

EXTRACTION OF OXYGEN AND METALS FROM LUNAR ORES

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Abstract — Consideration of the lunar environment suggests modifications of the Bayer-Hall approach leading to a conceptual process for extracting aluminum and oxygen from lunar soil. The process consists of electrowinning aluminum-silicon-iron-titanium alloy and oxygen from unrefined soil in a bipolar fluoride type cell with inert electrodes. Aluminum and other elements would be recovered from the alloy by vacuum fractional distillation. The silicon produced would be used to produce solar cells for additional electrical power.

1. INTRODUCTION

Energy is the major factor that encourages us to consider space industrialization. Terrestrial energy needs have increased to such huge levels that serious consideration is being given to constructing large solar power stations (SPS) in space to convert solar energy into microwave power and then beam microwaves to the earth for reconversion to terrestrial electricity. Solar energy is clearly available continuously to do work in space and space industrialization is technically feasible. However, the development of a space materials economy or space industrialization is strongly inhibited by the extremely high cost of transporting matter from earth with which to work in space.

The moon is a primary source of raw material for large scale use in space. The motivations for use of lunar materials are:

1. The moon is the largest source of matter near the earth. We possess considerable general knowledge of the entire moon and extremely precise knowledge of the specific areas of the moon.
2. Terrestrial technology can be transferred to the gathering of lunar materials and the processing of raw lunar materials into industrial feedstock. Devices and tools have been identified that can allow us to obtain materials from the moon for large scale use in space at considerably lower cost than will ever be possible by transporting materials into space from the earth.

Because the lunar escape energy is five percent of that of the earth, the cost of lunar ejections (by means of electromagnetic launchers) could be in the order of a few cents per kilogram. In addition, the moon has no atmosphere to cause drag and frictional heating.

3. The moon offers a large supply of the elements with which industry has experience in working and producing the broad range of goods that sustain our present style of life. About 92% of chemical elements used on the earth, exclusive of fossil fuels, can be obtained from lunar soil. The economically significant elements, like

oxygen, silicon, calcium, iron, aluminum, magnesium and titanium, can be extracted from the lunar soil. Space power stations could be constructed of approximately 90% lunar derived material.

2. LUNAR ENVIRONMENT

The principal distinguishing requirement for a successful lunar operation is that all materials unavailable from lunar sources must be shipped from earth and recycled with minimal loss.

The following constraints apply to processing lunar ore:

1. Lack of virtually inexhaustible supplies of air and water.
2. Lack of fossil fuels.
3. Lack of inexhaustible oxidizing and reducing agents. Carbon is very scarce on the lunar surface.
4. Lack of expendable halogens, acids and bases.
5. Lack of air and water makes the management of process waste heat especially important. Rejected heat will ultimately have to be transferred to space through radiation.
6. Processing conditions must be adjusted for the lower lunar gravity.

3. LUNAR ORE

The major lunar raw materials are ilmenite, plagioclase and anorthite. Anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) contains 19.4% aluminum, 20.2% silicon, 14.4% calcium, and 46% oxygen. A typical composition of lunar rock from Maria section would be silica 42%, titanium dioxide (TiO_2) 7.5%, alumina 13.9%, iron oxide (FeO) 15.7%, magnesium oxide (MgO) 7.9%, calcium oxide (CaO) 12.1%. The composition of lunar rock from the highland area would be silica 45.4%, TiO_2 0.5%, alumina 23.4%, FeO 7.4%, MgO 9.2%, CaO 13.4%, and traces of potassium oxide, sodium oxide, manganese oxide, phosphorus oxide, and chromium oxide (1).

The majority of lunar soil is completely anhydrous and has an average grain size of 30–70 microns. Eighty-five percent to 95 wt.% of the lunar powder is less than 1 mm in diameter.

4. REVIEW OF LUNAR EXTRACTION PROCESSES

Since carbon is very scarce on lunar surface, Rao and co-workers (2) decided quite early that carbothermic reduction of lunar soil would probably be impractical for space processing. They chose carbo-chlorination of lunar anorthite ($\text{CaAl}_2\text{Si}_2\text{O}_8$) and lunar ilmenite (FeTiO_3). A major advantage of carbo-chlorination is that it would require little water. However, the recycling of chlorine and carbon would require facilities much larger than the basic processing plant.

Of the nonelectrolytic processes studied to date, the hydrofluoric acid leach method appears to require the minimum operating mass to be transported to the moon. Waldron *et al.* (1) have described a low temperature hydrometallurgical step to remove the silicon from the other metallic oxides by conversion to fluorides and fluosilicates. This is followed by vaporization of the silica as SiF_4 , and separation of

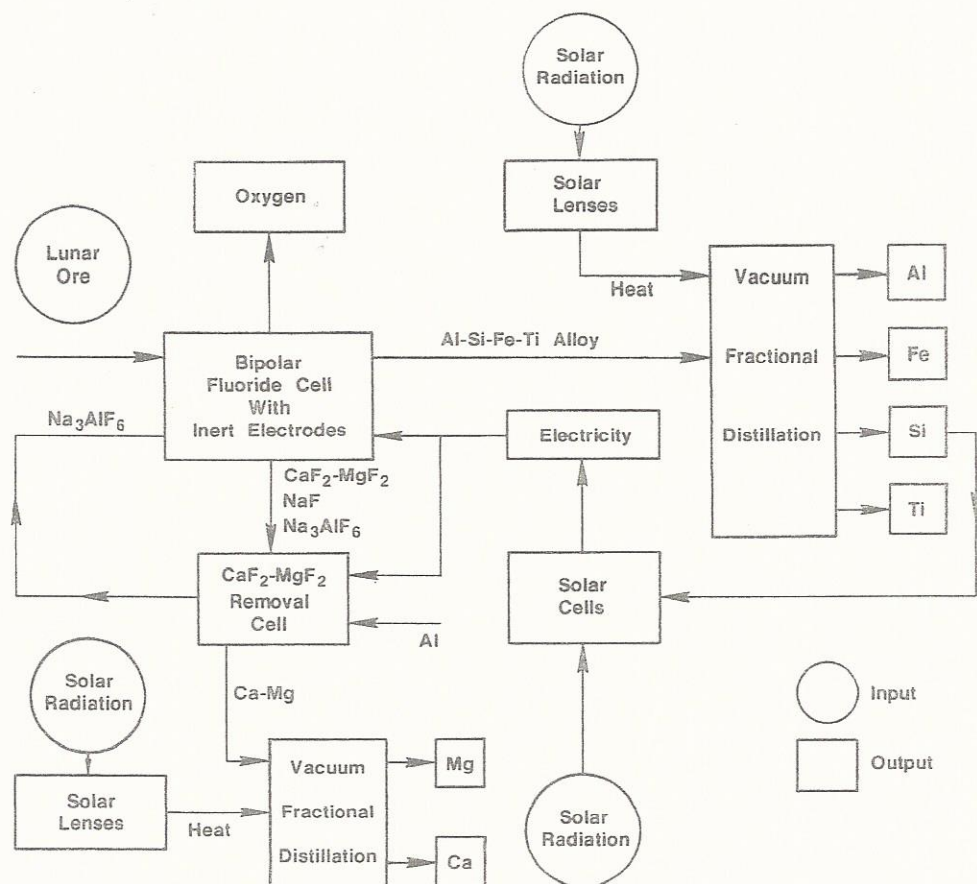


Fig. 1. Proposed system for lunar extraction of oxygen and metals.

the calcium and the structural metals (aluminum, iron, magnesium, titanium) by a variety of solution, precipitation, ion exchange or electrolyte steps. However, this process requires water or at least hydrogen to make water. This must be transported from earth, but it is recyclable. Electrolytic systems to process lunar materials have a strong appeal because of their potential simplicity and low use of water and other reagents.

Limited investigation of direct electrolysis of molten silicates of compositions similar to lunar soils have been performed (3,4). The high melting point and the

TABLE 1

Oxides	Solubility in cryolite at 970°C (%)	Decomposition potential at 970°C (volts)
Al ₂ O ₃	11	2.2
SiO ₂	8.8	1.8
FeO	6	1.0
TiO ₂	6.9	1.9

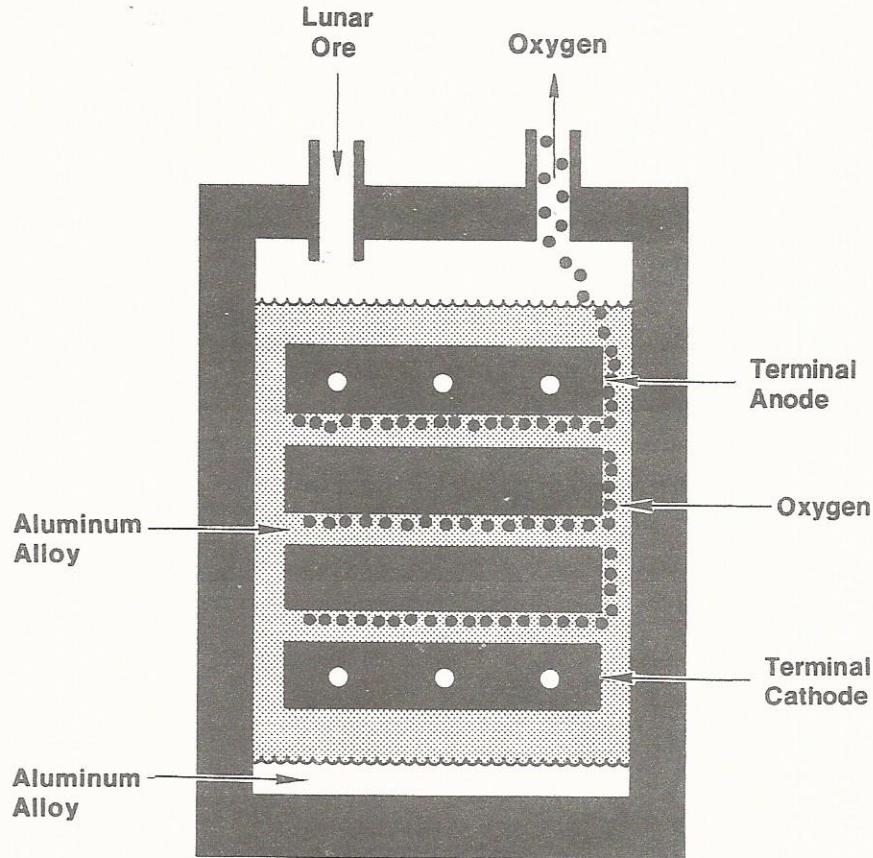


Fig. 2. Bipolar electrolytic cell.

viscosity of molten silicates have created problems and prompted studies of various fluxing additions to the melt. This modification, of course, negates the reagentless advantage of the direct electrolysis route and requires consideration of extraction and recycling of fluxing reagents. The chief objections are corrosion or durability of anodes used for oxygen recovery and purification and separation of cathodic reduction products which are likely to consist of iron, iron-silicon-aluminum alloy with minor amounts of additional impurities.

5. PROPOSED PROCESS

This paper describes a conceptual process scheme for obtaining oxygen, aluminum, silicon, iron, and titanium from anorthite ore. The lunar environment offers the following opportunities:

1. The abundant solar energy can be converted to electricity to operate electrolytic cells for producing an aluminum alloy and pure oxygen from lunar ores.
2. The complete vacuum (10^{-14} Torr) offers a chance to vacuum purify and separate aluminum, iron, silicon, and titanium metals from aluminum-silicon-iron-titanium alloys produced in the electrolytic cell.
3. By using suitable optics, solar energy can generate the high temperatures needed for vacuum fractional distillation.

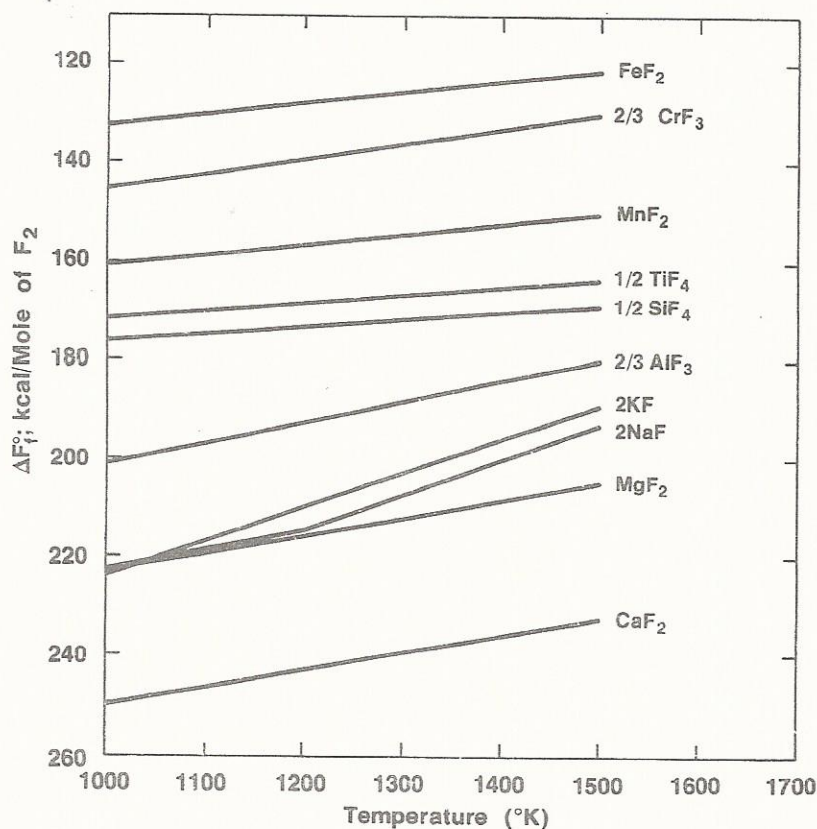


Fig. 3. Free energy of formation of selected fluorides as a function of temperature.

Figure 1 shows a schematic flow diagram of the proposed process for extracting desirable metals from lunar ores; it also produces oxygen for life support and for use as propellants.

6. BIPOLAR ELECTROLYTIC CELLS

In the proposed system, either unbeneficiated or mechanically beneficiated lunar dust would be used as ore. The fine particle size of the dust makes magnetic and electrostatic separation attractive. No grinding is necessary. All use of water would be avoided. The ore would be fed into a bipolar cell having a cryolite (Na_3AlF_6) base electrolyte. Lunar ore should dissolve easily in molten cryolite. The solubility in cryolite and the decomposition potentials of the various oxides in lunar ores are shown in Table 1.

The proposed bipolar cell would be similar to that used in the Alcoa Smelting Process for electrolysis of aluminum from aluminum chloride in molten chloroaluminate melts (Figure 2). Electric current would enter the cell through a terminal anode, flow through numerous bipolar plates between the terminal electrodes and exit through a terminal cathode. The top surface of each bipolar plate would act as a cathode while the bottom surface would act as an anode. The alumina (Al_2O_3), silica (SiO_2), ferrous oxide (FeO), and titania (TiO_2) content of the ore would be elec-

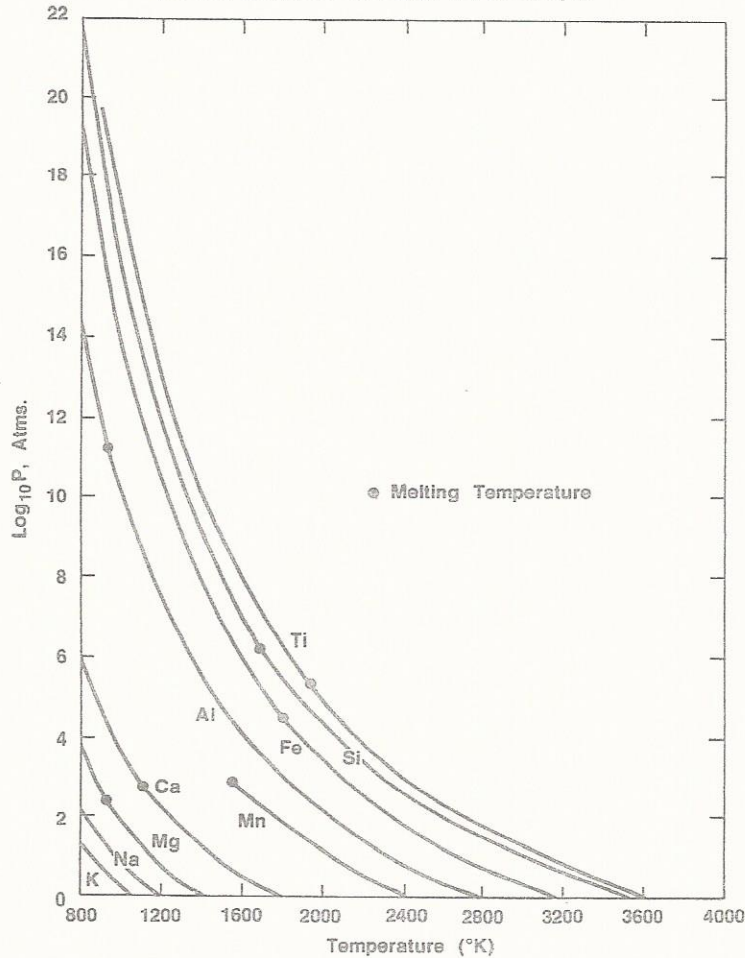


Fig. 4. Vapor pressure of selected elements as a function of temperature.

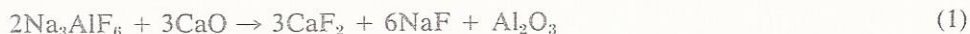
trolyzed, forming oxygen at each anode and an aluminum, silicon, iron and titanium alloy at each cathode. Oxygen gas would rise from each anode through the electrolyte providing circulation of the electrolyte and leave the cell at the top while the metal alloy would settle to the bottom and be tapped periodically. Calcium and magnesium compounds from the ore would accumulate in the electrolyte and have to be removed. A technique to accomplish this will be discussed in the next section.

Search for an inert anode material is being pursued actively by various aluminum companies. Not only would inert anodes alleviate the need for frequent replacement of consumable anodes but would also permit collection of essentially pure oxygen. Tin oxide (SnO_2) mixed with various other oxides such as ferric oxide (Fe_2O_3) and nickel oxide (NiO) have been suggested for inert anodes (5). Refractory hard metals, titanium diboride (TiB_2) in particular, presumably will make suitable inert cathodes (6).

7. ELECTROLYTE PURIFICATION AND RECYCLING SYSTEM

Since calcium fluoride and magnesium fluoride are thermodynamically more

stable than aluminum fluoride (Figure 3), the calcium oxide and magnesium oxide content of the lunar feed material would undergo the following reactions:



Calcium fluoride and magnesium fluoride dissolve in the electrolyte, lowering electrical conductivity, ore solubility and liquidus temperature. Their concentration will be allowed to build up until they pose an operation problem in the electrolytic cell. Once this limit approaches, the electrolyte will be purified. An attractive technique for this purification would be to discontinue feeding ore. When the oxides have been exhausted, the cell will start to electrolyze calcium and magnesium fluorides, at a somewhat higher voltage, producing fluorine instead of oxygen and a Ca-Mg alloy instead of the Al-Si-Ti-Fe alloy (Reaction 3). It might be more convenient to take a side stream of electrolyte off from the main cell and do this electrolysis in a separate small electrolytic cell:



The fluorine gas produced will be reacted with aluminum to make aluminum fluoride. This will be added back to the aluminum producing cells where it will combine with sodium fluoride to produce cryolite.



Calcium magnesium alloy produced by Reaction 3 can further be separated into its constituent elements calcium and magnesium by vacuum fractional distillation.

8. PURIFICATION OF ALUMINUM ALLOY

The existence of near vacuum (about 10^{-14} Torr) on the lunar surface, absence of any oxidizing gas, and wide differences in the vapor pressure of different elements (Figure 4) make the vacuum fractional distillation technically feasible for separating the Al-Si-Fe-Ti alloy into its constituent elements.

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