipulator or crane is necessary. Bricks may be employed for constructing unpressurised gravitationally-loaded structures.

Cast regolith is melted in a furnace at 1200–1500 °C and cooled slowly in a mould for crystallization to occur to form bricks or panels. Alternatively, rather than regolith, lunar basalt may be open-cast mined with minimal blasting and crushed into <0.1 m sized pebbles. It may be melted in a furnace with preheating to maximize heating uniformity and reducing the melt time significantly. It is cooled slowly to ensure crystal growth to create large structural components such as foundations, roads, bricks, and compressive structures. Lunar basalt may also be sintered into glass (Pletka 1993). Lunar basalt comprises 15%–35% plagioclase feldspar, 40%–65% pyroxene, 0%–35% olivine and, most critically, 0%–25% ilmenite which lowers its melting point. The basalt is crushed into a fine powder and poured into a solar-powered furnace at 1180–1240 °C to completely melt the basalt, which requires energy of 360 kWh/Mtonne. Casting of basalt follows that of metal casting offering the means for creating simple civil structures with high temperature and high abrasion conditions, and cast basalt has been used in the Czech Republic, particularly for pipe manufacture. The molten basalt is poured into a mould and subjected to 5–10 MPa through isostatic pressing to reduce porosity. In sand moulds, basalt is cooled slowly from 900 °C to 50 °C to partially recrystallize. Basalt may be extruded as glass fibre with rapid cooling for use as composite reinforcement. Cast basalt has a reasonably high strength of 30 MPa. To reduce the brittleness of cast basalt to accommodate tensile loads, higher melting temperatures of 1200–1300 °C may be implemented (Rogers and Sture 1991). Basalt powder may also be sintered for up to 3 days at ∼1100 °C under compression to reduce its porosity and yield a compressive strength of 350 MPa for fine grained basalt (coarse grained basalt yields much poorer compressive strength). Sintering with native glass can densify basalt at much lower temperatures ∼800 °C. Several hours cooling of basalt structures is required to prevent large temperature gradients and thermal shock. This can be avoided through microwave heating enhanced by basalt's ilmenite fraction. It has been suggested that late-stage residual molten melts may be foamed using CO gas to manufacture lightweight structures with enhanced enrichments of K_2O or P_2O_5 (Roedder 1981) but carbon is a scarce material on the Moon rendering it unsuitable for bulk applications. Cast basalt has very high compressive strength and high-moderate tensile strength (much higher than concrete) for the manufacture of columns, beams, tiles, shells, bricks, arches and pipes under compression. It has high abrasion resistance and is suited to piping or pipe lining applications for iron or aluminium pipes, e.g., oxygen, water, and sewage due to high corrosion resistance. Much of the compressive load function of ceramics such as cast basalt could be undertaken by metal alloys which also have tensile load superiority. However, cast ceramics offer high heat and corrosion-resistance and low thermal expansion. Refractories such as alumina are essential for handling high temperature materials for industrial processing, e.g., linings for solar furnaces, and casting moulds.

5. 3D printing compressive structures

There are several tasks required during construction of a lunar base: (*i*) site surveying; (*ii*) rock removal and site levelling; (*iii*) excavation and trenching; (*iv*) pipe laying (*v*) cable laying; (*vi*) transport and deposit cargo; (*vii*) facility construction and installation; (*viii*) base assembly and finishing. The first task must be surface surveying which may be achieved during rover traverse. We have demonstrated the use of wheel load sensors and wheel motor current measurements on our 32 kg Kapvik microrover to extract continuous estimates of standard civil engineering soil mechanics parameters (soil cohesion and friction angle) derived from the wheel-terrain interaction models during the rover's traverse of sandy terrain (Cross et al. 2013). Prior to emplacement of the habitat, it is necessary to create foundations to flatten and solidify the surface. The next task is to deploy a bulldozing blade to robotically excavate a level foundation to a depth of 1 m or more on which a habitat can reside. Shallow subsurface surveying may be undertaken using ground-penetrating radar (GPR), and we have demonstrated field magnetometer surveys on our 32 kg Kapvik microrover (Hay et al. 2018). The excavated regolith from the foundation depth may be employed as an overlying radiation shield. Solidification of surface regolith may be achieved using a solar sinterer such as a mobile Fresnel lens which can achieve the temperatures required for sintering, e.g., Marcus Kayser's solar sinterer. Sintering lunar regolith using solar concentrators was demonstrated on JSC-2A regolith simulant over 5 h 30 m (McKay et al. 1996). The regolith surface may be pre-prepared by thermal fusing of regolith into a paved glass layer using a Fresnel lens. Fused foundations support buildings and solid smooth roads support rovers while reducing dust elevation during operational activities. This dictates the central role of robotic vehicles in lunar base construction. Recently, the application of cartesian robots for the construction of lunar bases has extended its criticality in the form of 3D printing.

Large compressive structures may be 3D printed though with low accuracy and tolerances. Automated construction uses large-scale robotics to overcome the typical limits of 3D printing but do not require high positioning accuracy. Freeform construction has been demonstrated on Earth involving robotic additive layering of concrete with high degrees of automation (Buswell et al. 2007). Selective deposition of Portland cement using steam as the binding agent is compatible with layer-by-layer construction of buildings. It eliminates standardized concrete blocks and proceeds in a different direction to the modular concept of prefabricated modules (Balaguer et al. 2002). Terrestrial automated building robots for constructing multi-story buildings are reviewed in

Skibniewski and Wooldridge (1992). The most common approach is the electrically powered crane concept since it can lift large loads while mobile robots cannot (Leyh 1995). The sensorised RoboCrane has a suspended deposition nozzle supplied with cement feedstock for extrusion (Williams et al. 2004). RoboCrane itself is a 6 degree-of-freedom inverted Stewart platform with 6 actuating cables suspended from a large rigid overhead crane. The sensors were three rangefinder lasers to measure the location of the extrusion head.

The All-Terrain Hex-Limbed Extra-Terrestrial Explorer (ATHLETE) is a robotic rover chassis that can be employed as a precise positioning mechanism for 3D printing large civil engineering structures on the Moon (Howe et al. 2013). As civil engineering structures, they would not require precision manipulation and may be constructed from local regolith including prefabricated bricks or 3D printing (such as contour crafting). ATHLETE itself is a six-limbed rover where each 6 degree-of-freedom revolute jointed (YPPRPR) limb terminates in a wheel for high terrainability. It can wheel walk with locked wheels on rugged terrain and roll its wheels over more benign terrain. A variety of sample acquisition tools may be employed by ATHLETE such as dozer blades, backhoe shovels (such as in a JCB configuration), drills, bucket wheels, drums, etc. (Howe and Wilcox 2016). Our own Kapvik microrover has demonstrated sample recovery using a backhoe scoop. Each ATHLETE limb also has a tool adaptor interface to substitute wheels for tooling to double as manipulators. The chassis mounts a freeform additive construction system (FACS) comprising the sixth limb mounting a printhead for additively manufacturing compressive structures (paving, walls, domes, vaults and shielding) on planetary surfaces (Howe et al. 2015). There are four proposed printheads for additive manufacturing: (*i*) a tunable microwave sintering head to sinter/melt regolith in situ (microwave may also simultaneously recover regolith volatiles (Howe et al. 2016)); (*ii*) fibre-optic solar concentrator to sinter/melt regolith through a quartz rod focus; (*iii*) concrete slurry extruder head from which the slurry hardens on laying; (*iv*) polymer binder extruder head that extrudes regolith mixed with binder (20:1 ratio of regolith-to-binder). SinterHab is a modular hybrid lunar base concept based on imported inflatable membrane structures with pre-fabricated foldable rigid segments supplemented with a protective outer shell of microwave-sintered 3D printed regolith (Rousek et al. 2012). The Sinterator demonstrator comprised the ATHLETE lunar rover equipped with contour crafting head with a microwave magnetron generator. The five limb-wheels provide gross positioning while the sixth manipulator provides fine positioning with ~mm accuracy. Ground beacons may be employed to increase the accuracy of rover navigation to permit construction, including additive construction, of elements of a lunar base. CAD models of civil engineering structures could be FAXed to the planetary rover from Earth prior to human crew arrival (Howe et al. 2013). The elimination of handling of large modules through 3D printing eases the design of the robotic mechanisms. Analogue lunar regolith has been LENS-3D printed into dense hard ceramic/glass parts without macroscopic defects using laser energies $\sim$2 J/mm^2 (corresponding to a laser power of 50 W at a scan speed of 20 mm/s with powder feed rates of 12 g/min) (Baila et al. 2011). Basaltic 3D printing of habitat structures on Mars (equally applicable to the Moon) involves melting basalt powder beds using solar concentrators (Kading and Straub 2015). Concrete printing involves the extrusion of cement mortar of 54% sand, 36% cement and 10% water by mass (Lim et al. 2012) though other cements are plausible.

A recent concept is 3D printing of compressive structures on extraterrestrial bodies based on regolith (Mueller et al. 2016) such as contour crafting (Khoshnevis et al. 2005) and D-shape (Cesaretti et al. 2014) both of which have many similarities. In these cases, lunar regolith is mixed with a binder and then extruded into layers to form the outer shells of lunar bases. Contour crafting is a gantry-based 3D printing technique involving extrusion of a material paste such as concrete through nozzles which is smoothed with robotic trowels to directly construct buildings layer-by-layer (Leach et al. 2012; Khoshnevis and Zhang 2012). The extrusion nozzle has a top trowel and an outer side trowel which smooth the outer and top layer of concrete (inner surface remaining unfinished) once deposited. A gantry mounts the nozzle on an overhead crossbeam carried by two vertical cranes running on two parallel rails with the nozzle moving laterally to build structures within its work volume. The cranes raise the nozzle platform at each pass. The gantry frame must be transported between construction sites similarly to a dragline. Reinforcement mesh, piping and cabling may be inserted into conduits within walls as the layers are built up (Khoshnevis 2004). The mounting gantry provides a more rigid frame than a crane but it must be transportable for multiple use (Khoshnevis et al. 2005). The mobile gantry robot essentially comprises two rovers connected by an overhead crossbeam. During transport, motor joint compliance will be essential to minimize stresses; however, once positioned, all joints must be locked.

D-shape is a 3D printing method suited to large scale construction in a single process that is similar to fused deposition modelling. It involves the extrusion of lunar regolith premixed with a binder which is deposited into layers. D-shape provides a means to directly construct the outer protective shell of lunar habitats in any shape (Ceccanti et al. 2010; Cesaretti et al. 2014). It employs a gantry-mounted deposition head on a large plotting machine. The printer is based on a spraying head which moves in the *xy* plane. It sprays a layer of regolith with the binding fluid acting as an ink at rate of 10–20 cm/s with an accuracy of 5 mm. The frame moves in the *z* direction to create the multiple layers. The print head comprises multiple nozzles to spray the material rapidly while a levelling blade and rolling cylinders level and pressurize the layer respectively. The binder fluid is ejected through a thin nozzle beneath the surface of the regolith layer to minimize binding fluid evaporation. The liquid binder is a saturated salt solution of $MgCl_2.6H_2O$ which reacts with MgO in the regolith in the ratio of 1:3 to form hydrated Sorel cement $Mg_4Cl_2(OH)_6(H_2O)_8$ with a compressive strength of 70 MPa. A chemical reaction between the metal oxide in the regolith and the liquid salt forms Sorel cement ($Mg_4Cl_2(OH)_6(H_2O)_8$) which solidifies the regolith. Metal oxides in the regolith include MgO, SiO_2, FeO, CaO, and Al_2O_3 but if not, 15%–30% MgO must be added. The formation of Sorel concrete as a mixture of MgO and $MgCl_2$ salt requires 70% water solution. Sorel cement sets rapidly within a few hours to yield 70 MPa compression strength within a few hours. To avoid the ink solidifying too rapidly, it is deposited in small droplets. The D-Shape process of mixing lunar regolith with $MgO/MgCl_2$ binder has been demonstrated on the construction of a 1.5 tonne foam block. The components of Sorel cement may both be derived from lunar olivine through the lunar industrial ecology (Appendix A) by exploiting olivine's instability to hydration:

$$\underset{\text{forsterite}}{Mg_2SiO_4} + 4H_2O \rightarrow 2MgO + SiO_2 + 4H_2O$$
$$MgO + HCl \rightarrow MgCl_2 + H_2O$$

These 3D printing methods are suitable for the construction of outer shells. An inner inflatable skin is usually proposed to provide a pressurized inner membrane for habitation whilst the outer 3D printed structure provides impact, radiation and thermal protection. To maximize the leverage of in situ resources, a more sustainable approach is possible which does not require the import of inflatable fabrics from Earth. At a minimum, the habitat structure must provide shielding against external factors and integrity against internal air pressure of approximately 100 kPa depending on the habitat air pressure design. However, a greater degree of physical security can be implemented using local resources. Inner structural walls of aluminium metal provide air sealing around which fused regolith glass fibre thermal insulation is sandwiched to an outer structural wall of basalt or fused regolith. Lunar regolith glass may be manufactured by melting regolith and cooling it rapidly, especially glass fibres drawn during rapid cooling. They may be employed for structural purposes in composites but are useless for optical applications (for optical components, fused silica glass may be manufactured from pure silica by melting it at 2000 °C and cooling it rapidly to prevent crystallization). Alternatively, mineral wool is formed by spinning or drawing of molten mineral or rock with applications for high temperature thermal insulation, fire-proofing, soundproofing, vibration-damping and as a hydroponic growth medium. Aluminosilicate wool is a high temperature ceramic wool made from melted Al_2O_3/SiO_2 in a 50:50 ratio with application temperatures up to 900 °C. Kaowool is a very high temperature mineral wool made from kaolin with application temperatures of 1650 °C. Ceramic-fibre cloth forms a similar structure to Chobham armour to provide a high degree of physical protection from significant meteor impacts as well as micrometeoroid flux. Either or both walls may be reinforced with metal ribs to provide tensile resistance.

An outer shell of unprocessed regolith may be piled at high angles of repose due to its high frictional properties to provide radiation protection. Bulldozing of regolith to emplace regolith shielding against micrometeorites, radiation and thermal extremes to human habitations is one relatively modest capability that can be conducted by appropriately configured rovers. More challenging to pack but easier to stack would be sandbagging of regolith (Weaver and Laursen 1992) deployed to form compliant space-filling barriers (Soleymani et al. 2015). While typical terrestrial annual radiation exposure is 0.3 rem (1 rem = 10 mSv), the annual radiation dose on the Moon at solar minimum is 30 rem but during a solar flare reaches 1000 rem — annual radiation dose for radiation workers is restricted to 5 rem (dropping to 0.5 rem for the general public). A 1.5–3.0 m (nominally 2.5 m) thick regolith layer is sufficient to provide radiation shielding $>$400 g/cm^2 to reduce annual radiation exposure from 0.3 Sv to 0.05 Sv (5 rem limit for radiation workers) (Silberberg et al. 1985) reducing the required thickness of aluminium from 10 cm to 1–2 cm (Pham and El-Genk 2009). Internal radiation storm shelter may be implemented within a water-jacket providing $>$700 g/cm^2 cumulative shielding to reduce annual radiation exposure to under 5 rem – unlike polyethylene used in submarines, water is available in situ. The thermal diffusivity of lunar regolith is low at 6.6×10^{-9} m^2/s and its specific heat capacity is high at 1000 J/kg/K at 500 K and 1400 J/kg/K at 1300 K. Its thermal conductivity is low at 0.1 W/m/K at 500 K and 0.4 W/m/K at 1000 K peaking to 1.2 W/m/K at 1400 K. Hence, lunar regolith is an excellent thermal insulator reducing the lunar temperature excursion of -170 °C to +110 °C ($\pm$280 °C) to $\pm$10 °C at 20 cm depth and $\pm$1 °C at 40 cm depth around an equilibrium temperature of -20 °C. Hence, the regolith outer layer affords a layer of stable thermal insulation.

6. The complexity of the lunar habitat

A lunar habitat is far more complex than mere structure. Any extraterrestrial habitat must serve stringent functional roles simultaneously to ensure mission success — protection against hazards such as radiation and micrometeorites, life support functions (including breathable air, comfortable working conditions of warmth and humidity, supply and processing of food and removal of wastes), and promote psychological well-being. It must also serve a utilitarian function such as a scientific research station or industrial control centre. A lunar base is typically zoned: (*i*) the habitat area is supported by other adjacent areas; (*ii*) scientific laboratory areas; (*iii*); logistical staging areas; (*iv*) power generator areas; and (*v*) mining and material processing areas for ISRU activities. Any lunar base must also have peripheral assets such as roads, utilities (power, water, air), storage facilities and launchpads as well as mining/manufacturing facilities (Benaroya et al. 2002). In particular, we draw attention to: (*i*) lunar basalt may be cast to form piping for the distribution of water, sewage, and air through the habitat; (*ii*) electrical cabling and insulation for the distribution of electric power and electronic routing of data may also constructed from in situ resources. These two fundamental lunar habitat infrastructure systems go beyond mere structure to provide deepened functionality to the habitat.

The modular lunar base comprises several different functional modules:

(*i*) Life support systems are crucial for recycling air and water while providing thermal control. Natural light is favoured directed through mirrors and (or) fibre-optic cabling. Photosynthetically active electric lighting is also required when and if mirrored sunlight is not available. This provides a major ingredient to the implementation of lunar agriculture for closed loop ecological life support through food production. Such bio-regenerative life support is preferable to physico-chemical life support - both food production and atmosphere/water recycling with waste management are simultaneously enabled through a dedicated agricultural module illuminated by a combination of natural sunlight and artificial light. Bioregenerative life support requires a high proportion of crew time for maintenance, typically 2.5 hours per day but gardening activities are psychologically beneficial. It has been asserted that weekly exposure of 120–200 min of recreational contact with nature affords optimal mental health benefit suggesting a minimum apportionment of horticultural activity among the crew (Douglas 2021). High efficiency hydroponics and aquaculture for high protein insects and fish provide the major food groups which must be tended by robotic tractors and harvesters. Agriculture must be supported by recycling facilities to recover volatiles of all major CHONPS elements and all minor elements such as selenium. In general, garbage must be disposed at discrete locations, collected and processed for recycling of material, which requires design-for-recycling with ready separability of multiple materials. These agricultural facilities should be modularized into a minimum of two garden modules for redundancy and robustness.

(*ii*) A bridge/control room that constitute the central facility for all activities within and without the base involving control panels, computers and displays connected to a sensor network to monitor its status. General cabin environment monitoring for life support includes measurement of radiation, pressure, temperature and concentrations of oxygen, carbon dioxide, water vapour, and organic volatiles. Multiplexed quartz fibres sensitive to specific analytes is enabled by end-coating them with specific thin film coatings giving differential reflectance (Ramsden et al. 2007). The depressed immunity of astronauts during spaceflight renders them vulnerable to microbial infection and tumour growth during extended, high stress missions. Microbial contamination through the habitat may be monitored using similar methods to measure microbial loading of aerosols in habitat air (van Houdt et al. 2012). A more invasive approach to health monitoring of astronauts is analyzing body fluid samples such as blood serum using flow cytometry with fluorescent dyed-labelling analytes in immunoassays (Jett et al. 1985). It is essential to monitor the lunar base environment through miniaturized flow cytometry and DNA assays (Cohen et al. 2008). Flow cytometry requires sampled biological cells (microbial load, blood samples, urine, mucus, etc.) to be pre-stained with fluorescent molecules. It involves passing a laser signal through the stained cell suspension with a filtered photomultiplier measuring the fluorescent response of the cells. Filters allow light intensity measurements at different wavelengths. A variety of stains are possible depending on the cellular properties to be investigated. DNA assay implements microfluidic lab-on-a-chip diagnostics based on optical readout-based microarrays with automated polymerase chain reaction (PCR) amplification. Substitution of optical readout with microcantilever arrays eliminates the requirement for fluorescent labelling (also applicable to protein array technology). However, DNA may be more appropriately sequenced using nanopore technology (Lu et al. 2016). Proteomics is also an essential complement to genomics as the two are coupled but not through a one-to-one mapping (Weston and Hood 2004). Electrophoresis or liquid chromatography with surface enhanced laser desorption/ionization time-of-flight (SELDI-TOF) mass spectrometry is used in proteomics for protein biomarker diagnostics. Protein microarrays such as immobilized antibody arrays provide protein profiling in which arrays of different antibodies can detect specific antigens. Protein arrays are much more challenging than DNA arrays as there is no protein equivalent to PCR and proteins are highly variable in their properties and are much less stable than DNA.

(*iii*) A wardroom with galley is where the habitat crew congregate socially to eat together at mealtimes, bond and prevent cliques from forming. The galley must be equipped with a range of food preparation machines (Perchonok et al. 2012) — oil press for extracting peanut or soya oil, breadmaker for processing wheat, tofu/soyamilk maker for processing soyabean, extruder, grinding mill, food processor/blender, microwave oven, convection oven, centrifuge, refrigerator/freezer for organic material storage including food (and medical samples), autoclave for cleaning utensils and 3D food printers for food preparation. Heating units, refrigerator and freezer required for medical applications are included as part of the galley.

(*iv*) Individual or communal private quarters include bed, desk and storage and should be located at the extrema of the configuration away from work areas.

(*v*) Laboratory facilities for scientific and engineering analysis with scientific instruments typical of planetary exploration. Laboratory facilities will require gloveboxes, vented fume cupboard and clean sterilization areas with pipette delivery systems. Scientific analysis tools (Gronstal et al. 2007) include sample acquisition, preparation and processing tools, imaging cameras (UV to IR for mineralogical analysis), close-up imager, quartz microbalance, thermometers, pH meters, UV filter microscope with slides and microbiological dyes, petrographic microscope with thin section saw, confocal microscopy, scanning electron microscopy, atomic force microscopy, radiation monitors, neutron spectrometry, gamma-ray spectrometry, X-ray diffraction/reflectance spectrometry, Raman spectrometry, laser plasma spectrometry, isotope-mass spectrometry, seismometry, thermal measurement probes and bevameters. All instruments may be connected to a handheld tablet/laptop with imaging camera.

(*vi*) A desirable optional feature is support for local robotic lunar telescopes especially on the farside or poles. Gamma ray, X-ray, ultraviolet, optical, infrared, submillimetre, microwave, and radio telescopy are possible (particularly for out-of-the-ecliptic viewing), but far-infrared/submillimetre, microwave and interferometry are the most favoured options at the farside. Earth orbit is adequate for gamma and X-ray telescopes; ultraviolet telescopy is in decline; optical/infrared is implemented at Sun-Earth L2; far infrared-submillimetre is the most information-rich region of telescopy for both cosmology, early galactic-stellar-molecular astrophysics and the Moon offers a radio-quiet location for activities such as SETI and a large stable platform for near infrared interferometric planet imaging.

(*vii*) Computing facilities for multiple uses — real-time monitoring and control of lunar base systems (though this is a bridge function), scientific and engineering analysis, and teleoperative control of robotic vehicles and imaging cameras.

(*viii*) Communications system for local and Moon-Earth information trunks will require radiofrequency antenna towers linked either by radiowave or underground/overground electrical data cabling — antennas are required for communications to Earth. There is the possibility of exploiting similar technologies to generate microwave energy for remote energy transmission and (or) for lunar regolith beneficiation.

(*ix*) Robotic workshop and tooling systems to support all non-manual operations within and without the lunar base. All equipment must be inspected, maintained, serviced, calibrated and repaired. The workshop includes small, powered hand-tools for simple manual bolt exchange and repair, and workshop-based saws, drills, milling, turning and 3D printing facilities (fab-lab) for major repairs and construction of jigs. Some typical parts that may be 3D printed include clamps, bolts/nuts, manifolds, tools, and containers; however, the size of a full catalogue of lunar base parts can be controlled using a limited number of standardized families of parts that can be re-used in many diverse applications. This is the same philosophy behind the modular spacecraft concept such as NASA's multimission modular spacecraft capable of reconfiguration. The test case of the value of this approach was the Solar Maximum Repair Mission (1984) which comprised two main repairs: (*a*) replacement of a designed-for-servicing attitude control module involved 4 simple single-bolt exchanges (Davis 1987); (*b*) replacement of a not-designed-for-servicing main electronics box involved exchanging 14 $\times$ 10-32 non-capture screws, 4 $\times$ 10-32 captive cap screws, and 22 $\times$ 4-40 slotted head connector screws (Adams et al. 1987). Clearly, standardization and modularity will be essential for maintainability and, by implication, initial construction. The initial construction machines are used for the maintenance and repair of the constructed products.

(*x*) All human bases are required to serve exploration missions with rover traverses for field surveying over challenging terrain being essential. Fleet of robotic electrically-powered vehicles/trains of various capacities from small autonomous surveying rovers to long-range fully pressurized human-rated vehicles are required for exploration, surveying and transport of material, equipment, and people. All, including human-rated rovers, should be teleoperable from the lunar base through UHF link. The large rovers are essentially mobile habitats for two astronauts for 14 days with an average traverse speed of 20 km/h giving a daily range of 160 km over 8 h or 480 km over 24 h. Each human-rated rover must be equipped with a robotic manipulator for payload handling, a winch for self-towing, a towbar for hauling a trailer. Drawbar pull is generated only by powered wheels. The inclusion of trailers provides a flexible means for adding greater hauling capabilities (though unpowered trailers do not contribute to rover drawbar pull). Although human-rated rovers reduce the requirement for EVA, it does not eliminate it. The simplest mode of EVA is to depressurize the rover after the personnel have donned their EVA suits. An airlock to the pressurized compartment reduces air losses. Alternatively, suitports may be used in which EVA suits are mounted to ports on the rover. Once the astronaut has entered the suit, another astronaut seals the port. All rovers must be modular to ensure interchangeability of parts, e.g., our Kapvik microrover sported a modular change-out chassis (Setterfield et al. 2014). All human handling for changeout must involve common EVA interfacing protocols, e.g., ESA (1995). Connector plugs must require no more than a single-handed single-turn to disconnect, and any connector installation/removal tool must not contact adjacent connectors — this requires a minimum of 40 mm between rows of connectors and 64 mm between staggered rows of connectors.

(*xi*) Cargo-handling facilities are required for loading and unloading transported materials input-output to the lunar base — this involves cranes for packaged material or LHD (load-haul-dump) vehicles for raw material. The latter are also workhorses for mining operations suggesting a natural evolution towards mining facilities.

(*xii*) Launchpad facilities must be co-located to the lunar base for Earth-Moon supply and transport route for cargo and (or) personnel. Currently, it is assumed that local water ice from the south pole will be mined, split into hydrogen and oxygen for cryogenic storage. Liquid hydrogen storage requires actively-maintained cryogenic temperatures below 20 K and typically self-leak at a rate of 3%/day, i.e., 100% loss in 30 days. The cryogenic propellant must be transported to the launch pad which must be at least 0.5 km away from the habitation area to prevent dust contamination by the rocket exhaust plumes. An alternative is electromagnetic launchers for Moon-to-orbit launch of cargo (McNab 2003) which do not generate plumes — this trades renewable electric power against the combustion of finite lunar volatiles.

(*xiii*) A lunar base supporting 6–8 personnel requires 200–300 kW of power, but this does not include ISRU activities which will require power levels ∼MW depending on the ISRU processes adopted. In a near-equatorial location, the base will have access to solar energy generation at 1360 W/m^2 during the 14-day lunar day and require stored energy to consume during the 14-day lunar night. This may be supplied through solar energy generation during the lunar day and energy storage during the lunar night from which areal calculations may be estimated based on energy conversion efficiency. A solar cell farm with an output of 500 kW with 20% efficiency would require an areal coverage of almost 4000 m^2 including night-time storage. Nuclear reactors such as a nuclear fission Brayton cycle reactor offer both energy generation and storage simultaneously but locating, mining, and refining fissile fuel would not be feasible on the Moon. During the lunar night, thermal insulation and electrical heating will be essential for the lunar base. During the lunar day, heat rejection will be necessary using thermal radiators. Radiating surfaces are typically aluminium louvres which can reject heat at ∼250 W/m^2 by radiation during the lunar day. At peaks of eternal light at the poles, solar power can be generated through most of the lunar day-night cycle. Electrical power generation, storage and distribution may be centralized and (or) distributed. All mining and manufacturing processes require large amounts of energy far exceeding that required by the lunar base. Solar photovoltaic arrays are generally assumed but there are alternatives — the problem of p-n junction doping of photovoltaics on the Moon is usually not addressed, yet it is crucial to in situ manufactured solar cell performances which are usually poor. Nuclear reactor systems are generally favoured for their sun-independence, providing energy generation continuously day and night though it exacerbates the heat rejection problem during the lunar day. A small number of crew can be supported by a 30 kW nuclear reactor. However, space nuclear power sources are not being developed and the exotic materials that they require cannot be readily sourced locally. We address construction of power generation and storage from in situ resources in the next section.

(*xiv*) Sickbay facilities are essential to support human health and in particular the treatment of trauma due to accidents. Telemedicine increases medical autonomy of crews by providing the capability for remote medical communication and intervention from Earth through remote diagnosis (Grigoriev et al. 1997). All sickbays must include basic medical equipment – stretcher/trolley, operating table, infection control equipment, defibrillator, anaesthesia machine with ventilator, patient monitor (blood pressure thermometer, pulse oximeter), ECG/EEG machines, fibreoptic endoscope, surgical lamps, blanket warmers, suction pumps, and electrosurgical unit. Autoclave, microcentrifuge, histological microscopes, PCR reactor, lab-on-a-chip biochip microarrays will be included as part of standard medical analysis facilities but many of the scientific instruments may have applications in space medical research as well as biomedical monitoring. Home-operated medical equipment for outpatients, dominated by respiratory support devices, kidney dialysis machines, oxygen therapy, insulin pumps, and infusion therapy, illustrate the potential for non-expert medical care (ten Haken et al. 2018). Miniature production of pharmaceuticals such Bio-MOD (medications-on-demand) is based on a compact modular system of devices driven by a pump (Arnold 2019). A replaceable cassette containing freeze-dried DNA, RNA, enzymes, cell extracts, and other biomolecules is incubated in a small temperature-controlled incubator-shaker to produce proteins. The cassette contents are then extracted and mixed in an extractor/mixer with solutions to separate the drug. Syringes inject buffering solution to wash the drug as it passes through purifying and polishing columns. The purity of the drug is monitored by a UV absorbence sensor <0.1% impurities. Suitable pioneer drugs include the antihistamine diphrenylhydramine, the anaesthetic lidocaine, the sedative diazepam, the antidepressant fluoxetine and the antibiotic ciprofloxacin. The analgesic acetaminophen may be produced by engineered *Synechocystis* sp PCC 6803 in culture from acetate. Live yeast such as *Pichia pastoris* can be engineered to produce drugs suitable for humans. Other techniques may be adaptable to pharmaceutical production. 3D printing has been used to print drug delivery systems encapsulated in synthetic polymers with accurate, controlled release characteristics (Yu et al. 2008). Machine learning algorithms may be employed to search the Suzuki-Miyaura space of chemical reactions for organic synthesis as a step toward automated organic chemistry through small scale experimentation with real-time monitoring by infrared spectroscopy, nuclear magnetic resonance spectroscopy and mass spectrometry (Granda et al. 2018). More complex equipment such as ultrasonic imagers, CT scanners and MRI imagers will be standard medical diagnostic tools. CT imaging is based on the variable absorption of X-rays by different tissues; MRI is based on nuclear magnetic resonance in which nuclei align themselves with an applied magnetic field with the emission of radiofrequency. In both cases, tomographic reconstruction produces 2D cross sectional images. Advanced trauma life support (treatment of airway obstruction, haemorrhaging, haemothorax and pneumothorax care) and advanced cardiac life support implemented on ISS permits medical evacuation within 24 h, an option unavailable to lunar base personnel (Drudi et al. 2012). This suggests that surgical intervention may be essential in the event of accidents which are likely given the hazardous environment and demanding astronaut task lists. Anaesthesia and surgery require skilled intervention which must be conducted by EMT-trained crew with on-site robotic surgery under cramped conditions (Houtchens 1993). For anaesthesia, barbiturate and ketamine-based intravenous infusion supplemented with narcotic bolus is favoured over epidural nerve blocking (Ball et al. 2010) (although gas is disfavoured, nitrous oxide is safe and simple to manufacture from urea, nitric acid and sulphuric acid: $2(NH_3)_2CO + 2HNO_3 + H_2SO_4 \rightarrow 2\ N_2O + 2CO_2 + (NH_4)_2SO_4 + 2H_2O$). Intravenous anaesthesia is reckoned to be safer than spinal anaesthesia due to microgravity fluid distribution (but the effect is diminished under lunar gravity). Blood released during surgery would form domes around the bleeding tissues due to surface tension which can be controlled with sponges and cauterization (diminished under lunar gravity). Internal organs tend to float if exposed under microgravity (diminished under lunar gravity). Telemedicine, a medicine practiced from a distance, will be a key capability in the delivery of surgical services (Haidegger and Benyo 2008). We assume that simple scientific and medical tools may be manufactured in situ through 3D printing but that complex diagnostic and robotic equipment must be imported from Earth.

(*xv*) Airlocks or suitports are required at multiple locations to support ingress/egress of people for extravehicular activity (EVA). Backup EVA suits are critical but certain critical safety issues must be addressed (Trembley 1994): (*a*) loss of carbon dioxide removal and cooling capability; (*b*) external leakage of oxygen; (*c*) suit overpressurisation; (*d*) rupture of pressurised oxygen bottles; (*e*) loss of primary oxygen supply; (*f*) oxygen fire; (*g*) LiOH dust in ventilation loop; (*h*) helmet fogging from dehumidification failure; (*i*) free water in suit; (*j*) decompression sickness. Internal gas pressure favours low cabin pressure with higher oxygen content to reduce buffering gases, minimize leakages and reduce EVA pre-breathing requirements. The Space Shuttle dictated two major protocols, the latter being subdivided into two options: (*a*) for 14.7 psi cabin pressure, 4 h of suit prebreathe was required; (*b*) for 10.2 psi exposure for 24 h, a 40 min suit prebreathe was required; (*c*) for 10.2 psi cabin pressure exposure for 12 h, a 75 min pre-breathe was required. Prior to the cabin depressurization to 10.2 psi, a 1 h mask prebreathe was required. The airlock must therefore implement pre-breathe protocols. EVA excursions will also be required from the pressurized rover as well as operating teleoperated microrovers deployed from the pressurized rover. The former involves potential hazards that should be minimized using the latter. The suitport eliminates the requirement for airlocks by externally mounting spacesuits on the habitat for EVA. Crewmembers climb into the back of the suit from an internal entry and then detach. However, the use of suitports require the astronaut to be able-bodied to step back through the port so injury might cause difficulty. At least one airlock is required with dust mitigation facilities to prevent interior dust contamination while minimizing air loss (nominally 10% losses) — a water spray can remove dust. EVA suits are rigid cocoons with only partial flexibility at the joints limiting astronaut posture. This makes EVA physically and mentally demanding. There are circumstances when astronauts may be required for longer and more demanding EVA excursions such as during habitat construction, upgrading, servicing and repair. The EVA suit may be augmented with exoskeleton gloves armed with force sensors and actuators to provide assistive capabilities to the astronaut to compensate for the high stiffness of pressurized suits (Matheson and Brooker 2012).

(*xvi*) Personal and base hygiene devices — air filtration to remove lunar dust, personal cleaning facilities, vacuum cleaners for removing dust and dirt and washer/dryers for cleaning textiles. Lunar dust is a ubiquitous problem and it can be extremely damaging for human health — seals/gaskets, moving parts and optical components are particularly susceptible to dust invasion (Kruzelecky et al. 2011).

7. Contribution of in situ resources to lunar habitats

We propose a fundamental list of basic universal materials required to leverage an entire extraterrestrial infrastructure (except the compressive structures considered earlier) extracted from a handful of lunar minerals (ilmenite, anorthite, orthoclase, olivine and pyroxene), asteroidal material (nickel-iron-cobalt-tungsten-selenium metal) and regolith volatiles (water and carbonaceous-nitrogenous-sulphurous gases): (*i*) wrought (pure) iron for tensile structures; (*ii*) tool steel (iron and tungsten alloy with small amounts of carbon) for subtractive manufacturing tools; (*iii*) electrical steel (iron and silicon alloy) for magnetically soft rotors; (*iv*) ferrite (cobalt-iron oxide) for permanent magnet stators; (*v*) permalloy (iron and nickel alloy) for magnetic shielding; (*vi*) kovar (iron, nickel and cobalt alloy with minor amounts of silicon and carbon) for high temperature electrical wiring; (*vii*) silicone plastic/oils from syngas for elastomeric electrical insulation; (*viii*) nickel for anodic/control grid electrodes and electrical wiring; (*ix*) tungsten for cathodic electrodes; (*x*) fused silica glass for transparent optical components such as optical fibres and solar concentrators; (*xi*) alumina as high temperature ceramics for kiln linings; (*xii*) silica for thermal insulation and pressure-sensitive quartz sensors; (*xiii*) quicklime for cathode coatings; (*xiv*) aluminium for electrical wiring and tensile structures; (*xv*) selenium for photon-sensitive sensing and imaging; (*xvi*) water as a hydrogen source for silicone manufacture; (*xvii*) silicate/oxide minerals as a general oxygen source; (*xviii*) kaolinite/porcelain as a ceramic matrix for soft magnets, electric motors, transformers and electrical insulation.

The manufacture of these functional materials comprise our lunar industrial ecosystem (see Appendix A) which describes all required thermochemical–electrical processes required to build and support an industrial infrastructure. All mineral oxides can be reduced to high purity metals using the Metalysis FFC process (Ellery et al. 2017). Our industrial ecology follows the principle that Earth-imported reagents that are recycled are favoured over those that are consumed (Waldron 1988) — in this case, NaCl salt which is required as a recycled reagent. Sodium in the form of bytownite, a minor plagioclase mineral, is more abundant in lunar highlands than the mare regions but it is highly depleted by an order of magnitude in comparison to Earth. Apatite $Ca_5(PO_4)_3(F,Cl,OH)$ is common mineral grain in lunar mare basalt and is the main carrier of Cl and F with a concentration of 1000–5000 ppm typical in apatite grains but Cl is required in quantities sufficient to justify its import from Earth (though it is recycled as a reagent rather than consumed as a product — it is crucial as HCl for pre-processing lunar minerals through artificial chemical weathering). Hence, NaCl is imported from Earth as a recycled reagent.

We focus here on how these lunar resource-derived materials can be employed to construct specific systems required for a lunar base. We have addressed elsewhere how lunar in situ resources may be leveraged to construct mechatronic components to construct robotic machines (Ellery 2016). Robotic machines comprise the means of production for leveraging a lunar base from in situ resources. Mining and manufacturing facilities (metals, plastics, glasses, ceramics and volatiles) including robots (including their cartesian variant – 3D printers) are essential for ISRU including for on-site supply of spares and component repair using 3D printing and recycling of waste material. The lunar base must be designed to ensure that materials are readily separable for recyclability so the base can be re-customized *ad infinitum*. Foundries must be automated and regulated. For example, a CVD (chemical vapour deposition) tube furnace system, Robofurnace, has demonstrated semi-autonomous thin film manufacture (Oliver et al. 2013). In general, the key to automation is the sensor suite to provide observability with closed loop control — thermochemical processing will require a distributed set of temperature control, pressure control and gas detection systems. Lunar material-derived compressive load-bearing constructions require manufacturing facilities (regolith-derived material, cast basalt, glass, etc.) supported by civil construction equipment including cranes, bricklaying machines, and 3D printers. Similar paving machines are required for site preparation and road construction - the same paving robots provide for both construction of roadways and foundations and their maintenance and repair. Surface roadways for transport may be paved or railed which require robotic rovers to deploy. Subsurface facilities are favoured for physical and thermal protection, especially for utility piping and storage facilities, e.g., lava tubes. Subway tunnels may be implemented as an alternative, safer mode of transport for people between modules (minimizing airlocks) over surface roadways. Subways are also used in several types of subsurface mines — subways are generally railed. Subways tunnels must be constructed by tunnel boring (drilling) machines with railway tracks laid for subway carriages. 3D printing or sintering a borehole lining as drilling proceeds can protect against borehole collapse. All infrastructure (roadways, electrical cabling, pipelines, etc.) and all equipment must be maintained and repaired serving all aspects of the lunar base — this should be accomplished remotely robotically. Furthermore, maintenance and repair must be undertaken assuming minimal stock of spare parts to minimize wastage imposed by warehousing. This implies that spare parts must be manufactured on demand in situ. Robotic leverage will be key to the construction and maintenance of lunar bases.

The lunar base power system must also be leveraged from in situ resources. Direct thermal power generation is essential for physico-chemical processing of raw material — this is likely to be generated locally at demand due to the inefficiency of thermal pipelining and even greater inefficiency of solar-electrical-thermal conversion. Thermionic conversion from solar concentrators represents a promising technique because of its compatibility with thermal sources by solar concentrators required for their in situ manufacture (Ellery 2019). Waste heat from the conversion process can be exploited for space heating rather than radiated to space — typically, approximately 50% of waste heat could be recovered, stored and transmitted as hot water. Electrical energy storage during the two-week lunar night is a challenge — large battery or supercapacitor banks are not feasible but rechargeable fuel cells and flywheels are options. Flywheels in particular are attractive for their favourable characteristics of manufacturability from in situ resources (Ellery 2019). They may be installed below ground for safety.

Here, we focus on the construction of electrical cabling, water pipes and air ducts — these will require the excavation of cavities or the ability to 3D print such cavities in wall-ceiling-floor structures for piping/cabling and other prefabricated units. The nominal power rating for a spacecraft is 28 V DC but the ISS generates 160 V DC for electrical power distribution over a larger area. Higher voltage distribution over distances beyond 100 m require AC transmission as used terrestrially, a common choice being 240 V AC at 60 Hz. Underground/overground electrical power cabling will be required to distribute electrical energy to multiple demands. Electrical cabling will require metal (aluminium) conductors that are integrated within an electrically insulated structure. Electric power cables comprise arrays of conducting wires with multiple layers of protective flexible insulation. Bare wiring and cabling may be buried in regolith which itself provides electrical insulation but this does not accommodate wiring interior to the habitat. The most appropriate form of electrical wiring for a lunar base manufactured from lunar resources is knob-and-tube wiring. The porcelain conduits prevent conduction between the conductor and the structural material with which it might react (aluminium metal reacts with alkalis in cement). Knob-and-tube wiring may comprise of single-insulated aluminium conductors running within wall/ceiling cavities using protective insulating tubes of porcelain through which wire is passed. The wires may be wrapped in fibreglass cloth. The porcelain tubes are supported periodically by cylindrical porcelain knobs nailed to walls or ceilings. Porcelain bushings, junction structures and other standoffs may also be used for more complex connections using fibreglass cloth to provide flexible insulation for damping. Porcelain is a ceramic material formed through firing kaolin (china clay) — a paste rich in kaolinite but including feldspar and quartz — in a kiln up to 1400 °C (both of which are derived from lunar resources). Once fired, it has high corrosion-resistance, electrically insulating to high voltages and resistant to thermal shock. Knob-and-tube wiring is robust and safe.

Life support systems are required to support human life in the lunar habitat at multiple locations including the supply and regulation of air, moisture, temperature, and pressure. This requires pumped air circulation and sensor arrays. Temperature control requires distributed heating (thermal radiators) and cooling (fluid circulant) systems which impose convection currents that must be exploited for thermal control. Air ducts are typically metallic - usually aluminum alloy - which provides a protective oxide layer but non-rusting stainless steel is a possibility. Silicone plastic is unsuitable as a sealant coating as it is permeable to gases though it is impermeable to liquids. Fluid handling in general is an important aspect of ISRU involving sedimentation, lubrication, heat transfer and pumping. Even unit chemical processors are reactor cavities in which motorized pumps maintain the flow of reagents/products. Motorized pumps control the flow of fluids through pipes and ducts. Pneumatic conveyance of material in a pipeline is determined by the minimum "saltation" velocity (Sullivan et al. 1994):

$$v_s = 14.77\mu^{0.375}\sqrt{g} \tag{4}$$

where μ = solid/gas flow ratio dependent on gas pressure. This implies that saltation velocity decreases somewhat with reduced g.

Water supply may be mined from water ice with oxygen supplied from oxide mineral extraction. Water must be piped to multiple demand sites — this includes domestic and industrial uses but must be regulated as a scarce resource. Similarly, sewage waste must be collected from multiple distributed toilet locations, piped with water and processed to extract water for recycling and to produce solid manure for agriculture. A plumbing system of water/sewage pipes with valves and regulators is required where multiple pipe segments must be connected but allow access by robotic pigs for maintenance and repair of leaks. They must incorporate pumps and valves to control pressure and drive water transport from water storage tanks. Engineering piping is typically designed to minimize construction costs so pumps must be powerful to drive fluids through their small cross section. Biological systems minimize pumping energy so pipe cross sections are optimized. Hence, there is a trade between material and energy (both manufacturing and operational) that must be determined. Cast iron or stainless steel pressurized water pipes are durable and leak-free. Water pipes will require silicone plastic or cast basalt interior for water sealing. Lunar regolith offers high thermal insulation which may be exploited by burying water piping and water storage tanks supported by pumps. Reduced gravity reduces buoyancy-driven convection and sedimentation but under lunar gravity conditions, diffusion will not become dominant as the primary mechanism for fluid mixing (as it would be under microgravity conditions). The reduction in convection is not as severe as in the microgravity environment but may nevertheless require compensation through capillary effects and (or) active fluid pumping. Under partial gravity conditions, fluids exhibit special behaviours (Ostrach 1982). Fluids are subjected to buoyancy-driven convection but there is a balance between buoyancy and viscous forces that yield fluid velocities determined by different regimes:

$$\begin{aligned} V &= \frac{\beta g \Delta T L^2}{\upsilon} = Gr\left(\frac{\upsilon}{L}\right) \text{ for } Gr \le 1 \text{ and } Ra \le 1 \\ V &= \sqrt{\beta g \Delta T L} = \sqrt{Gr}\left(\frac{\upsilon}{L}\right) \text{ for } \sqrt{Gr} > 1 \text{ and } Pr < 1 \\ V &= \frac{\sqrt{\beta g \Delta T L}}{\sqrt{Pr}} = \sqrt{\frac{Gr}{Pr}}\left(\frac{\upsilon}{L}\right) \text{ for } \sqrt{Gr} > 1 \text{ and } Pr > 1 \end{aligned} \tag{5}$$

where L = characteristic length, β = volumetric expansion coefficient, $Gr = \frac{\beta g \Delta T L^3}{\upsilon^2}$ = Grashof number (buoyancy term), $Ra = PrGr$ = Rayleigh number, $Pr = \frac{\gamma c_v \mu}{k}$ = Prandtl number, $\gamma = \frac{c_p}{c_v}$ = ratio of specific heats. Under low gravity conditions, there are increasingly influential surface tension gradients such as Marangoni convection. Marangoni instability occurs when there is a gradient of surface tension at interfaces analogous to buoyancy gradients generating complex thermocapillary convective fluid flow patterns. Under low gravity conditions, the relative importance of gravity to surface tension quantified by the Bond number $Bo = \frac{\varrho g L^2}{\sigma}$ is reduced where ρ = fluid density, L = characteristic dimension, σ = surface tension. On Earth, gravity suppresses surface tension except under configurations of very small dimensions. Marangoni number is given by $Ma = PrRe$ defining thermocapillary flow. For viscous flow, $Re\left(\frac{D}{L}\right)^2 \ll 1$ where D = perpendicular length scale to L due to negligible inertia so surface tension is dominant with $\frac{GrAr}{Re} = Bo\beta\Delta T$ where $Ar = \frac{gL^3\rho_0\Delta\varrho}{\mu^2}$ = Archimedes number due to density differences. Velocity of Marangoni convective turn-over is given by:

$$v = \frac{2\nu}{L}\left(\frac{ma}{Pr}\right)^{1/3} \tag{6}$$

where ν = viscosity, m = convecting mass, Pr = Prandtl number. Wetting due to contact angle at solid/fluid interfaces such as pipes is also affected by the gravity field. Diffusion as mass transfer of a fluid induced by a concentration gradient may also be affected by gravity. Water filtration may be achieved with permeable (unglazed) porcelain filters that exclude any microbes above

0.2 μm in size. The Chamberlain filter is an inner porcelain pipe sleeve through which outer pipe water percolates to yield filtered water within the sleeve. Similar issues apply to chemical reactors as the core of a chemical plant that converts raw material into a final product. They usually involve multiple phases of material: gases, liquids and (or) solids that require different handling mechanisms. Networks of reactors are connected by piping to convey streams of fluids, slurries or gases between them. These transport processes involve the transfer of mass, momentum, and heat.

Internal aspects of habitation and other modules such as furnishings for human comfort and aesthetics have not been addressed before. Individual quarters provide privacy and the opportunity for personal intervention. Individual and cultural tastes vary in the attribution of beauty and style and may be expressed through interior decoration within the living spaces of their habitat to prevent monotony. Internal decorative flowers that provide life, colour and beauty will be essential. The ornamental French marigold plant *Tagetes patula* has been grown on a terrestrial anorthosite analogue substrate using microbial communities including Bacillus species to release metal ions (Kozyrovska et al. 2006). All furniture must be designed to accommodate reduced gravity conditions. Reduced gravity has a debilitating effect on bone and muscle metabolism necessitating extensive exercise facilities. Roombots is a concept in which building blocks may self-assemble into mobile furniture which locomote on the basis of neural net-based central pattern generators (Sproewitz et al. 2009). Each truncated spherical Roombot module comprises three motorized joints with a high gear ratio gearbox including a diametric axis, an independent controller and slip-rings for electrical energy supply. Active mechanical connectors provide robust but reversible attachment between modules. However, we assume that furnishings will take a more traditional form. There is no reason that furnishings cannot exhibit the warmth of a Victorian reading room rather than the starkness of a submarine cabin.

Drywall is gypsum ($CaSO_4.2H_2O$) plaster which may be mixed with fibreglass. Hydrated gypsum ($CaSO_4.2H_2O$) plaster mixed with glass fibre can be sandwiched between fibreglass mats to form plasterboard for internal walls and ceilings; however, sulphur is not plentiful but must be husbanded. Kaolinite (and other) clays that constitute the waste products of the lunar industrial ecosystem (Appendix A) may be used sun-dried as plaster. Cement, as discussed earlier, is preferential to clay for its greater hardness and may be employed as mortar with regolith and water. Sodium silicate (Na_2SiO_3) — waterglass — has multiple uses as a binder, as high temperature insulation, as an adhesive, a flocculant in colloids and in the production of silica gel. It is manufactured from caustic soda and silica with hot steam in a reactor (though sodium must be imported from Earth):

$$2NaOH + SiO_2 \rightarrow (Na_2O)_xSiO_2 + xH_2O$$

Sodium silicate is often used with vermiculite or perlite for a wide range of uses. Perlite and vermiculate are lightweight refractory materials that can be moulded into fireproof insulation and wallplaster or mixed with Portland or other cement for lightweight roofing and flooring. Vermiculite is a hydrous phyllosilicate clay used as a growing medium in soilless hydroponics due to its retention of air, water, and nutrients. Artificial forms of vermiculite or perlite may potentially be manufactured from lunar resources: artificial perlite may be formed from lunar glass comprising 70%–75% silica and 12%–15% alumina with other metal oxide constituents impregnated by 3%–5% water; expanded vermiculite-like clays may be formed through heating lunar mineral-derived clays in a rotary kiln to 1200 °C in which released gas bubbles — primarily water — form a honeycomb structure. Natural materials should be emulated such as walnut dashboards for consoles, porcelain (vitrified kaolin) tile flooring (including classical black diamond in white patterns or wood-like effects), faux wood-like polylactic acid (derived from corn starch) panelling on walls and wood-look painted furniture. The garden carpet is a woollen floor covering depicting a bird's eye view of a Persian garden with highly styled arrangements of a central island within a water stream with typically four tributaries dividing the carpet into four quadrants surrounded by a tree-lined perimeter and the garden populated with shrubs, flowers, fish, birds, and animals. Garden carpets can be transplanted anywhere and they served to beautify nomadic tents throughout the Middle East becoming more stylized and variable in design over time under Islamic influence but retaining their floral motifs. Although wool is impractical for a lunar base, silk from silkworm is feasible but requires large-scale production for textile carpets as a possibility.

Coloured paints may be manufactured from local resources — ochre is a mixture of clay and haematite offering colours from mustard yellow to earthy red, both products are within the lunar industrial ecosystem (Appendix A). The addition of small amounts of manganese oxide, if it can be sourced (but not part of our industrial infrastructure), provides sienna, a browner hue. These colours are natural earthy colours. Other pigments that may be sourced locally include white (TiO_2) and black (Ti_2O_3) derived from ilmenite. Egyptian blue $CaCuSiO_4O_{10}$ may be manufactured from heating hydrated copper carbonate, quartz sand, calcium carbonate and a small amount of natron (mixture of hydrated soda ash and baking soda):

$$Cu_2CO_3(OH)_2 + 8SiO_2 + 2CaCO_3 \rightarrow 2CaCuSi_4O_{10} + 3CO_2 + H_2O$$

However, copper is rare on the Moon eliminating this form of blue pigment. However, cobalt blue may be manufactured by sintering cobalt oxide with alumina at 1200 °C to form $CoAl_2O_4$. If Cr_2O_3 can be sourced (chromite is relatively abundant on the Moon but does not form part of our lunar industrial ecology as its extraction would impose significantly greater complexity), then this provides green but this may otherwise be created by mixing cobalt blue with yellow ochre. Walls may be painted earthy brick-red/burnt-orange in relaxation areas contrasting with colder blue/green (such as teal) in work areas, earthy green or blue in the galley and sterile off-whites (such as haematite-tinged battleship grey) to reduce glare in the sickbay and laboratories to demonstrate cleanliness.

External views of the monotonous planetary environment may be substituted by polymeric wallpaper or screens displaying seasonal, mountainous, forest and coastal views and noises for stimulation and (or) relaxation. A common arrangement for living areas has been the relationship between building and garden. This illustrates the importance of one or more greenhouses. In the broader context of the Moon Village, an inspiration might be the garden city design. Gardens are not a luxury but a necessity — the garden city movement in urban planning combined town and country elements and was initiated by Sir Ebenezer Howard in 1898 inspired by Edward Bellamy's novel *Looking Backward 2000–1887* (1888). The garden city was based on self-contained urban communities surrounded by greenbelts for agriculture and public parks with radial boulevards for high sustainability. The most representative examples of the garden cities are Letchworth (1899) and Welwyn (1919) garden cities both in Hertfordshire UK, but it evolved into the New Town movement including modernistic variants like Milton Keynes (1967) in Buckinghamshire. Lunar bases must incorporate gardens into their functionality.

A variety of potteries can be manufactured in situ from lunar resources. Porcelain is formed by heating kaolinite to 1200–1400 °C. Although invented in ancient China, Chinese porcelain characterized by its blue-and-white wares was exported via the Silk Road by the Ming dynasty to Renaissance Europe. English bone china is a variant of porcelain that includes 50% bone ash (with its high CaO content) developed in 1748 to compete with Chinese porcelain culminating in the beautiful Royal Crown Derby, Spode, and Wedgewood bone china wares. Underglazing prior to firing had traditionally been limited to cobalt blue yielding the traditional blue and white porcelain. More decorative overglazing post firing involves the use of vitreous enamel formed by fusing powdered glass mixed with pigments at 750–850 °C for a greater range of colours. Although it is unlikely that extraterrestrial resources could be returned to Earth (Craig et al. 2014), perhaps, the next evolution in porcelain products will be high-value wares constructed from lunar minerals and imported back to Earth with returning astronauts.

Soft furnishing and climbing vine vegetation on walls reduce acoustic noise from rotating machinery. Soft furnishing may be provided as a byproduct of an agricultural facility from silkworms (edible protein source) and hemp (which has a wide range of uses unlike cotton). Although tweed is usually woven from sheep's wool, tweed may be woven from plant fibre such as hemp which has high durability with a texture similar to that of cotton while exploiting the earthy dye colours.

Self-cleaning of lunar dust and dirt in general in a lunar base would be a highly desirable capability. Colloidal particles in suspension can be excluded from hydrophilic surfaces such as Nafion, a perfluorosulphonic ionomer comprising a polytetrafluoroethylene backbone with side groups terminated by sulphonate ionic groups (Klyuzhin et al. 2008). Nafion exhibits a surface electrical potential of −160 mV and particles suspended in water solution migrate away from such hydrophobic regions. The lotus (*Nelumbo nucifera*) leaf exhibits a self-cleaning property by virtue of its nanostructured surface - its surface is covered in a variety of waxes forming self-assembled nanostructures which determine the surface's low wettability (hydrophobic). Hence, self-cleaning requires water for its operation as it exploits the higher affinity of particles for water. Instead of Nafion, thin films of silicone may be used as thin film coatings. Nanostructured surfaces comprising nano-hairs can trap particles at their apices preventing particles from abrading the surface. Nanoparticles of TiO_2 (derived from lunar ilmenite) have both hydrophobic and photocatalytic properties. It has applications in surface photocatalysis for UV light-assisted production of water in the presence of ethylene or other organics (Fujishima et al. 2008):

$$TiO_2 + C_2H_4 + 3O_2 + h\nu \rightarrow TiO + 2CO_2 + 2H_2O$$
$$TiO + {}^1\!/_2 O_2 \rightarrow TiO_2$$

This is the basis of thin film <20 μm TiO_2 surface coatings decomposing organic contaminants in the presence of solar UV light as the basis of self-cleaning and antifogging including disinfecting indoor air and contaminated water (Fujishima et al. 2000). These technologies have yet to be explored in the context of lunar bases.

8. The selenic architectural style

If constructed from in situ materials, the design of lunar habitats will no longer be restricted to launch fairing volume constraints. Furthermore, local in situ materials introduce a wider choice beyond traditional spacecraft aluminium alloy permitting deeper exploration of architectural styles. Architecture attempts to shape the landscape to human needs and desires for living and working through the construction of buildings. Because the lunar landscape is not natural for humans, we must shape it to resemble our natural landscape on Earth but within the constraints imposed by the Moon. Psychological stresses are chronic due to astronaut isolation from the norms of human social life; astronauts experience extensive confinement within the habitat imposed on them by the need for protection against the hazards of radiation, micrometeorites, large temperature excursions, vacuum, dust, and reduced gravity. We expect that most external explorations would be conducted robotically to minimize the dangers of EVA sorties which will increase their sense of confinement. These psychological considerations impose further requirements associated with aesthetic.

Architectural design of space habitats must consider the psychological effects of long-duration spaceflight by contributing to an ambience of well-being for the human occupants (Martinez 2007). The environment is experienced through the senses — light intensity, colour, acoustics, smell, and texture. Light is the most important calibrator of the human circadian clock which control the entire human metabolism; if it is out-of-kilter, it causes seasonal affective disorder (SAD) (Kolodziejczyk and Orzechowski 2016). Windows represent structural weak points for crack initiation in the structure, so natural light should be transmitted into and throughout the habitat via mirrors. Solar-like lighting and ambient colour should follow circadian rhythms with a central skylight in each module enabled by mirrors. Smell evokes strong associations, e.g., scented flowers. Visual appeal is an obvious approach, e.g., walnut dash can mellow the starkness of instrument panels. The green zone is a state of experience that is harmonic with the environment. Nature is an important part of psychological experience through plants and their arrangement in space and their association with other aspects of the environment (Kaplan and Kaplan 1989). Mental health is enhanced by experience of the natural world as a product of evolutionary psychology (Bratman et al. 2012) — this is the biophilia hypothesis. Naturalistic landscapes such as gardens, meadows, trees, and waterways induce positive emotional states and reduce cognitive stresses. Greenhouses may thus serve an essential psychological function as well as physiological one in closed ecological life support systems. As well as individual well-bring, social well-being must be maintained in minimizing conflict. Fine art, which includes architecture as well as painting and sculpture, was the quest for beauty, and nature is the embodiment of beauty. Humans evolved in grassland and savanna environments inspiring landscape aesthetics such as John Constable's paintings of natural landscapes rather than dark satanic mills. Modern art and architecture have become divorced from nature, devoid of its fundamental quality. Decoration has been entirely omitted from architecture due to the expense of craftsmanship. Modern mass-produced architecture, found in every North American city, is characterized by steel frames, concrete cladding, prefabricated panels and extensive use of glass to minimize cost, and so, minimize individuality. Enrico Dini envisages 3D printing re-introducing decorative architecture at low cost (Dini E (2018) private communication). Perhaps 3D printed lunar bases can sport traditional decorative features like balconies and balustrades, columns and cornices, facades and fanlights, eaves and gables, pediments and porticos, bays and oriels, columns, cornices, and mouldings. For psychological reasons, it is essential to harmonize the artificiality of the environment within a lunar base with naturalness and beauty of form. Natural construction seeks to retain the elan vital of the natural world in architecture through orderliness, growth through deploying structures, sensibility to environmental conditions, and energy transduction and management (Gruber 2008). An example is biomimicry as a natural architectural style that improves ecological integration and balance regarding biological form, process and ecosystem (Arslan 2014). Biological principles have also been applied to environmental issues related to the wider urban infrastructure (Tarr 2002) — cities require many environmental inputs and generate waste but must reach equilibrium with their environment to survive. They effectively metabolize land, air and water which are subject to conflicts such as the conflict between clean air and the requirement for energy.

Biomimicry-style architectures may be applied to reversible deploying structures common in nature including folding/unfolding (e.g., plant leaves, insect wings, flower petals), rolling/unrolling (e.g., probosci, ovipositors) and tensegrity structures (Gruber et al. 2007). Tensegrity is a structural engineering technique developed by Buckminster Fuller (Motro 2012; Yu et al. 2008). The extraction of specific tensile (iron or aluminium) materials and compressive (ceramic) materials from in situ resources introduces the possibility of tensegrity-based structures. Tensegrity structures comprise lightweight configurations of compressive struts and tensile cables in a balanced self-stressed state that is robust to perturbations. The hallmark of tensegrity structures comprises prestressed tensile cables enclosing compression bars in equilibrium thereby imparting rigidity to the entire structure. Actuators may be implemented to alter cable lengths to reconfigure the tensegrity structure, say, from initial configuration to its final configuration. The point to note is that actuators are fundamentally involved in all mechanical processes inherent in a lunar base. Of course, a space habitat is not embedded with an ecosystem but implements an artificial one directly. Sustainability is a related ecosystem concept that emphasizes our responsibility for stewardship of our environment. This has two interpretations: the pragmatic whereby sustainability relates to future human needs and the sacred whereby sustainability has a theological, even pantheistic, foundation.

The use of bonded regolith and basalts permit compressive structures such as bricks, columns, beams, arches, vaults, and domes. Andrea Palladio's *Four Books of Architecture* (1570) founded the Palladian architectural movement that emphasized classical Roman architectural forms including the influence of Vitruvius: the first book concentrated on the five classical orders and other building elements; the second book discussed his own designs of urban and country houses around Venice; the third book covered city planning of streets, piazzas, and basilicas; the fourth book was devoted to Roman temple architecture. It seems that a Palladian approach to lunar base architecture would retain the five classical orders — Tuscan, Doric, Ionic, Corinthian and Composite — in the language of planetary architecture (Summerson 1963). However, reduced gravity implies the potential for tall thin buildings with thin columns and walls. The circular arch (as in Roman aqueducts) is most appropriate for resisting internal pressurization of lunar bases rather than the parabolic arch developed to resist gravitational loads on Earth (Benaroya and Bernold 2008). The catenary arch is the ideal non-parabolic arch with a hyperbolic cosine curve for a free-standing arch with no vertical load except its own weight. It is an inversion of a hanging chain in which only compressive forces are acting, e.g., the domes of Brunelleschi's Florence Cathedral (Gothic) and Wren's St Paul's Cathedral (Renaissance). The Moon offers a return to classically-derived architectural forms introduced by low-cost customization of 3D printing — a selenic architectural style.

In his *Ten Books on Architecture* (c 20 BC), the Roman architect Vitruvius devoted the first 8 books to buildings, ninth book to astronomy and geometry and the tenth book to machines. Vitruvius was a Roman artilleryman/engineer in which capacity, his job was to destroy fortifications using siege machines (Shephard 1994). Machines are thus an integral part of the architectural "whole" (Rasmussen 1964). Habitats, as spacecraft, are machines for living in, literally rather than figuratively. While buildings are immovable structures, machines are dynamic mechanisms and the latter, in the form of technology have been transformative in our social experience (Shephard 1994). It is fitting therefore to concentrate on machines as a neglected but critical aspect of lunar base architecture. We widen the potential for 3D printing enormously beyond mere structures to encompass on-site 3D printing of complex kinematic machines. The most basic components for a kinematic machine are mechanical levers, cable pulleys, wheels, electric motors, gear transmission and piston engines – these are collectively redundant in that piston engines can be replaced by electric motors, cable pulleys replaced by motorized cranes, and electric motors are the core component to powered levers and wheels, without any loss in functionality. The control of kinematic machines also requires electronics to drive the motorized mechanisms. From such components — structural linkages, electric motors, sensors, and electronics — it is possible to construct tools (powered and unpowered) such as milling stations and lathes, and robots (rover vehicles such as bulldozers/load-haul-dumpers or drills for mining and manipulators for assembly tasks) and indeed 3D printers. Hence, 3D printing can be applied to the most challenging of components — mechatronic components and systems including electric motors, electrical circuitry, sensors, and general-purpose computing — to construct the machines of production rather than the products themselves.

9. Conclusions

We have considered the requirements for the construction of a lunar habitat given the constraints of the in situ resources that are readily recoverable. We suggest that most of the lunar habitat can be constructed from lunar resources, including civil engineering structures, mechatronic components, robotic machines, and even basic internal decorum. This goes far beyond traditional primary structures. We propose therefore that lunar habitat design should proceed directly to Class III leapfrogging the previous classes as hindrances to self-sustainability of a Moon Village. Class I and II developmental stages of lunar exploration represent an approach in which terrestrial technology is transported to the Moon, an alien environment from which servicing, maintenance and repair options will be limited. All engineered constructions will require such support which cannot be supplied from Earth in a timely or cost-effective manner. This limits the supportability and permanence of Class I and II lunar bases. Class III lunar habitats constructed from lunar resources will be the only option that is fully supported by local lunar resources for maintenance and repair. This necessarily requires the prior implementation of a sophisticated robotic lunar infrastructure to prepare the way for human presence. We have proposed a scalable means to accomplish this (Ellery 2016). There are many similarities between a lunar base and a Martian base (Parkinson and Wright 2006) but Mars offers a much wider selection of material resources suggesting that much of the technology outlined here is applicable to Mars bases (Ellery and Muscatello 2020). However, on the Martian surface, there is reduced solar energy availability $\sim$500 W/m^2 and potential reduction in solar availability due to dust storms. This has potential implications for thermal processing such as sintering of regolith unless nuclear power sources are adopted. Nevertheless, 3D printing offers enormous scope for architectural design as well as affording a practical and versatile mode of construction. Just as the spires of Gothic cathedrals reached out to God, so our lunar cathedrals much reach higher to point the way to the stars. Our architecture must reflect that our destiny has always been the stars.

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Appendix A

Lunar industrial ecology

The following lists all the major chemical processing reactions comprising the near closed loop lunar industrial ecology — feedback loops are not explicitly shown but may be deduced by linking reaction products to reactants for different chemical processes. Emboldened materials are pure metal oxides that are input to the Metalysis FFC process for direct reduction to high purity metal or semiconductor. It is important to note that all the volatiles (with the exception of carbon compounds) extracted from regolith are recycled as reagents and not consumed. In the case of carbon compounds, we have proposed the manufacture of silicone plastics as electrically insulated elastomers – however, we can minimize this by exploiting glass cloth and porcelain of knob-and-tube technology.

Lunar Ilmenite

$Fe^0 + H_2O \rightarrow$ ferrofluidic sealing

$FeTiO_3 + H_2 \rightarrow \mathbf{TiO_2} + H_2O + Fe$

$2H_2O \rightarrow 2H_2 + O_2$

$2Fe + 1.5O_2 \rightarrow Fe_2O_3/Fe_2O_3.CoO$ - ferrite magnets

$3Fe_2O_3 + H_2 \leftrightarrow Fe_3O_4 + H_2O)$ – formation of magnetite at 350-750°C/1-2 kbar

$4Fe_2O_3 + Fe \leftrightarrow 3Fe_3O_4$)

Nickel-Iron Meteorites

W inclusions – high density of 19.3 $\rightarrow$ Thermionic cathodic material

		Alloy	Ni	Co	Si	C	W
Mond process:							
$Fe(CO)_5 \leftrightarrow 5CO + Fe$ (175°C/100 bar)	$\rightarrow$	Tool steel				2%	9-18%
$Ni(CO)_4 \leftrightarrow 4CO + Ni$ (55°C/1 bar)	$\rightarrow$	Electrical steel			3%		
$Co_2(CO)_8 \leftrightarrow 8CO + 2Co$ (150°C/35 bar)	$\rightarrow$	Permalloy	80%				
S catalyst		Kovar	29%	17%	0.2%	0.01%	

$4FeS + 7O_2 \rightarrow \mathbf{2Fe_2O_3} + 4SO_2$

(Troilite) $SO_2 + H_2S \rightarrow 3S + H_2O$

$FeSe + Na_2CO_3 + 1.5O_2 \rightarrow \mathbf{FeO} + Na_2SeO_3 + CO_2$

KNO_3 catalyst $Na_2SeO_3 + H_2SO_4 \rightarrow Na_2O + H_2SO_4 + Se \rightarrow$ photosensitive Se

$Na_2O + H_2O \rightarrow 2NaOH$

$NaOH + HCl \rightarrow NaCl + H_2O$

Lunar Orthoclase

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

orthoclase illite silicic acid (soluble silica)

$2KAl_3Si_3O_{10}(OH)_2 + 2HCl + 3H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2KCl$

kaolinite

$[2KAlSi_3O_8 + 2HCl + 2H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2KCl + \mathbf{SiO_2} + H_2O]$

$KCl + NaNO_3 \rightarrow NaCl + KNO_3$

$2KCl + Na_2SO_4 \rightarrow 2NaCl + K_2SO_4$

Lunar Anorthite

$CaAl_2SiO_8 + 4C \rightarrow CO + \mathbf{CaO} + \mathbf{Al_2O_3} + 2Si$ at 1650°C $\rightarrow$ CaO cathode coatings

$CaO + H_2O \rightarrow Ca(OH)_2$

$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$

$CaAl_2SiO_8 + 5HCl + H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + \mathbf{SiO_2}$ $\rightarrow$ fused silica glass + FFC electrolyte

$AlCl_3.6H_2O \rightarrow Al(OH)_3 + 3HCl + H_2O$ at 100°C

$Al(OH)_3 \rightarrow \mathbf{Al_2O_3} + 3H_2O$ at 400°C $\rightarrow 2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$ (thermite)

$\rightarrow$ AlNiCo hard magnets

Lunar Olivine

$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3\mathbf{SiO_2} + 2H_2O$

fayalite magnetite

$Mg_2SiO_4 + 4H_2O \rightarrow \mathbf{2MgO} + \mathbf{SiO_2} + 4H_2O$ → 3D Shaping binder

forsterite $MgO + HCl \rightarrow MgCl_2 + H_2O$ → 3D Shaping binder

Lunar Volatiles

$CO + 0.5\ O_2 \rightarrow CO_2$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300°C (Sabatier reaction) → $CH_4 \rightarrow C + 2H_2$ at 1400°C for steel/anode regeneration

Ni catalyst

850°C 250°C

$CH_4 + H_2 \rightarrow CO + 3H_2 \rightarrow CH_3OH$ 350°C

Ni catalyst Al_2O_3 $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$ 370°C $+nH_2O$

Al_2O_3 $CH_3Cl + Si \rightarrow (CH_3)_2SiCl_2 \rightarrow ((CH_3)_2SiO)_n + 2nHCl$ → silicones

$N_2 + 3H_2 \rightarrow 2NH_3$ (Haber-Bosch process)

Fe on $CaO+SiO_2+Al_2O_3$

$4NH_3 + 5O_2 \rightarrow 4NO + 6H_2O$

WC on Ni

$3NO + H_2O \rightarrow 2HNO_3 + NO$ (Ostwald process)

$2SO_2 + O_2 \leftrightarrow 2SO_3$ (low temp)

$SO_3 + H_2O \rightarrow H_2SO_4$

Salt of the Earth

$2NaCl + CaCO_3 \leftrightarrow Na_2CO_3 + CaCl_2$ (Solvay process) → FFC electrolyte

350°C/150 MPa

$Na_2CO_3 + SiO_2(i) \leftrightarrow Na_2SiO_3 + CO_2$ → piezoelectric quartz crystal growth (40-80 days)

1000-1100°C

$CaCO_3 \rightarrow \mathbf{CaO} + CO_2$ (calcination)

$NaCl(s) + HNO_3(g) \rightarrow HCl(g) + NaNO_3(s)$