Regolith

Metallurgy for a Vacuum World

Abstract

Most visions of lunar industry begin with resources. This framing is incomplete.

The Moon is not merely a repository of raw materials. It is a fundamentally different metallurgical environment. Nearly every terrestrial extraction process was developed under assumptions of atmospheric pressure, abundant oxygen, accessible water, established logistics networks, and continuous human intervention. None of these assumptions hold on the lunar surface.

Lunar regolith contains substantial quantities of oxygen, silicon, aluminum, iron, titanium, magnesium, and calcium. The challenge is not resource discovery but resource transformation. These elements exist primarily as stable oxides whose reduction requires the expenditure of free energy.

The central problem of lunar industry is therefore not mining.

It is metallurgy.

1 The Moon as an Oxide World

Unlike Earth, oxygen is not available as a free atmospheric resource. Instead, oxygen exists chemically bound within silicate and oxide minerals.

$$SiO_2$$
$$Al_2O_3$$
$$FeO$$
$$TiO_2$$
$$MgO$$
$$CaO$$

From a metallurgical perspective, these compounds represent reservoirs of oxygen and metal stored in thermodynamically stable states.

The industrial challenge is to transform these oxides into useful products.

$$FeO \rightarrow Fe + \frac{1}{2}O_2$$

$$TiO_2 \rightarrow Ti + O_2$$

$$Al_2O_3 \rightarrow 2Al + \frac{3}{2}O_2$$

2 Free Energy as the Fundamental Constraint

The feasibility of oxide reduction is governed by Gibbs free energy.

$$\Delta G^\circ = \Delta H^\circ - T\Delta S^\circ$$

The Ellingham diagram provides a thermodynamic ranking of oxide stability and therefore a ranking of extraction difficulty.

Viewed in this way, the Ellingham diagram is not merely a metallurgical chart.

It is a map of the energetic cost of lunar industrialization.

3 Lunar Metallurgy

The Moon provides conditions unavailable on Earth:

- ultra-high vacuum
- negligible oxygen partial pressure
- high solar irradiance
- reduced gravity
- limited volatile inventory

Vacuum processing is effectively free.

Contamination from atmospheric gases is minimized.

Electrochemical extraction pathways become more attractive.

The objective is not to reproduce Earth industry on the Moon.

The objective is to discover industrial processes native to the lunar environment.

4 Molten Regolith Electrolysis

One of the most promising approaches to lunar resource utilization is molten regolith electrolysis.

At the anode:

$$2O^{2-} \rightarrow O_2 + 4e^-$$

At the cathode:

$$Fe^{2+} + 2e^- \rightarrow Fe$$

The process simultaneously generates oxygen and metallic products directly from regolith feedstocks.

The process transforms lunar soil into infrastructure.

5 Conclusion

The Moon is oxygen-poor environmentally but oxygen-rich geologically.

The central challenge of lunar industry is not discovering resources but transforming stable oxides into useful materials.

Metallurgy therefore becomes the foundation upon which all future lunar industry is built.

Thesis

The Moon is not resource-constrained.

It is free-energy constrained.

Lunar regolith already contains the oxygen, metals, and mineral resources required for industrial development. The central challenge is supplying sufficient free energy to transform matter from its existing thermodynamic state into a useful one.

The future of lunar industry will be determined by our ability to redesign metallurgical systems for a vacuum world.