Lunar Demandite—You Gotta Make This Using Nothing but That

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ABSTRACT

We consider whether an entire spacecraft can be constructed from lunar resources by consideration of its materials availability. We first consider what functional materials would be required to construct all the major spacecraft subsystems. We then examined each lunar mineral to determine what metals, ceramics, and glasses can be extracted. We suggest that lunar resources—with certain provisos—can indeed supply all the functional materials required to construct a spacecraft. We suggest that this could constitute a first generation ISRU capability and that a subsequent generation to extract KREEP materials would offer enhanced performance but no significantly greater capacities.

INTRODUCTION

In-situ resource utilisation makes possible the construction of a lunar infrastructure (Steurer 1982). We have developed an inventory of functional materials available on the Moon and scoped their applications to determine the degree of self-sufficiency attainable without reliance on an Earth-based supply chain. If we take a long-term view, the decisions made today will impose legacy effects on future lunar settlers. We must eliminate the Earth-based supply chain as early as possible to prevent the foreseeable political strife of imbalanced opportunity for self-determination for which near-self-sufficiency is a prerequisite. The construction of a lunar infrastructure such as an evolving Moon Village (even perhaps Lunar University) will require a range of products – lunar base complexes, closed ecological life support systems including lunar agriculture, robotic and human-rated rovers, etc – with consumables support – energy, water, oxygen and other recyclable CNPKS, etc - and machines to implement such constructions – mining machines, unit (electro/thermo)chemical processors, manufacturing and assembly machines. Such a Moon Village must be as self-sufficient and self-maintainable as is feasible without reliance on the extensive Earth-based infrastructure that has evolved to serve Earth.

THE DEMANDITE

We begin with an hypothetical but typical robotic spacecraft comprised of all the major subsystems as a core requirement for construction from lunar resources on the observation that all space systems are variations on a spacecraft. This provides us with our demandite concept.

These are the approximate breakdowns for an orbital space vehicle – if we are manufacturing spacecraft on the Moon, this is a reasonable starting point though a solar power satellite's design would be dominated by its energy chain. Similarly, propulsion from the lunar surface includes launch – we ignore this aspect here other than to observe that launch to the Gateway requires an LH2/LOX mass fraction of close to 2.5 including tankage. If we are concerned with lunar bases (Ellery 2021), this table must be interpreted carefully – human-rated spacecraft include extensive

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environmental control and life support systems which we exclude from our dry mass allocation. Terrestrial materials consumption is dominated by bulk civil engineering structures. We might expect lunar bases to utilise regolith-derived material for compressive structures but these are primarily conceived as outer shells for radiation /micrometeoroid protection and thermal insulation. It seems reasonable that inner structure would include metal frames and panels. Thermal control on spacecraft is primarily passive involving redistribution between short hot sunlight and cold eclipse cycles - on the Moon, the two-week sun/eclipse periods suggest that thermal control will be more challenging. A lunar base on the other hand is a static structure unlike a spacecraft so it requires no GNC/ACS or propulsion. Common features to both lunar bases and space vehicles that are expected to be approximately similar associated with avionics - the power system (though a lunar base has fewer restrictions on deployed size), wiring harness, communications and onboard computing systems. We have adopted a standard 25% for tensile structure for a spacecraft assuming that additional compressive structure required for a lunar base would constitute a significant additional mass. Thermal insulation (nighttime) and thermal radiators (daytime) have been allocated 3% each – for lunar bases, outer regolith protection offers thermal insulation during both day and night. Thermal straps re-distribute heat internally. The wiring harness – dominated by electrical power distribution - common to spacecraft and bases comprises electrical wiring and some electrical insulation (glass fibre) and allocated 8%. Given that avionics constitutes an increasing fraction of spacecraft and bases or both computing, control and communications, it is allocated 12%. Mechanical actuation and sensors are allocated 5% each because both spacecraft and lunar bases require orientable mechanisms and sensory networks – in the latter case, this includes rover/manipulator support. Most spacecraft payloads are based on imaging systems so we allocate 11% for optical systems – in the case of lunar bases, this is dominated by mirrors/lenses for thermal ISRU processing. Hard structures and high thermal tolerance material are also specialized requirements for ISRU processing allocated 3% and 4% respectively. Hence, ISRU thermal processing systems constitute 18% of the lunar base mass. Power generation and storage are allocated 20% for both spacecraft and lunar base.

Table 1. Typical subsystem mass allocation to 100% spacecraft mass (adapted from Brown C (2002) Elements of Spacecraft Design, AIAA Education Series)

Subsystem	Subsystem mass allocation of on-orbit dry mass
Structure/Mechanisms	26-29%
Thermal Control	3%
Attitude Control	9-10%
Power System	19-21%
Wiring Harness	7-8%
Propulsion	13-15%
Communications	6-7%
CDHS	6-7%
Payload	11%

We examine the Moon's inventory, aware that the Moon is deficient in certain elements, most notably Cu, Na and halogens. The Moon exhibits a range of resources from volatiles to regolith to minerals from which useful ceramics, metals and possibly plastics may be extracted (Appendix). Although volatiles are relatively scarce, careful husbanding of carbon in small

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quantities may provide a valuable resource. This defines gaps to realising the construction of this spacecraft from lunar resources but there are material substitutions that can be made or strategies implemented to minimise the use of deficient materials, e.g. recycling Earth-imported reagents so that they are not consumed. A key facet is in the exploitation of multi-functionality of materials. There are two related issues that must be relegated to future studies and are not addressed here: (i) the influence of minor natural "contaminants" in minerals which on reduction will yield contaminant metals in the metal product; (ii) the omission of deliberately added alloy constituents in product alloys due to their lack on the Moon. Most metal alloys comprise a majority metal with minor additives such as weldalite, an Al-Li alloy (<2.45% Li) has a low density of 2700 kg/m^3 for lightweight cryogenic structures. Lithium would be challenging to source from lunar resources (Dreibus et al 1977) so this is not a first generation ISRU option. High entropy alloys comprise typically five main metals in near equal proportions that form hard intermetallic compounds, e.g. Cantor (chromium, manganese, iron, cobalt and nickel) is tough at liquid nitrogen temperatures (77 K) (Savage 2021). Although attractive for lunar pole environments, the challenges in extracting Cr and Mn from lunar minerals renders this option a future consideration. One of the primary uses of Cr in alloying is in protection from oxidative corrosion which does not occur on the Moon. We focus on pure metals and a selection of specific alloys. We must determine the required relative throughputs for each material based on its use and determine what are the critical materials with low concentrations.

Table 2. Lunar-derived functional materials

Functionality (mass fraction)	Lunar-Derived Material
Tensile structures (25%)	Wrought iron Aluminium
Compressive structures (+50%)	Cast iron Regolith + binder
Elastic structures (trace)	Steel springs/flexures Silicone elastomers
Hard structures (3%)	Alumina
Thermal conductor straps (1%)	Fernico (e.g. kovar) Nickel Aluminum
Thermal radiators (3%)	Aluminium
Thermal insulation (3%)	Glass (SiO_2 fibre) Ceramics such as SiO_2
High thermal tolerance (4%)	Tungsten Alumina
Electrical conduction wire (7%)	Aluminium Fernico (e.g. kovar) Nickel
Electrical insulation (1%)	Glass fibre Ceramics (SiO_2, $Al_2O_3$and TiO_2) Silicone plastics Silicon steel for motors

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Active electronics devices (vacuum tubes) (12%)	Kovar Nickel Tungsten Fused silica glass
Magnetic materials for actuators (5%)	Ferrite Silicon steel Permalloy
Sensory transducers (5%)	Resistance wire Quartz Selenium
Optical structures (11%)	Polished nickel/aluminium Fused silica glass lenses
Lubricants (trace)	Silicone oils Water
Power system (20%)	Fresnel lens + thermionic conversion Flywheels
Combustible fuels (+250%)	Oxygen Hydrogen

We do not address all these materials but focus on a few critical ones – both general bulk and special functional materials. We note that the richest regions with the most varied geology on the Moon maty be the transitions regions between the anorthosites of the highlands and the basalts of the mare regions.

LUNAR OLIVINE

We begin with consideration of olivine, a common mineral on the Moon, oft neglected compared with ilmenite of the maria regions and anorthite of the highland regions. Olivine may be subjected to Pidgeon reduction at high temperature to yield magnesium metal directly ($Mg_2SiO_4 + 2CaO \rightarrow Ca_2SiO_2 + 2Mg$). However, the simplest treatment of olivine is with water. The olivine fayalite treated with water releases magnetite, silica and hydrogen:

$$\underset{\text{fayalite}}{3Fe_2SiO_4} + 2H_2O \rightarrow \underset{\text{magnetite}}{2Fe_3O_4} + \underset{\text{silica}}{3SiO_2} + 2H_2$$

This yields silica and magnetite as highly useful ceramics, the former for multiple applications including fused silica glass and the latter for permanent magnets. Furthermore, it acts as a source of hydrogen which is a useful reductant without mining water. Pyroxenes ($MgSiO_3$, $CaSiO_3$ and $FeSiO_3$) are also appropriate sources of silica (SiO_2). Hydration of the olivine forsterite forms serpentine:

$$\underset{\text{forsterite}}{2Mg_2SiO_4} + H_2O \rightarrow \underset{\text{serpentine}}{Mg_3Si_2O_5(OH)_4} + Mg(OH)_2$$

At 332°C, magnesium hydroxide decomposes endothermically to magnesia, one of the two components of Sorel cement:

$$Mg(OH)_2 \rightarrow MgO + H_2O$$

The other component of Sorel cement, $MgCl_2$, can be synthesized by treating MgO with HCl:

$$MgO + HCl \rightarrow MgCl_2 + H_2O$$

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MgO and $MgCl_2$ together constitute Sorel cement which may be used as a binder for 3D printing of regolith into civil engineering structures, particularly outer protective shielding (Cesaretti et al 2014). The hydration of olivines offer an alternative route from the Sabatier reaction - forsterite and fayalite in water at 300°C and 500 bar converts CO_2 into CH_4:

$$\underset{\text{forsterite}}{18Mg_2SiO_4} + \underset{\text{fayalite}}{6Fe_2SiO_4} + 26H_2O + CO_2 \rightarrow \underset{\text{serpentine}}{12Mg_3Si_2O_5(OH)_4} + \underset{\text{magnetite}}{4Fe_3O_4} + CH_4$$

This is the favoured explanation for the existence of methane gas emissions on Mars (Nicol et al 2018).

LUNAR ANORTHITE

Metals have a wide range of applications due to their specific physical properties. The most effective thermal conductors are silver and copper but aluminium is a commonly substituted at low temperatures below 520°C or so (imposed by its modest melting temperature of 660°C) with a thermal conductivity of 235 W/m.K. The most commonly used electrical conductors are copper and aluminium, the latter being employed in pylon-mounted overhead electrical cables. Hence, aluminium is a diverse metal that can be used for a multitude of applications – structural metal in tension as in spacecraft structures, metal electrically conductive wiring, metal thermally conductive straps, thermal radiator/louvre surfaces and as a constituent of AlNiCo permanent magnets. An immediate observation is that any spacecraft or lunar base will require a significant amount of aluminium – some 40-50% of the total dry mass.

The most common lunar minerals are the plagioclases $(Ca,Na)(Al,Si)_4O_8$ of which anorthite ($CaAl_2Si_2O_8$) is the commonest. In some highland areas of the Moon, anorthite (calcium-rich feldspar $CaAl_2SiO_8$) comprises >90% of highland anorthosite rock - aluminium enrichment is up to 33% by mass. Anorthite is highly soluble to HCl acid leaching at low temperature yielding amorphous silica and alumina with high recovery efficiencies via $AlCl_3.6H_2O$. It is a two-part process. HCl leaching of anorthite as HCl gas is carried out at 160oC followed by precipitation and crystallization of $AlCl_3.6H_2O$. Silica is removed during this stage by filtration. Removal of Cl and H2O is achieved by heating at 400°C which recycles HCl. Roasting $AlCl_3$ at a maximum of 900°C for 90 minutes in oxygen yields alumina. Lunar orthoclase may similar be treated with HCl acid to yield silica and kaolinite. Kaolin – rock bearing kaolinite – is the basis of porcelain. On Earth, alumina is often extracted from kaolin using HCl leaching (Pak et al 2019) adding orthoclase as another source of silica and alumina.

Both alumina and silica are refractory ceramics with wide utility especially in thermal control applications – silica for thermal insulation and alumina for reactor crucible lining. Lime (CaO) can be reduced to the metal Ca that is more than twice as electrically conductive as Cu – in the vacuum of the Moon, it will not oxidise. Ca is malleable and therefore offers a source of electrically conducting wiring. Alumina can also be reduced to aluminium metal. The Washington monument completed in 1885 was capped with aluminium as an expression of extravagance - aluminium was an extremely precious metal until the development of the Hall-Heroult electrolytic process in the late 1880s. The low melting point of Al and cryolite permitted the input of liquid solution of aluminum oxide in cryolite and liquid metal output. For the Moon, the FFC electrochemical process can reduce both aluminium and silicon independently to high metallurgical purities >99% (Ellery et al 2021). It is worth noting that aluminium extracted from bauxite requires 227-342 MJ/kg while steel manufactured from iron ore requires 40-75 MJ/kg (Raabe et al 2019). The FFC process requires considerably less energy for metal reduction including aluminium as it operates in the solid state. As well as its desirable qualities as a high specific strength structural material and electrical conductor,

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Al powder may be burned in oxygen as a solid fuel or fed as a fluid fuel by a powder pump or auger but it has poorer performance than hydrogen/oxygen. Silicon has traditionally been earmarked for solar cell construction but several disadvantages of PV solar cells that render its manufacture and use marginal (Ellery 2021). It has other uses including as a as a metal alloy additive (such as silumin with 87% Al and 13% Si). Silicon carbide powder is a versatile material that may be pressure-pressed at >1400 bar and sintered at around 2000°C but carbon in lunar volatiles is relatively scarce. Silicon's primary use is in its oxide form, silica as a source of fused silica glass.

LUNAR ILMENITE

Lunar ilmenite has often been touted as a source of oxygen through hydrogen (or less commonly carbon) reduction but here we adopt it as a source of iron and titanium: $FeTiO_3 + H_2 \rightarrow Fe + TiO_2 + H_2O$. The water is electrolysed to yield oxygen and recycled hydrogen. Although chemical reduction requires temperatures of 900-1000°C, a temperature of 1600°C yields molten iron (liquation) which can be tapped off. Iron offers the basis of many different functional alloys (steels) and as a constituent of permanent magnets as metal or ferrite. Steel structures are typically formed from I-beams which impart high stiffness relative to their cross-section area. Silicon steel (up to 3% Si) has dramatically increased electrical resistivity for electromagnet and motor cores. We have sourced the silicon additive but further additives are required for other iron alloys Kovar (53.5% Fe, 29% Ni, 17% Co, 0.3% Mn, 0.2% Si and <0.01% C) is a type of fernico alloy with high electrical and thermal conductivity as a replacement for copper and/or aluminum conducting wire at high temperatures (such as within vacuum tubes). We assume that Mn and C can be omitted – Mn is added for fixing oxygen and sulphur at high temperature to improve malleability; C is added for hardening against malleability. Permalloy (20% Fe and 80% Ni) offers high magnetic permeability but very low coercivity – the very high permeability provides magnetic shielding around motor devices to protect adjacent electronics from stray magnetic fields. We address the sourcing of Ni and Co later. It is worth noting that for structural purposes, wrought (pure) iron is strong and workable and is not subject to corrosive rusting on the Moon so stainless steels or zinc galvanisation are unnecessary.

Rutile (TiO_2) has uses itself, e.g. FeS_2 may form composites with TiO_2 to form thin-film photocatalysts with a large bandgap of 3.2 eV responsive to UV light (Heift 2019). However, rutile is a source of titanium metal - the FFC electrochemical process was designed to reduce it into >99% pure titanium (Ellery et al 2021). Titanium has very high tensile strength and toughness, superior strength-to-weight ratio than steel and aluminium, and excellent corrosion resistance at high temperature up to 400°C. The most common alloy comprises 6% Al and 4% V (Ti6Al4V) and <0.25% Fe which is significantly stronger than pure Ti. Despite its enhancement of titanium's corrosion resistance as an additive, vanadium is omitted from medical applications due to its toxicity suggesting that it's omission in not a significant issue. Where combinations of high temperature, lightweight and corrosion-resistance are an advantage such as reactor vessels, titanium is the material of choice.

LUNAR METEORITIC NICKEL-IRON

As well as local lunar minerals, there are reckoned to be asteroidal resources located in certain shallow-angle craters including nickel-iron resources (Collins 2012; Wieczorek et al 2012) from which a suite of alloys can be manufactured. Most Ni on Earth is mined as the sulphide ore pentlandite $(Ni,Fe)_9S_8$. Ni is extracted from sulphide ores which is subjected to froth

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flotation to concentrate the ore. The ore is then smelted to produce metals which are separated through solvent extraction. Similarly, Co is in complex mineral compounds such as cobaltite (CoAsS). Froth flotation concentrates the cobalt minerals followed by roasting which converts cobalt into its sulphide forms CoS_2 and Co_2S_3. Leaching with sulphuric acid yields Co_3O_4 and $CuSO_4$ solution. Cobalt oxides do not react with hydrogen at elevated temperatures so they are reduced by smelting with C in a blast furnace. Such processes are unnecessary with meteoritic nickel-iron alloy. Transition metal carbonyls $M_x(CO)_y$ are highly volatile compounds that may be exploited to yield high purity metal by thermal decomposition (Visnapuu & George 1987). The metal carbonyl must obey the 18-electron rule offering 9 valence orbitals for metal-ligand bonding. $Ni(CO)_4$, $Fe(CO)_5$ and $Co_2(CO)_8$ are the readily formed from Ni, Fe and Co directly with CO at 25-100 atmosphere pressure and 100-200^{o}C accelerated by small amounts of H_2S promoter. The Mond process involves the formation of $Ni(CO)_4$ at 50-60^{o}C; $Fe(CO)_5$ is formed at 200^{o}C and 100-300 atm; $Co_2(CO)_8$ is formed at 95-110 atm at 120^{o}C. $W(CO)_6$ is formed under similar conditions to Fe, Ni and Co carbonyls. The Inco pressure carbonyl process allows simultaneous extraction of Ni, Fe and Co from mixtures at 110-130^{o}C with small additions of NH_3 to improve recovery rates. Ni and Co are used primarily as alloying materials, Ni for heat tolerance and Co for corrosion-resistance in steels. Nickel is used as electrodes ad grids in vacuum tubes, as electroplating material and as a catalyst. Cobalt has replaced copper for very short on-chip wiring which suffers from less electromigration at ultrasmall scales which become dominant over its superior conductivity.

Invar (64% Fe with 36% Ni) has a low coefficient of thermal expansion (<1 x 10^{-6}/K) for high precision mechanisms and valves. Inovco (62.5% Fe, 33% Ni and 4.5% Co) has an even lower coefficient of thermal expansion (0.55 x 10^{-6}/K). Elinvar (59% Fe, 36% Ni and 5% Cr) is non-magnetic Ni-based steel alloy whose elastic modulus is relatively independent of temperature making it useful in clockwork movements – Cr is more difficult to extract from lunar resources so this option is not viable in first generation ISRU. Similar arguments apply to the more complex nickel-chromium-based superalloys (Inconel such as NiCr15Fe with minor additives) for high temperature corrosive environments. Fernico is a class of Fe-Ni-Co alloys with good electrical conductivity suitable for high temperatures (up to 800^{o}C) or cryogenic temperatures (down to -180^{o}C). Kovar (53.5% Fe, 29% Ni, 17% Co, 0.2% Si and 0.3% Mn) is the high temperature fernico alloy with a low thermal expansion ratio similar to borosilicate glass (6.5 x 10^{-6}/K) so it is used in glass seals such as vacuum tubes. Mn compensates for brittleness so its omission yields no loss in functionality. Cryogenic fernico trades a small amount of Co for Ni with 31% Ni and 15% Co, the rest being the same as the high temperature kovar.

Lunar highland rock is more enriched in tungsten than lunar basalt at an average of 0.3 μg/g but NiFe asteroids are often enriched in tungsten microparticle inclusions – this favours the use of tungsten in only essential applications. Tungsten has the highest tensile strength and the lowest coefficient of thermal expansion of any metal. Alternative metals are both inferior (rendering them more challenging to extract) and more rarified (Table 3):

Table 3. Properties of candidate cathode materials

Element	Melting Point (^{o}C)	Density (g/cm^3)
Tungsten	3410	19.3
Tantalum	2996	16.6
Niobium	2668	8.66
Molybdenum	2622	10.22

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Tungsten has the highest melting point of any metal at 3422°C but it may be melted in liquid heavy rare earths such as Sc at temperatures under 2150°C (Dennison et al 1966). This latter process is clearly not feasible in first generation ISRU. Tungsten is manufactured using powder metallurgy involving sintering with a cobalt, nickel or iron binder rather than melting. Tungsten can be joined through spot welding with nickel, brazing with nickel or welded by electron beams. For electric arc generation in vacuo and X-ray tubes, alloying with <10% Th improves its ignition but this is not essential. As well as wire filaments, tungsten is used as electrodes in tungsten inert gas (TIG) arc welders. Tungsten alloys with 22% Rh to improve its structural properties are typically employed in corrosion resistant, extreme temperature piping and furnace linings in chemical and nuclear industries. However, the scarcity of tungsten favours the use of refractory ceramics for high temperature ceramic moulds. Although tungsten carbide WC is one of the hardest carbides with many applications (cutting tools, high temperature rocket nozzle steel, etc), its reliance on carbon renders it infeasible. Alumina ceramic may be employed for these applications. WS_2 is a high temperature lubricant that may be substituted for the more commonly used dry lubricant MoS_2. However, silicone oils represent a possible alternative as a wet lubricant. There is a single use of tungsten that we suggest - W is used as electrodes such as the high temperature filament in vacuum tubes, electron beam tips, X-ray tube filaments and interconnects in integrated circuits. Hence, tungsten is essential to permit lunar-sourced active electronics but if restricted to this application, only small amounts are required.

LUNAR CERAMICS

Most emphasis has been on metals for their excellent tensile properties and their high electrical and thermal conductivity but ceramics (metal oxides, carbides, etc) have highly desirable properties such as high temperature tolerance to ~1000-1500°C, high electrical and thermal insulation properties, resistance to corrosion and high strength (hardness) but they exhibit poor toughness (brittleness).

The refractoriness and chemical inertness of ceramics lend them to use as reactor crucibles for melting metals, e.g. Al_2O_3. Their hardness permits tooling applications. Steel often requires the addition of small amounts <2% carbon as the dominant additive. Tool steel (<2% C and 9-18% W) is durable steel used for cutting tools for low wear (which may be enhanced with the addition of Cr and W but which will be challenging to extract or scarce). However, carbon is a scarce resource found in lunar volatiles where it is dominant. Ceramic options are favoured. Cermet tools comprise titanium carbide and tungsten in a nickel or cobalt binder but carbides require carbon. A feasible alternative tooling material is high temperature sintered alumina with high compressive strength, temperature tolerance to 1800°C and physical properties second only to diamond. Some ceramics are electrically conducting that exploit their high melting temperature - ceramic heating elements include the electrically conductive molybdenum disilicide ($MoSi_2$) and tungsten disilicide (WSi_2) with melting points exceeding 2000°C for high temperature applications up to 1800°C. To overcome brittleness, glass fibres may be incorporated into ceramic matrices.

The very high melting point of ceramics renders casting and 3D printing difficult and their brittleness makes machining difficult. Ceramics are typically processed through thermal sintering at high temperature. In 3D printing, ceramics are typically processed as ceramic particle-impregnated polymers, through liquid binder jetting of ceramic particles or direct laser sintering of ceramic particles. Colloidal inks with 40-50% ceramic particle (SiO_2 or Al_2O_3) suspensions in

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plastic fluid requires sintering after deposition at 900-1300°C. Siloxanes have been proposed for non-flammable ceramic-forming electrical insulation (Kopylov et al 2014). The addition of up to 30% ceramic particles ($CaSiO_3$, $Al(OH)_3$, MgO, kaolin, $CaCO_3$ with catalytic iron metalloorganosiloxanes) into a silicone matrix promotes solidification by thermal sintering at <900°C. $CaSiO_3$ may be formed from heating at 850°C with SiO_2: $CaCO_3 + SiO_2 \rightarrow CaSiO_3 + CO_2$. However, the difficulty in the formation of the catalytic additives and the poor strength of the resultant composites renders this approach untenable. Hence, direct thermal sintering of ceramic powders offers the most viable solution – indeed, Fresnel based thermal sintering in-situ regolith may be adopted for the formation of foundations to reduce the dust environment.

Mare basalts contain glasses with high silica and FeO content enriched in potassium. Lunar regolith may be formed into glass at 1300°C. Regarding the manufacture of soda lime glass, the commonest terrestrial glass, the constituent soda (Na_2O) is scarce on the Moon. Furthermore, the contamination of lunar glasses from iron renders them useless for optical applications (though basaltic glass in fibre form may be employed as thermal and electrical insulation). This favours the transformation of pure silica as fused silica glass. Glass is an amorphous vitreous solid that exhibits a transition from a hard, brittle state to a viscous state. It is a durable transparent material that is resistant to chemicals, heat up to 1000°C and mechanical stress. For use as optical fibres, a means to incorporate internal reflection must be devised – this is usually through an internal gradation of refractive index between the glass/plastic core and glass/plastic cladding. It is plausible that metallic cladding of nickel or cobalt might be employed (Klainer et al 1991). Amplification of light signals within an optical fibre may be achieved by doping the silica of the fibre by the rare earth element erbium. This can be pumped by a diode laser to emit stimulated photons at higher power. The use of chalcogenide glasses containing elements from group 16 (such as S) allows the fibre to act as a resonating cavity. Although S is available from lunar/asteroidal resources, rare earth element availability relegates optical signal processing from first generation ISRU. Reinforced glass may permit use as a structural material - alkali-aluminosilicate “gorilla” glass is toughened through ion-exchange by immersion in a molten alkaline potassium salt bath at 400°C. Replacement of sodium ions (soda glass) by larger potassium ions in the surface layer generates high residual compressive stresses increasing its strength. It is unclear if fused silica glass can be strengthened in a similar manner.

LUNAR PLASTICS

Plastics are mouldable lightweight hydrocarbon-based materials that are highly versatile but their specific unique properties are their use as flexible insulation (elastomers). Elastomers are used for seals and gaskets, shock and vibration mounting and flexible connections such as electrical insulation, expansion joints, transmission belts and fluid hoses. The radiation resistance of epoxides is higher than other polymeric resins due to the presence of benzene ring structures. Synthetic rubber such as styrene-butadiene was developed during to World War 2 when Axis forces gained control of natural rubber supplies. Common rubber replacement synthetics include polybutadiene $(CH_2\text{-}CH{=}CH\text{-}CH_2)_n$ used in tyres. For space use, polyethyleneterephthalate (PETE) is the core polyester in Dacron fibre and Mylar film. Its versatility is illustrated in Spectralon, a translucent polymer constructed from compressed and sintered tetrafluoroethylene powder for use in diffuser optics. Plastic is usually injection moulded in which the plastic is automatically injected into a closed cavity under heat. Trimming may be accomplished by reducing the temperature below its glass transition temperature and

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bombarded with beads to remove excess material. Alternatively, a lathe may trim away excess material. Fused deposition moulding is an extrusion-based 3D printing technique has become common for constructing thermoplastic structures (Jones et al 2011). However, plastics require a dependable source of carbon and hydrogen, the former of which is not plentiful on the Moon.

Silicone plastics reduce the amount of carbon required by adopting a O-Si-O backbone so only the side chains require carbon. Silicone rubber is an elastomer of silicone which is stable to high temperatures up to 300^{o}C and UV radiation-resistant. It is a highly adhesive gel uncured forming a solid in its cured or vulcanised state. They may be one-part or two-part polymers and may contain fillers. Glass fibre and iron oxide powder fillers offer high thermal tolerance and high thermal conductivity respectively yet retaining electrical insulation. Room-temperature vulcanised silicone is a one-part system in which silane is cured by crosslinking through hydrolysis by exposure to water at room temperature. Cured silicone is an effective sealant and adhesive. Polyorganosiloxanes added to platinum-cure silicone mixtures constitutes an adhesive (Lin et al 2013). There are other non-carbon backbones that may be exploited. Ferrocene $Fe(C_5H_5)_2$ is an organometallic sandwich compound formed by the cyclopentadiene with Fe at 350^{o}C: $Fe + 2C_5H_{6(g)} \rightarrow Fe(C_5H_5)_2 + H_{2(g)}$. Metalosiloxane polymers based on alternating Si-O and Al or Ti (such as aluminosiloxanes) may be produced by hydrolising metal siloxanic compounds. Such "plastics" are stable to temperatures above 300^{o}C. Aluminosiloxane with Al-O-Si backbones - $Al(O'Pr)_2(OSiMe_3)$ - may act as an organic precursor to a transparent refractory ceramic ($92Al_2O_3$-$8SiO_2$) via gelation followed by heat treatment (Pouxviel et al 1987). Aluminosiloxane is synthesised through transesterification of cyclohexane with trimethylacetoxysilane: $Al(O'Pr)_3 + yMe_3SiO(CH_3CO) \rightarrow Al(O'Pr)_{3-y}(OSiMe_3)_y + y(CH_3CO)O'Pr$ where y=1-3. Similarly, titanosiloxanes have Si-O-Ti backbones (Davis & Murugavel 2005). Unfortunately, these precursor materials require complex chemical processing. Prior to the invention of plastics, the only mouldable materials were natural rubber, glass and wet clay that hardened into brittle ceramics. In fact, prior to plastics, porcelain was used as electrical insulation but the use of glass cloth offers a flexible insulation solution. Lunar plastics may be dispensed with.

LUNAR MAGNETIC MATERIALS – A FUNCTIONAL MATERIAL FOR ACTUATION

If electric motors can be constructed from lunar resources, machines can be built in-situ, i.e. machines of production, the basis of a self-sustaining industrial infrastructure. Permanent magnet motors are more compact than magnetic induction motors so DC/AC electric motors require permanent and soft magnets.

Iron core is the most traditional soft magnetic core material for its a high magnetic capacity and a relatively high magnetic permeability. It has significant magnetic capacity of 1.3 T. As Fe is an electrical conductor, it will conduct eddy currents. Heat is generated by the flow of eddy current which imposes limits to tolerance. At high temperatures, permanent magnets lose their magnetic strength - iron loses its magnetism above 600^{o}C. The addition of 3% Si to iron forms silicon steel (with a magnetic capacity of 1.6 T) which reduce eddy currents by increasing electrical resistance. The addition of Cr to form FeSiCr (3.5% Si and 4.5% Cr) further improves soft magnet performance but this option is not feasible for first generation ISRU. Eddy currents are also minimised with laminations into which electrical insulation is embedded. The insulation used is typically polyamide, polyurethane or other insulation. Most insulation is limited to a maximum of ~125^{o}C with polyurethane being rated up to 120^{o}C. Current-carrying copper wire

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is wound around the iron core. The coil of wire around the core generates the applied magnetic field when a DC passes through the coils. The higher the number of coils, higher the magnetic field generated. Typical wire coil insulation is enamel or cotton-insulated wire but modern wire is commonly coated in polyester, polyurethane or other insulator. Glass laminations and glass cloth respectively may offer options for lunar-derived motors. Ferrite is an iron (III) oxide (Fe_2O_3 - rust) ceramic that is chemically bound to another metal to form MFe_2O_4 where M=divalent metal cation. Ferrite is electrically resistive but ferrimagnetic. Soft ferrites have low coercivity (easy to demagnetise) for ferrite cores, e.g. $NiFe_2O_4$. Ferrites are typically manufactured through a series of procedures (Bhalla et al 2012) which can be adapted readily to lunar conditions: (i) metal oxides are mixed in water and dried at 150°C; (ii) powders are calcined (pre-heated in air at 75% sintering temperature ~900°C); (iii) powders are ball milled to ensure particle size ~5-15 μm; (iv) powders are mixed with a binder, lubricant and water to form a slurry which is sprayed with hot air into granules; (v) the granules are pressed into components in a mechanical or isostatic press with a pressure of 100-150 MPa; (vi) pre-sintering in a furnace up 800°C in air to evaporate binder and other impurities, then sintering to 1000-1300°C in inert gas to prevent oxidation (unnecessary on the Moon); (vii) component shrinks by 15-20% and surface machined by grinding with a hard ceramic wheel with water cooling. Traditional ceramic magnet manufacture is through casting because selective laser sintering/binder jetting yield porous structures. Ceramic ferromagnets such as soft ferrites ($NiFe_2O_4$) have been fabricated from metal oxide powders (NiO/Fe_2O_3) through extrusion-based freeforming (EFF) followed by high temperature solid state reactions (Peng et al 2017). EFF (robocasting) involves deposition of a ceramic paste through an orifice, the size of which determines the print resolution. The metal oxide powder <1 μm size was suspended (34-35% powder) in water containing polyvinyl alcohol as a binder, polyethylene glycol as a plasticiser and dispersant to obtain high fluid viscosity within the range 10-100 Pa.s. The paste was extruded using a standard fused deposition modelling 3D printer to construct objects layer by layer. Heating beyond 350°C evaporates the water then the organic material was burned off. Following printing, sintering above 1300°C for 60 h yields dense microstructures of ferrite with minimal porosity due to diffusion and grain growth but with 20% shrinkage yet retention of shape. The solid state reactions that occurred during sintering is given by: $NiO + Fe_2O_3 \rightarrow NiFe_2O_4$. The magnetisation increased with sintering temperature to a maximum at 1350°C of 48 emu/g for soft magnet nickel-iron oxide. Structures printed included mesh, helical gear, ring and cylinder structures. These techniques are potentially applicable to other ferrites such as $CoFe_2O_4$. For the Moon, the binder might be substituted with clay which also doubles as a plasticiser.

The stator permanent magnets have commonly adopted iron and ferrite (Fe_2O_3) though their magnetic densities are modest. Hard ferrites have high coercivity (hard to demagnetise) for permanent magnetic stators, e.g. $BaFe_{12}O_{19}$ (maximum magnetic field capacity of 0.35 T). Barium is not feasible to source on the Moon so hard ferrites are not an option. Cobalt ferrite $CoFe_2O_4$ is a semi-hard ferrite that may be substituted which also has magnetostrictive properties. Fe-Co has the a high induction rating at saturation of 2.2 T (with Tc =940°C). Ferrites may be formed through heating a mixture of the metal oxides (CoO and Fe_2O_3) to high temperature and pressed into a mould. As well as hard ferrites, more powerful ferromagnetic materials include iron-cobalt alloys, samarium-cobalt, alnico-iron alloys and rare earth magnets. Ferrous AlNiCo (aluminium-nickel-cobalt) alloy magnets double the magnetic energy density from iron and ferrites. Ferrous-AlNiCo (35% Fe, 35% Co, 15% Ni, 7% Al, 4% Cu and 4% Ti) alloys are hard magnetic materials usable up to 540°C with T_c=850°C with a coercivity of 50

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kA/m. They were commonly used in high torque motor applications prior to the development of rare earth magnets. Rare earth elements offer compact permanent magnets for their high magnetic fields. The first rare earth magnets were SmCo alloys $Sm_2(Co,Fe,Cu,Zr)_{17}$ which further doubled magnetic energy density from AlNiCo. They are usable up to 300°C with T_c=720°C offering a coercivity of 160-240 kA/m. The highest magnetic field capacity is offered by rare earth magnets of NdFeB alloys – they comprise the rare earth element Nd with Fe and B and small amounts of the rare earth element dysprosium offering a high field coercivity of 300-450 kA/m. However, the superior NdFeB alloys are usable up to only 140°C with T_c=310-400°C (α=-0.0012/°C). If the maximum temperature rating of the permanent magnet is exceeded, demagnetization will occur. The maximum temperature rating for SmCo (α=-0.0004/°C) is 300°C and AlNiCo (α=-0.0002/°C) is 540°C. Given the material limitations on the Moon and the high temperature tolerance of motors required, AlNiCo permanent magnets are favoured for lunar construction assuming that Cu component can be omitted without major loss of function – Cu is typically added to improve ductility which may be unnecessary if 3D printed.

Permalloy comprises 20% Fe and 80% Ni though 45 permalloy comprises 55% Fe and 45% Ni – it offers an even higher magnetic permeability of 100,000 and is used in transformer laminations over silicon steel. Variations include supermalloy (79% Ni, 16% Fe and 5% Mo) which offers a very high magnetic permeability of 800,000 and excellent soft magnetic properties. Magnetic shields are not usually necessary for electric motors but may be used in photomultiplier tubes and electron guns to prevent stray magnetic fields from deflecting the electron beam. For radiofrequency magnetic fields above 100 kHz, magnetic shielding is implemented by electrically conductive screens - Faraday shields. Faraday shields are metal mesh or screen enclosures to block electric fields by distributing electric charges to cancel interior electric fields. They are ineffective against low varying magnetic or static magnetic fields <100 kHz. The holes of the mesh must be much smaller than the wavelength of electromagnetic radiation to be shielded such as radio waves.

Amorphous metallic glasses are formed when the complex molten alloy – including the Ln-Al-TM family such as $Al_{90}Fe_5Ce_5$ and $La_{55}Al_{25}Ni_{20}$ - is cooled rapidly at ~10^5-10^6 K/s to prevent crystallisation (Greer 1995). This can be accomplished through melt spinning – molten alloy is sprayed onto the rim of a rapidly rotating wheel. They are brittle but there do exist high tensile strength species such as $Al_{88}Ni_9Ce_3Fe_1$. They possess soft magnetic properties with very low coercivity and but poor magnetic saturation. Fe-Co-based magnetic glasses – $Fe_{36}Co_{36}B_{19}Si_5Nb_4$ - exhibit superior magnetic softness than silicon steel and much lower power losses (Lesz 2017) but require exotic materials. Fe-based bulk metallic glasses such as those based on FeB alloy ($Fe_{80}B_{20}$, $Fe_{78}B_{12}Si_{10}$, etc) have soft magnetic properties with high saturation magnetisation of 1.3 T with applications in electromagnetic actuators (Suryanarayana & Inoue 2013). The simpler Fe-based metallic glass $Fe_{80}P_{13}C_7$ may be manufactured from raw Fe steel and FeP alloy through combined fluxing and J-quenching. It has high fracture strength has good soft magnetic properties with a saturation magnetisation of 1.4 T and low coercivity at 7.2 A/m (Ling et al 2015). However, metallic glasses require boron or carbon making them infeasible for lunar use. The discovery of Fe-based high temperature superconductivity offers promising applications (Beasley 2013). High temperature superconductors such as BSCCO and REBCO can create high magnetic flux >23 T in large electric motors to reduce their dimensions (Maeda & Yanagisawa 2014). High temperature superconducting wires for winding coils such as YBCO cooled to 25 K can generate current densities of 200 A/mm^2 (Frauenhofer et al 2006; Smitchler 2010). However, these are also beyond lunar resources but may be a future option for lunar electromagnetic launchers.

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CONCLUSIONS

We have shown that all the major functional systems of a spacecraft can be sourced from lunar resources. We will require a new design philosophy that emphasises maximum utilisation of resources rather than optimal energy efficiency or minimum mass as adopted in traditional spacecraft design. In particular, we examine the notion of sourcing material required to construct electric motors which constitute the key component for building manufacturing machines. This also appears feasible. The option for a second generation of ISRU technology suggests that accessing KREEP minerals will yield greater performance to functional systems but no radical new capabilities from the first generation.

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APPENDIX

<u>Lunar Ilmenite</u>

$Fe^0 + H_2O \rightarrow$ 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

$4Fe_2O_3 + Fe \leftrightarrow 3Fe_3O_4$)

<u>Nickel-Iron Meteorites</u>

W inclusions	$\rightarrow$	Thermionic cathodic material					
Mond process:		Alloy	Ni	Co	Si	C	W
$W(CO)_6 \leftrightarrow 6CO + W$							
$Fe(CO)_5 \leftrightarrow 5CO + Fe$ (175°C/100 bar)	$\rightarrow$	Tool steel				2%	9-18%
$Ni(CO)_4 \leftrightarrow 4CO + Ni$ (55°C/1 bar)	$\rightarrow$	Electrical steel			3%		

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$Co_2(CO)_8 \leftrightarrow 8CO + 2Co$ (150ºC/35 bar) → 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
↑____________|
$Na_2O + H_2O \rightarrow 2NaOH$
$NaOH + HCl \rightarrow NaCl + H_2O$

<u>Lunar Orthoclase</u>
$3KAlSi_3O_8 + 2HCl + 12H_2O \rightarrow KAl_3Si_3O_{10}(OH)_2 + 6H_4SiO_4 + 2KCl$
orthoclase illite silicic acid (soluble silica)
$2KAl_3Si_3O_{10}(OH)_2 + 2HCl + 3H_2O \rightarrow 3Al_2Si_2O_5(OH)_4 + 2KCl$
illite kaolinite
$[2KAlSi_3O_8 + 2HCl + 2H_2O \rightarrow Al_2Si_2O_5(OH)_4 + 2KCl + \mathbf{SiO_2} + H_2O]$
$KCl + NaNO_3 \rightarrow NaCl + KNO_3$
$2KCl + Na_2SO_4 \rightarrow 2NaCl + K_2SO_4$

<u>Lunar Olivine</u>
$3Fe_2SiO_4 + 2H_2O \rightarrow 2Fe_3O_4 + 3\mathbf{SiO_2} + 2H_2$ → magnetite for hard magnets
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

<u>Lunar Anorthite</u>
$CaAl_2Si_2O_8 + 4C \rightarrow CO + \mathbf{CaO} + \mathbf{Al_2O_3} + 2Si$ at 1650ºC → CaO cathode coatings
$CaO + H_2O \rightarrow Ca(OH)_2$
$Ca(OH)_2 + CO_2 \rightarrow CaCO_3 + H_2O$
$CaAl_2SiO_8 + 8HCl + 2H_2O \rightarrow CaCl_2 + 2AlCl_3.6H_2O + \mathbf{SiO_2}$ → fused silica glass + FFC electrolyte
$AlCl_3.6H_2O \rightarrow Al(OH)_3 + 3HCl + H_2O$ at 100ºC
↑______________________________|
$2Al(OH)_3 \rightarrow \mathbf{Al_2O_3} + 3H_2O$ at 400ºC → $2Al + Fe_2O_3 \rightarrow 2Fe + Al_2O_3$ (thermite)
AlNiCo hard magnets
Al solar sail

<u>Lunar Pyroxene</u>
$Ca(Fe,Al)Si_2O_6 + HCl + H_2O \rightarrow Ca_{0.33}(Al)_2(Si_4O_{10})(OH)_2.nH_2O + H_4SiO_4 + CaCl_2 + Fe(OH)_3$
Augite montmorillonite silicic acid iron hydroxide

<u>Lunar Volatiles</u>
$CO + 0.5\ O_2 \rightarrow CO_2$
$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300ºC (Sabatier reaction)
Ni catalyst
850ºC 250ºC
$CH_4 + H_2O \rightarrow CO + 3H_2 \rightarrow CH_3OH$ 350ºC
Ni catalyst Al_2O_3 $CH_3OH + HCl \rightarrow CH_3Cl + H_2O$ 370ºC $+nH_2O$
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)
$SO_3 + H_2O \rightarrow H_2SO_4$

<u>Salt of the Earth</u>
$2NaCl + CaCO_3 \leftrightarrow Na_2CO_3 + CaCl_2$ (Solvay process) → FFC electrolyte

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350ºC/150 MPa

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

1000-1100ºC

$CaCO_3 \rightarrow$ **CaO** + CO_2 (calcination)

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

$2NaCl(s) + H_2SO_4(g) \rightarrow 2HCl(g) + Na_2SO_4(s)$

<u>Metalysis FFC Process ($CaCl_2$ electrolyte)</u>

$MO_x + xCa \rightarrow M + xCaO \rightarrow M + xCa + \frac{1}{2}xO_2$ where M=Fe, Ti, Al, Mg, Si, etc

$CO + 0.5\ O_2 \rightarrow CO_2$

$CO_2 + 4H_2 \rightarrow CH_4 + 2H_2O$ at 300ºC (Sabatier reaction) $\rightarrow CH_4 \rightarrow C + 2H_2$ at 1400ºC $\rightarrow$ FFC anode regeneration

Ni catalyst

Fig A. Near closed loop lunar industrial ecology (emboldened materials are pure metal oxides for direct reduction using the FFC Cambridge process)

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