FFC Cambridge Process with Metal 3D Printing as Universal In-Situ Resource Utilisation

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Preamble

- Fundamental problem of human spaceflight
- Human is weakest component of a spacecraft – it requires enormous inputs of material and energy resources while expelling enormous outputs of material waste
- Closed ecological life support system (CELSS) attempts to compensate by recycling material throughput
- Ecology implies closed recycling system to minimise irreversible consumption
- Imperfect recycling → requirement for supply source
- CELSS supplemented by in-situ resource utilisation (ISRU)
- Most ISRU technologies to date are concerned with supplying consumable inputs to conventional environment control and life support system (ECLSS)
  - water
  - oxygen
- This is shallow ISRU
A Question of Morality

- Deep ISRU relates in-situ infrastructure construction, maintenance, repair and growth
- CELSS approach to deep ISRU on the Moon
- Objectives
  (i) near-100% supply from in-situ resources
  (ii) near-100% closed cycle industrial ecology
- Question - is it desirable for humans to bring their profligate and destructive habits with them as they embark into the space environment?
- Answer – we already have, by trailing our detritus with us up to GEO
- Commitment – we must not continue to degrade everything we touch beyond GEO
- Solution – sustainable exploration is built on two pillars:
  (i) dematerialisation through minimisation of material consumption
  (ii) detoxification of waste
- Industrial ecology addresses (ii) by converting waste into resources
ISRU through Industrial Ecology

- Industrial ecology must be built into human exploration and colonisation goals UPFRONT as a fundamental design requirement, not as an ad hoc afterthought.
- **IPAT equation** quantifies impact to be minimised – impact is complex function of cost of launch of materiel from Earth.
  
  \[
  I = P \times A \times T
  \]
  
  - \( I \) = population of industrial products produced by deep ISRU
  - \( A \) = cumulative resource units consumed per product produced (dematerialisation)
  - \( T \) = impact per resource unit consumed (detoxification)

- **Industrial ecology** seeks to reduce impact \( T \) through recycling.
- **Self-replication technology** requires minimisation of \( A \) for material and energy closure.
- Industrial ecology minimises waste of one process by feeding it as input to other processes.
- Closed loop recycling with 100% is highly desirable.
- Cradle-to-cradle sustainability requires recycling at EOL – this is enabled by 3D printing of powdered feedstock.
- Only imported reagent is NaCl (salt contingency) which is recycled.
- FFC Cambridge process and 3D printing lie at the core of our evolving lunar industrial ecology.
FFC Cambridge Process

- Electrolytic reduction vs thermochemical reduction
  - higher product yields
  - reduced impurities
- FFC Cambridge process reduces mineral oxides to 99% pure metal
- Sintered metal cathode in CaCl\textsubscript{2} electrolyte at modest temperatures
- Thermal heating may be implemented by Fresnel lenses
- Electric al energy may be supplied by thermionic conversion with 10% efficiency
- Product is metal alloy sponge that can be crushed, powdered and sintered into rods
- O\textsubscript{2} released and stored for human consumption or propellant oxidiser
Metalysis Process Overview

- Proven electrolytic process which can reduce metal oxides or ores into pure metals or alloys
- Relatively low temperature operation and lower energy consumption than melting technologies
  - reduction takes place in the solid state
- Inexpensive components for electrolysis:
  - metal oxide cathode;
  - graphite anode;
  - molten salt.
- No toxic gases used – only waste-product is CO/CO$_2$ and by product is Graphene.
- Powder feed to powder product: pre-alloyed or ore feedstock may be used directly
- The technology is well-suited to the manufacture of powders for 3D printing applications.
Engineering Development Roadmap

2004 - PRESENT
GEN1
Prove concept
Production of Grams
✓ Research

2008 - PRESENT
GEN2
Prove development
Production of Kilograms
✓ Developme nt

2014 - PRESENT
GEN3
Commercial development
Production of Tonnes
✓ Producing

2016/ 2017
GEN4
Industrial production
Production of 10s of Tonnes
✓ Scale up

2018+
GEN5
Large scale, industrial production
Production of 1000s of Tonnes
## Lunar Material Inventory

<table>
<thead>
<tr>
<th>Functionality</th>
<th>Lunar Material</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Tensile structures</strong></td>
<td>Wrought iron</td>
</tr>
<tr>
<td><strong>Compressive structures</strong></td>
<td>Cast iron</td>
</tr>
<tr>
<td><strong>Elastic structures</strong></td>
<td>Steel springs/flexures</td>
</tr>
<tr>
<td></td>
<td>Silicone elastomers</td>
</tr>
<tr>
<td><strong>Thermal conductors</strong></td>
<td>Fernico (e.g. kovar)</td>
</tr>
<tr>
<td><strong>Thermal insulation</strong></td>
<td>Glass (fibre)</td>
</tr>
<tr>
<td></td>
<td>Ceramics such as TiO$_2$</td>
</tr>
<tr>
<td><strong>Thermal tolerance</strong></td>
<td>Tungsten</td>
</tr>
<tr>
<td><strong>Electrical conduction</strong></td>
<td>Fernico (e.g. kovar) Nickel</td>
</tr>
<tr>
<td><strong>Electrical insulation</strong></td>
<td>Glass</td>
</tr>
<tr>
<td></td>
<td>Ceramic such as TiO$_2$</td>
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<tr>
<td></td>
<td>Silicone plastic</td>
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<tr>
<td></td>
<td>Silicon steel</td>
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<tr>
<td><strong>Active electronics</strong></td>
<td>Kovar</td>
</tr>
<tr>
<td></td>
<td>Nickel</td>
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<tr>
<td></td>
<td>Tungsten</td>
</tr>
<tr>
<td></td>
<td>Glass</td>
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<tr>
<td><strong>Magnetic materials</strong></td>
<td>Silicon steel</td>
</tr>
<tr>
<td></td>
<td>Permalloy</td>
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<tr>
<td><strong>Sensors and sensory transduction</strong></td>
<td>Quartz</td>
</tr>
<tr>
<td></td>
<td>Selenium</td>
</tr>
<tr>
<td><strong>Optical structures</strong></td>
<td>Polished nickel</td>
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<tr>
<td></td>
<td>Glass</td>
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<tr>
<td><strong>Liquids</strong></td>
<td>Silicone oils</td>
</tr>
<tr>
<td></td>
<td>Water</td>
</tr>
<tr>
<td><strong>Gases</strong></td>
<td>Oxygen</td>
</tr>
<tr>
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<td>Hydrogen</td>
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Lunar Volatiles

- Lunar rover provides surface mobility for resource mining – scoop regolith (bucket wheel) into a hopper
- RPM will demonstrate extraction of **volatiles** from lunar regolith - 96% $\text{H}_2$ (~120 ppm), almost 4% He, variable $\text{H}_2\text{O}$, and trace amounts of $\text{CO}$, $\text{CO}_2$, $\text{CH}_4$, $\text{N}_2$, $\text{NH}_3$, $\text{H}_2\text{S}$, $\text{SO}_2$, and noble gases such as $\text{Ar}$
- Gases are preferentially adsorbed onto small particles of ilmenite ($\text{FeTiO}_3$) – extracted magnetically/electrostatically
- Heating regolith to 700°C releases 90% of volatiles
- **Fractional distillation** may be employed to separate fractions: He (4.2 K), $\text{H}_2$ (20 K), $\text{N}_2$ (77 K), $\text{CO}$ (81 K), $\text{CH}_4$ (109 K), $\text{CO}_2$ (194 K) and $\text{H}_2\text{O}$ (373 K)
Silicone plastics offer advantages over hydrocarbon plastic

(i) UV radiation resistant
(ii) High operational temperature tolerance (350°C c.f. 120°C)
(iii) Si backbone minimises C resource consumption
(iv) use of flexible thermal insulation (wire sheathing)

Formation of syngas at 850°C and 4 MPa over Ni catalyst: \( \text{CH}_4 + \text{H}_2\text{O} \rightarrow \text{CO} + 3\text{H}_2 \)

Formation of methanol (or higher alcohol) at 250°C and 5-10 MPa over \( \text{Al}_2\text{O}_3 \) catalyst:
\[ \text{CO} + \text{H}_2 \rightarrow \text{CH}_3\text{OH} \]

Formation of chloromethane by HCl action at 350°C \( \text{Al}_2\text{O}_3 \) catalyst:
\[ \text{CH}_3\text{OH} + \text{HCl} \rightarrow \text{CH}_3\text{Cl} + \text{H}_2\text{O} \]

Formation of dialkyl dichlorosilane from Si at 370°C in presence of catalyst (Ni replace Cu?):
\[ 2\text{CH}_3\text{Cl} + \text{Si} \rightarrow (\text{CH}_3)_2\text{SiCl}_2 \]

Formation of polydimethylsiloxane (PDMS) – simplest siloxane – by hydrolysis:
\[ n(\text{CH}_3)_2\text{SiCl}_2 + n\text{H}_2\text{O} \rightarrow ((\text{CH}_3)_2\text{SiO})_n + 2n\text{HCl} \]

HCl is recycled – Cl required from salt contingency
FFC Cambridge Process – Raw Minerals

- FFC Cambridge process reduces lunar ilmenite (FeTiO$_3$) from maria regions to FeTi alloy:
  (i) general purpose structures
  (ii) Ferrotitanium (45-75% Ti) alloy for oxidant mop-up purification
  (iii) Pyrotechnic powder fuel with O$_2$
- Properties of FeTi alloy requires investigation

- FFC Cambridge process reduces lunar anorthite (CaAl$_2$Si$_2$O$_3$) from highland regions to AlCaSi alloy:
  (i) general purpose structures
  (ii) Silumin (3-25% Si) alloy for high durability, e.g. moving parts for machines
- Properties of AlCaSi alloy requires investigation

- FFC Cambridge process reduces lunar olivine (Mg$_2$SiO$_4$) from crater regions to MgSi alloy
  (i) general purpose structures
  (ii) small amounts of Mg$_2$Si additive to Al produces high strength Al alloy
- Greatest use of FFC Cambridge process is the reduction of pure oxides
Any Old Iron

- **Hydrogen reduction of ilmenite** at 1000°C:
  \[ \text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O} \]
  \[ 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2 \]
- Further heating to 1600°C allows bleeding of molten Fe
- \( \text{H}_2 \) is recycled and \( \text{O}_2 \) stored
- We have demonstrated **Fresnel lens smelting of Al alloy**
- **Wrought iron** is tough and malleable for structures
- **Tool steel** (<2% C + 9-18% W) for cutting tools
- **Silicon (electrical steel)** (up to 3% Si and 97% Fe) for electromagnets and motor cores
- **Kovar** (53.5% Fe, 29% Ni, 17% Co, 0.3% Mn, 0.2% Si + <0.01% C) has high electrical/thermal conductivity
- **Permalloy** (20% Fe + 80% Ni) provides magnetic shielding
From ilmenite reduction, impure Fe may be further purified using FFC Cambridge process.

Originally developed to replace Kroll process to extract Ti from rutile ($\text{TiO}_2$).

**RUTILE INPUT**

Carbothermic reduction of anorthite at 1650°C yields $\text{Al}_2\text{O}_3$ to be reduced to Al.

$$\text{CaAl}_2\text{Si}_2\text{O}_8 + 4\text{C} \rightarrow \text{CaO} + \text{Al}_2\text{O}_3 + 2\text{Si} + 4\text{CO}$$

Artificial weathering of anorthite with HCl yields $\text{SiO}_2$ to be reduced to Si.

$$\text{CaAl}_2\text{Si}_2\text{O}_8 + 8\text{HCl} + 2\text{H}_2\text{O} \rightarrow \text{CaCl}_2 + 2\text{AlCl}_3.6\text{H}_2\text{O} + 2\text{SiO}_2$$

This produces **CaCl$_2$ electrolyte** for FFC Cambridge process.

Si for fused silica glass manufacture, quartz production and for silicon steel.
Mascons in impact craters indicate location of NiFe meteorite ores – sometimes as magnetic anomalies, eg. rim of South Pole Aitken crater - similar to Sudbury astrobleme

Kamacite/taenite (NiFe alloys) is typically contaminated with Co

Mond process at 40-80°C reacts impure Ni with CO and S catalyst which is reversed at 230°C/60 bar: Ni(CO)₄ ↔ Ni + 4CO

S catalyst recovered at 750-1100°C from troilite (FeS) in meteoritic inclusions, lunar regolith (~1%), or lunar volatiles

Co fraction of NiFe alloy adjusted by mixing recovered Fe and Ni metal

Permalloy may be used as mu-material for magnetic shielding with \( \mu_r \sim 10^5 \) (replace 5% Ni with Mo gives supermalloy with \( \mu_r \sim 10^6 \))

Meteoritic NiFe alloys enriched in W microparticle inclusions which can be crushed and separated by froth flotation (W has high density of 19.3 and high melting temperature of 3500°C)
Additive/layered manufacturing (3D printing) involves cartesian robot configurations without tooling – **SLS** (multimaterial), **EBF3** (metal), **FDM** (plastic)

- Solar concentrator-based printing on Moon (**Fresnel lenses**)

- FFC Cambridge process outputs metal powders
  - direct input to powder bed such as SLS/SLM (e.g. Renishaw)
  - powder sintered into rod for EBF3 (e.g. NRC)

- SLS-printed structure from Ti powder

- 3D printing is a versatile manufacturing method that offers much potential
UC is a machine that can manufacture any other machine *including a copy of itself* (generalisation of the universal Turing machine)

RepRap can print its own plastic parts **but** it cannot print:
(i) structural metal bars (metal printing – discussed earlier)
(ii) joinery (replaced with cement/adhesive)
(iii) **motors**
(iv) **electronics/computer**
(v) **self-assembly** (by proxy)

Motor system – actuators, control electronics and sensors - is **core of all machines**: 3DP, milling, turning, pumping, surface finishing, robots, vehicles, drills, etc
3D Printed Motor Core

Our motor core comprises Fe powder in a plastic matrix
- 50% silicon steel particles in PLA matrix (NRC Canada)

- Pancake motor to test lithographically-printed wiring patterns
- We are working on a completely printed motor
DIY Multi-Material 3D Printing

- New “hobbyist” 3D printer to print in multiple materials
- An integrated **milling head** will provide surface machining
- **Fresnel lens** feed into fibre optic bundle
- Deposit molten Al wire tracks onto silicone plastic insulation:
  - Al alloy (440°C m. p.) ↔ silicone (350°C op temp)
- Temperatures of 1600°C are sufficient for **steel alloys**
- Print kovar wire onto ceramic silica substrates
- **Silicone plastic converted to silica ceramic** by high temperature combustion in oxygen
  - \( \text{SiO}_x\text{C}_y + (1-x+2y)\text{O}_2 \rightarrow \text{SiO}_2 + y\text{CO}_2 \)
- Silicone plastic 3D printed using FDM – converted to ceramic with \( \text{CO}_2 \) recovery – steel printed onto silica substrate
3D-Printable Electronics

- Solid state electronics requires complex processing so cannot be manufactured in-situ.
- **Vacuum tubes** are of simple construction that is potentially printable.
- They are thermionic diodes which use kovar resistance wire to heat tungsten cathode to 1000-2000°C to nickel anode in a evacuated glass envelope.
- CPU-based architectures grow **exponentially** but neural nets grow **logarithmically**.
- **Recurrent neural nets** are Turing-equivalent.
- Neural net act as compressed program output of 3D printer (TM model).
- Our modified **Yamashida-Nakaruma** hardware “printable” neuron comprises a weighted input, summing integrator and signum output.
- We have demonstrated a two-neuron hardware circuit on a desktop rover implementing real time obstacle avoidance.
Power of Self-Replication

- Low-cost enabled through lunar **in-situ resources** (ISRU) and **self-replication** technology
- **Exponentially** increasing productive capacity as $\sim (x+1)^n$
- Consider launch of a single 1 tonne self-replicating factory to the Moon at a cost of $2B$

<table>
<thead>
<tr>
<th>Number of offspring per generation</th>
<th>Number generations</th>
<th>of Population</th>
<th>Specific Cost ($/kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>10</td>
<td>1024</td>
<td></td>
</tr>
<tr>
<td>2</td>
<td>7</td>
<td>2187</td>
<td>&lt;$1000/kg$</td>
</tr>
<tr>
<td>2</td>
<td>13</td>
<td>1,594,323</td>
<td>&lt;$1.25/kg$</td>
</tr>
</tbody>
</table>

- Cumulative population is over $2 \times 10^6$ after **13 generations**
- On reaching full capacity, each of the $10^6$ factories can produce $10^6$ products/cycle
- My approach is to build from the bottom-up like the biological evolution rather than top-down like Agency-ese!
Wrap-Up

- We are working towards a fully 3D printed RAD-HARD cubesat including motors and circuits
- Multifunctional structures – neural net embedding
- Electric power from Fresnel lenses heating cathode for thermionic emission (as in nuclear reactors) with $\eta\approx 10\%$ - vacuum tube technology
- Energy storage by motorised flywheels
- Combination of FFC Cambridge and multimaterial 3D printing offer the prospect of universal construction
- We have the beginnings of an industrial ecology to support general purpose manufacturing on the Moon