Sustainable Lunar In-Situ Resource Utilisation = Long-Term Planning

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Sustainability requires consideration of future ISRU requirements

Water mining by heating regolith – higher temperatures yield highly valuable volatiles at 700°C releasing 90% of volatiles esp from smaller ilmenite particles: H₂, He, CO, CO₂, CH₄, N₂, NH₃, H₂S, SO₂, Ar, etc

Carbon compounds = very valuable resource

**Fractional distillation** for well-separated fractions: He (4.2 K), H₂ (20 K), N₂ (77 K), CO (81 K), CH₄ (109 K), CO₂ (194 K) and H₂O (373 K)
Hydrogen reduction of ilmenite at ~1000°C to create oxygen, iron and rutile:
$$\text{FeTiO}_3 + \text{H}_2 \rightarrow \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O} \text{ and } 2\text{H}_2\text{O} \rightarrow 2\text{H}_2 + \text{O}_2$$

Wrought iron is tough & malleable for tensile structures.

TuNiCo metals + W from nickel-iron meteorite impact craters (Mond process).

Tool steel (<2% C + 9-18% W) for milling tools.

Silicon (electrical) steel/ferrite (<3% Si and >97% Fe) for electromagnets and motor cores.

Kovar (53.5% Fe, 29% Ni, 17% Co, 0.3% Mn, 0.2% Si and <0.01% C) – type of fernico alloy with high-temp electrical conductivity.

Permalloy (20% Fe + 80% Ni) for magnetic shielding.
### Minimal Demandite

**Demandite for generic robot/spacecraft**

All materials are derivable from Moon except imported NaCl reagent (recycled)

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![Carleton University Logo](image)
### Lunar Ilmenite

Fe\(^0\) + H\(_2\O\) → ferrofluidic sealing  
FeTiO\(_3\) + H\(_2\) → TiO\(_2\) + H\(_2\O\) + Fe  
2H\(_2\O\) → 2H\(_2\) + O\(_2\)

2Fe + 1.5O\(_2\) → Fe\(_2\)O\(_3\)/Fe\(_2\)O\(_3\).CoO - ferrite magnets

### Nickel-iron meteorites

Fe(CO)\(_5\) ↔ 5CO + Fe (175°C/100 bar)  
Ni(CO)\(_4\) ↔ 4CO + Ni (55°C/1 bar)  
Co\(_2\)(CO)\(_8\) ↔ 8CO + 2Co (150°C/35 bar)  
S catalyst

4FeS + 7O\(_2\) → 2Fe\(_2\)O\(_3\) + 4SO\(_2\)  
(Troilitite)  
SO\(_2\) + H\(_2\)S → 3S + H\(_2\O\)

FeSe + Na\(_2\)CO\(_3\) + 1.5O\(_2\) → FeO + Na\(_2\)SeO\(_3\) + CO\(_2\)  
KNO\(_3\) catalyst

\(\text{Na}_2\text{SeO}_3 + \text{H}_2\text{SO}_4 \rightarrow \text{Na}_2\text{O} + \text{H}_2\text{SO}_4 + \text{Se} \rightarrow \text{photosensitive Se}\)

W inclusions – high density of 19.3  
→ cathodic material

### Olivine

Mg\(_2\)SiO\(_4\) + 2CH\(_4\) → 2CO + H\(_2\) + MgO + Si at 2000°C  
\(\text{MgO + HCl} \rightarrow \text{MgCl}_2 + \text{H}_2\O\)  
→ 3D Shaping binder  
CO + 0.5 O\(_2\) → CO\(_2\)

CO\(_2\) + 4H\(_2\) → CH\(_4\) + 2H\(_2\O\) at 300°C (Sabatier reaction)  
→ CH\(_4\) + C + 2H\(_2\) at 1400°C for steel

Ni catalyst

### Lunar Anorthite

CaAl\(_2\)SiO\(_8\) + 4C → CO + CaO + Al\(_2\)O\(_3\) + 2Si at 1650°C  
CaO + H\(_2\O\) → Ca(OH)\(_2\)  
Ca(OH)\(_2\) + CO\(_2\) → CaCO\(_3\) + H\(_2\O\)

CaAl\(_2\)SiO\(_8\) + 5HCl + H\(_2\O\) → CaCl\(_2\) + 2AlCl\(_3\).6H\(_2\O\) + SiO\(_2\)  
AlCl\(_3\).6H\(_2\O\) → Al(OH)\(_3\) + 3HCl + H\(_2\O\) at 100°C

\(\text{Al(OH)}_3 \rightarrow \text{Al}_2\text{O}_3 + 3\text{H}_2\O\) at 400°C  
→ 2Al + Fe\(_2\)O\(_3\) → 2Fe + Al\(_2\)O\(_3\) (thermite)

AlNiCo hard magnets  
Al solar sail

### Lunar Volatiles

\(\text{CH}_4 + \text{H}_2 \rightarrow \text{CO} + 3\text{H}_2 \rightarrow \text{CH}_3\O\)  
\(\text{Ni catalyst}\)

Al\(_2\)O\(_3\)  
CH\(_3\O\) + HCl → CH\(_3\)Cl + H\(_2\O\)

Al\(_2\)O\(_3\)  
CH\(_3\)Cl + Si → (CH\(_3\))\(_2\)SiCl\(_2\) → ((CH\(_3\))\(_2\)SiO)\(_n\) + 2nHCl → silicone plastics/oils

3NO + H\(_2\O\) → 2HNO\(_3\) + NO

\(2\text{SO}_2 + \text{O}_2 \leftrightarrow 2\text{SO}_3\) (low temp)

SO\(_3\) + H\(_2\O\) → H\(_2\)SO\(_4\)

### Salt of the Earth

NaCl + CaCO\(_3\) → Na\(_2\)CO\(_3\) + CaCl\(_2\)  
\(350°C/150 \text{ bar}\)  
→ metalsysis electrolyte

Na\(_2\)CO\(_3\) + SiO\(_2\)(l) ↔ Na\(_2\)SiO\(_3\) + CO\(_2\) → piezoelectric quartz

NaCl + HNO\(_3\) → HCl + NaNO\(_3\)

### Lunar Orthoclase

2KAl\(_2\)Si\(_3\)O\(_8\) + HCl + 9H\(_2\O\) → H\(_4\)Al\(_2\)Si\(_2\)O\(_8\) + 2KCl + SiO\(_2\) + H\(_2\O\)

Kaoalinite  
KCl + NaNO\(_3\) → NaCl + KNO\(_3\)

### Sustainable Lunar Industrial Ecology
Electrolytic Metalysis FFC Cambridge Process = Universal Chemical Processor

- Cathode is sintered metal oxide, e.g. TiO$_2$
- **CaCl$_2$ electrolyte** at 900°C with O$_2$ evolved at the anode (assumed non-eroding) (graphite anode yields CO/CO$_2$ – recyclable through **Sabatier process** – Mars analogue field test)
- Product is **99%+ metal alloy sponge** that can be powdered for 3D printing
- TiO$_2$ powder → Ti powder → 3D printed Ti parts

- Output powder has been directly 3D printed into Ti test parts with selective laser sintering (SLS)
- Metalysis process applicable to ALL metal oxides
3D Printer = Universal Construction Mechanism

- **RepRap** FDM 3D printer can print many of its own **plastic parts**

- Full self-replication requires 3D printing:
  1. structural metal bars and components (SLS/M or EBAM)
  2. joinery (replaced with cement/adhesive)
  3. **electric motor drives**
  4. **electronics** boards
  5. **computer hardware/software**

- Full self-replication also requires:
  1. self-assembly (proxy for manipulator motors)
  2. self-power (solar-thermionic/flywheel)
  3. material processing into feedstock - **ISRU**

From 3D printed electric motors and electronics, **omnia sequitur**…

- JCBs - excavators - drills – milling machines – etc
3D Printed DC Motor

- Motor core - 50% Fe powder in PLA matrix
- Stator – ditto
- 3D printed permanent magnet stators (Oak Ridge National Lab USA)
- LOM-printed wiring
Multi-Material 3D Printer

- New “hobbyist” but rigid multi-material 3D printer to print in metals and plastics using FDM (motors have been added)
- Solar furnace based on 1.2 m x 0.9 m Fresnel lens for melting Al alloy in ceramic crucible → 3D printing by Fresnel lenses
- We have deposited molten Al wire tracks onto silicone plastic insulation: $\text{Al alloy (440°C m. p.) } \leftrightarrow \text{ silicone (350°C op temp)}$
- We have demonstrated metal deposition on plastic!
- Two extrusion heads being added – fibre optic and silicone plastic extrusion head
- Phase 2 - 3rd milling head for integrated surface finishing
- Phase 3 – 4th wrist assembly head for component assembly
- Phase 4 – Migrate to steels/silicone-derived ceramics
Analogue Neural Nets = Turing Complete

- **Vacuum tubes** = thermionic devices – kovar wire - tungsten cathode - CaO coating - Ni anode and control grid - glass envelope
- Direct model of original Turing machine:
  - **Input tape** = magnetic core memory (same components as motor)
  - **Output tape** = analogue neural net circuits
  - **Read/write head** = 3D printer
- Modified **Yamashida-Nakaruma** hardware “printable” neuron
- New learning neural net circuit (BP cct)
Anne Bell’s Artist Impression