Materials refining on the Moon

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Abstract

Oxygen, metals, silicon, and glass are raw materials that will be required for long-term habitation and production of structural materials and solar arrays on the Moon. A process sequence is proposed for refining these materials from lunar regolith, consisting of separating the required materials from lunar rock with fluorine. The fluorine is brought to the Moon in the form of potassium fluoride, and is liberated from the salt by electrolysis in a eutectic salt melt. Tetrafluorosilane produced by this process is reduced to silicon by a plasma reduction stage; the fluorine salts are reduced to metals by reaction with metallic potassium. Fluorine is recovered from residual MgF and CaF_2 by reaction with K_2O.
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1. Background

Oxygen, a major component of rocket fuel and also critical for human life support, is a high-priority resource to be produced on the Moon. Many processes have been proposed to manufacture oxygen from lunar regolith [1–6]. In the longer term, sustained habitation and industrialization of the Moon will require the ability to produce other raw materials from lunar materials [7]. It would be desirable to produce industrial materials as a co-product of oxygen manufacture. This paper discusses some engineering materials that can be made as a byproduct of oxygen production by reduction of lunar regolith, and presents a reduction technique that will produce these raw materials as well as oxygen.

Solar arrays are one product that has been suggested as a valuable item that could be made from lunar materials [7–10]. The process of lunar production of solar

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cells has been addressed by several researchers [8–14]. Silicon is of significant interest here, since it is the only semiconductor which can be refined from the major components of lunar soil. Silicon may also be useful for production of silane as a possible rocket fuel [15], to reduce the amount of hydrogen used. Other valuable products include the raw materials needed to produce habitation modules, fuel tanks, and components for spacecraft.

This work will focus on production of the raw materials, including developing workable production systems to reduce the lunar soil and produce the refined feedstock materials for making structural elements, electrical conductors, and solar arrays from materials available on the lunar surface, from the reduction of regolith to produce oxygen.

Table 1 shows the elemental breakdown of the average composition of the lunar surface, showing the elements present in the lunar soil at abundances of 0.1% (by weight) or higher [16,17]. The processing sequence chosen should optimally recycle all reagents and waste

Table 1
Average composition of major materials on the lunar surface (percent by weight)

Element	Amount (wt%)
O	43.4
Si	20.3
Mg	19.3
Fe	10.6
Ca	3.22
Al	3.17
Cr	0.42
Ti	0.18
Mn	0.12
H	([a])

[a]Hydrogen: while hydrogen is present in surface soil at approximately 50 ppm by weight, it is a major soil component in high-latitude (near polar) craters only.

products that are not available on the lunar surface. The following materials are the useful feedstocks to be manufactured:

Metals (structural).
Composite structural materials: glass fiber and matrix.
Transparent materials: glass.
Electrical conductors (wiring): aluminum or calcium.
Semiconductors: silicon.
Semiconductor dopants: aluminum (p), phosphorus (n).

2. Refining of regolith

2.1. Regolith refining strategies

Extraction of purified feedstocks from the lunar regolith cannot be done using the industrial production processes currently in use on Earth. Terrestrial silicon production uses as a raw material high-silica sand, while lunar regolith is primarily mixed igneous silicates such as anorthosites. Also, the terrestrial production methods reduce ores to metal by carbon reduction with coal, using up one mole of carbon for each mole of metal produced. Any production process for the Moon must not use reactants that are not completely recycled.

Unbeneficiated lunar soil ("regolith") is powdered igneous rock. Table 1 shows the average composition of the lunar surface; Fig. 1 shows the average composition of lunar regolith. It consists primarily of iron, calcium, aluminum, and magnesium silicates, with small amounts of chromium, titanium, and manganese. In some places, the soil also contains sodium, potassium, and rare-earth oxides. The exact composition varies from site to site, and possibly from sample to sample at a given site. Regolith composition and mineralogy are
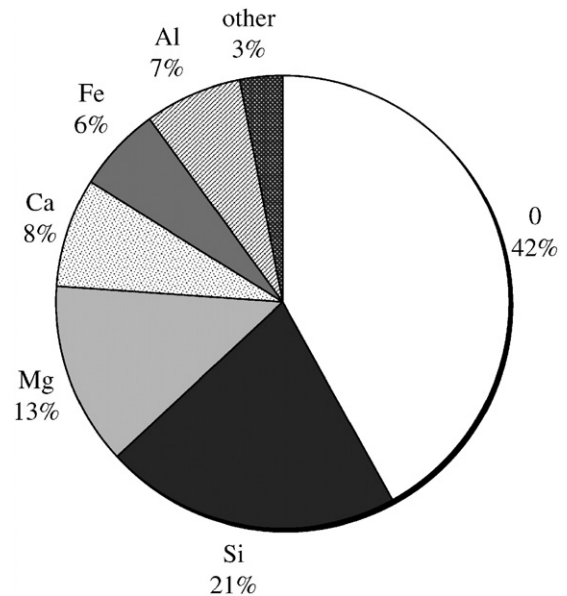

Fig. 1. Composition of the lunar regolith.

discussed in detail in the Lunar Sourcebook [16] and elsewhere [17].

Several different production processes were examined. Good reviews are found in several references [1–3]. Many of the commonly proposed processes for reduction of regolith to produce oxygen from lunar resources, such as hydrogen reduction of ilmenite [6], were not applicable, since they did not produce reduced silicon. Others were discarded because reduced feedstocks, although byproducts, were not separated from other materials reduced in the oxygen production process. Finally, processes were selected based on a requirement that the materials be produced in a form that would allow easy purification.

Since the site of the lunar base is likely to be chosen on the basis of other criteria, it is desirable that the process chosen should be suitable for use on "average" lunar regolith, that is, the process should not require prospecting for a particular ore or a soil which is high in concentration in a particular mineral. For simplicity in materials handling, raw lunar regolith used in the production sequence should be able to be used with no pre-processing or beneficiation to concentrate particular mineral compositions in the soil.

2.2. Fluorine processing

Fluoride extraction [5] was chosen as the primary method to remove the oxygen from the rock, followed by potassium displacement to produce the raw material
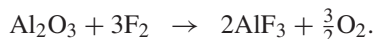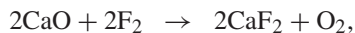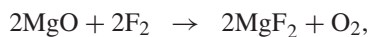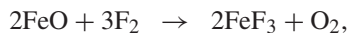
for reduction and refining. The fluorine process has two distinct advantages over the other processes considered. First, it can be used on unbeneficiated lunar soil without processing to enrich the content of any particular mineral. Second, raw materials can be separated out at the fluoride stage, allowing production of many reduced materials in a relatively refined form. Silicon is produced in the form of tetrafluorosilane, which can be easily purified to semiconductor grade by removal of contaminating traces of the other metals by distillation. The process leads in a straightforward manner to production of reduced metallic titanium, aluminum, and iron, and purified oxides of calcium and magnesium.

Fluorine is brought to the Moon in the form of potassium fluoride (KF). The KF is then electrolyzed to produce potassium and fluorine. Both potassium and the fluorine are used as reactants in the process.

The basic reduction process is to heat the regolith in the presence of fluorine. The fluorine will displace the oxygen, which is collected as a useful byproduct. Silicon and titanium produce volatile fluorides:

$$SiO_2 + 2F_2 \rightarrow SiF_4 + O_2,$$

$$TiO_2 + 2F_2 \rightarrow TiF_4 + O_2.$$
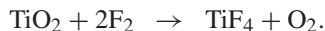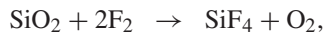
The remaining metals are produced in the form of fluoride salts, which must be purified and reduced to the metals. The primary reactions are:

$$2FeO + 3F_2 \rightarrow 2FeF_3 + O_2,$$

$$2MgO + 2F_2 \rightarrow 2MgF_2 + O_2,$$

$$2CaO + 2F_2 \rightarrow 2CaF_2 + O_2,$$

$$Al_2O_3 + 3F_2 \rightarrow 2AlF_3 + \tfrac{3}{2}O_2.$$

The silicon, titanium, aluminum, and iron are reduced. The calcium and magnesium remain in the form of oxide. A block diagram of the basic mass flow process is shown in Fig. 2.

The initial regolith heating step will also outgas volatiles, primarily materials implanted from the solar wind, out of the regolith. These will include hydrogen (in the form of water), oxygen, carbon monoxide, nitrogen, fluorine, sulfur, helium, and trace amounts of other volatiles. These can be captured after the heating but before the fluorine reaction is initiated by the use of a condenser, or a series of condensers. The evolved fluorine (which will be released as hydrogen fluoride, HF) may be useful for replacement of process losses. The

other evolved volatiles will also be valuable, although only present in small amounts.

This fluorine process is different from that suggested in earlier work [8,9], which proposed use of a fluxed aluminothermic reduction. For the production of oxygen, the fluoride process suggested here is insensitive to the composition of the regolith source material, and thus a better one for a production process that will operate at a site without extensive prospecting to find "good" rock types, and without extensive beneficiation processing to isolate the desirable type of source material. The only useful beneficiation would be to separate the smallest particle size fraction for use as feedstock. This has no effect on the ultimate reaction endpoint, but use of small particle sizes will increase the reaction rate, since small particles have the highest surface area to mass ratio. If metallic aluminum is to be produced as a major product, it may be useful to beneficiate the soil by using high-alumina soil as a feedstock.

2.3. Silicon and titanium

The net silicon and titanium fluoridation processes produce oxygen along with tetrafluorosilane (silicon tetrafluoride) and titanium tetrafluoride, respectively. These two materials are gaseous at the processing temperature, and are drawn off separately from the remainder of the salts.

The tetrafluorosilane produced is liquefied at $-86\,°C$, and must be distilled to purify the resultant product from the oxygen produced and from the unreacted fluorine, and to remove trace contaminants. This distillation process is similar to that used industrially to purify silane for semiconductor production.

The condenser must separate the tetrafluorosilane from the oxygen evolved from the sample, and must recover the unreacted fluorine. This is done by fractional liquefaction (distillation). Tetrafluorosilane will liquefy at $-86\,°C$, oxygen at $-183\,°C$, and fluorine at $-188\,°C$. Since any manufacturing sequence will undoubtedly also manufacture liquid oxygen for rocket fuel and other applications, liquefaction equipment will be present in any case, and it is only necessary to adapt the equipment to allow progressive liquefaction of the individual gases. This liquefaction process will require radiators to reject the waste heat to space [18]. Since the boiling points of fluorine and oxygen are close, it may be necessary to repeat the distillation process to adequately purify the product gasses and recover the fluorine reactant.
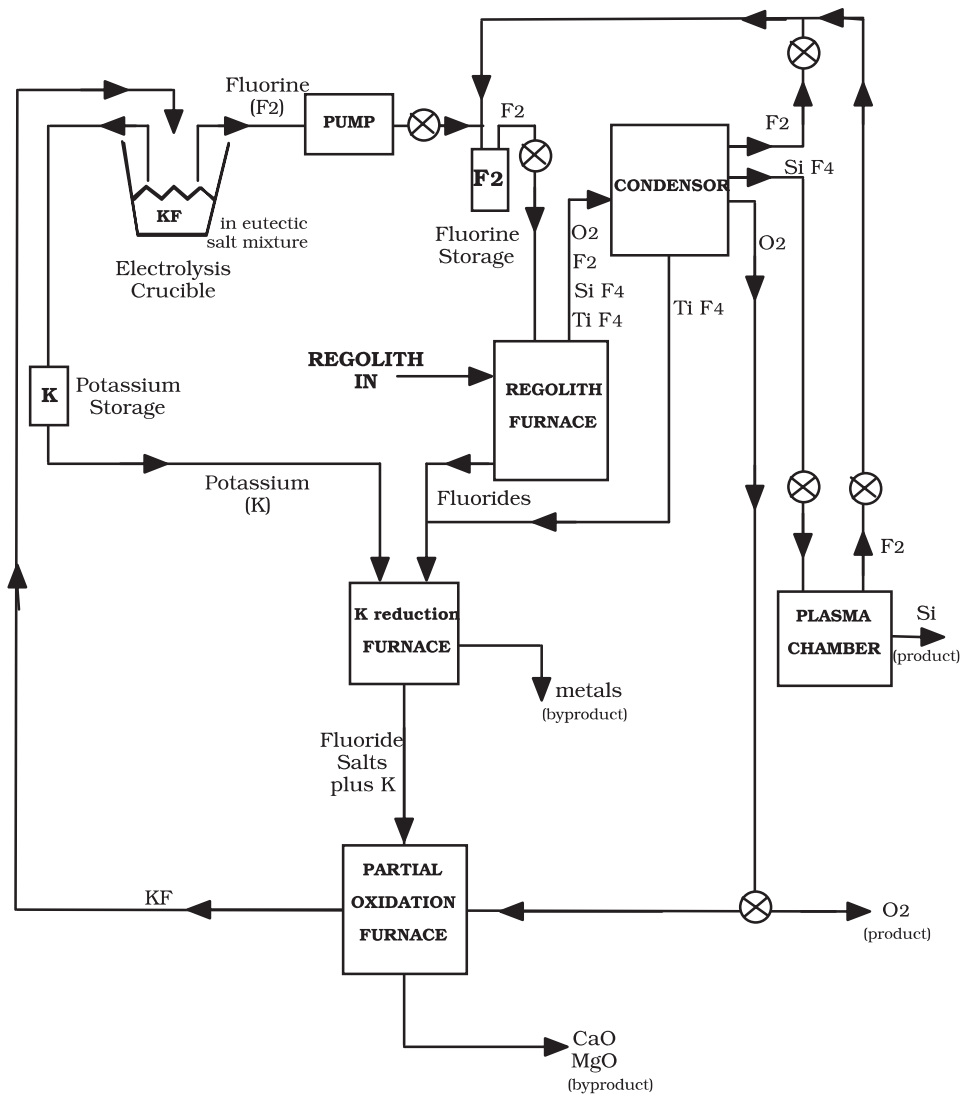
Fig. 2. Block diagram of silicon and oxygen production steps.

In addition to fluorosilane, in soil with significant titanium content the other volatile fluoride which is likely to be produced is titanium fluoride, TiF_4. With a sublimation point of $284\,°C$, TiF_4 will be a gas at the reaction temperatures of interest, but is a liquid at standard temperature. The TiF_4 vapor must be condensed on a cold finger before the vapors enter the main condenser. If it is desirable to produce purified titanium out, this will be easy to do. The titanium fluoride will also include trace amounts of other volatile fluorides, as discussed later; if it is necessary to produce titanium free of even trace contaminants, it may have to be purified further, probably by additional fractional distillation.

Once distilled to pure tetrafluorosilane, elemental silicon can be produced by potassium reduction:

$$SiF_4 + 4K \;\rightarrow\; Si + 4KF.$$
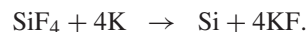
The potassium must be recovered in a later electrolysis step. A similar reaction can be used to recover titanium from the distilled titanium tetrafluoride, if present:

$$TiF_4 + 4K \;\rightarrow\; Ti + 4KF.$$
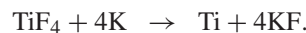
Potassium reduction is not typically employed for the production of silicon in the terrestrial semiconductor industry, since for many semiconductor devices, alkali ions are undesirable contaminants. Unless

potassium contamination is acceptable, an alternate process is proposed, direct decomposition:

$$SiF_4(+energy) \rightarrow Si + 2F_2.$$
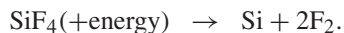
Both plasma deposition processes (primarily producing amorphous silicon) and chemical vapor deposition processes (direct thermal decomposition producing either amorphous or polycrystalline Si) are commonly used in the solar cell industry to produce elemental silicon from silane (SiH_4). Silicon production has also been demonstrated by plasma decomposition of tetrafluorosilane instead of silane. If silane is preferable to tetrafluorosilane for reasons of silicon properties, successive disproportionation of tetrafluorosilane to silane can be done. This is a multi-step chemical replacement of fluorine with hydrogen at high pressure and temperature, or could be done by disproportionation of the tetrafluorosilane with lithium–aluminum hydride ($LiAlH_6$) to produce lithium–aluminum fluoride and silane.

2.4. Recovery of metals

After removal of the volatile fluorides and oxygen, the remaining regolith is in the form of fluoride salts. By weight, the primary salts produced will be FeF_3, MgF_2, CaF_2, and AlF_3. All of these are solid at room temperature. Small amounts of other fluoride salts will also be formed from the trace components of the regolith such as sodium and lithium; these will not be abundant enough to serve as major raw materials, but must be accounted for in the fluorine recovery step.

It is necessary to recover the fluorine from these salts in order to make the cycle a closed process (and also to produce useful byproducts). The iron and aluminum fluorine salts are directly reduced with potassium to recycle the fluorine into potassium fluoride:

$$FeF_3 + 3K \rightarrow 3KF + Fe,$$

$$AlF_3 + 3K \rightarrow 3KF + Al.$$
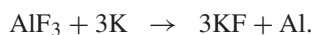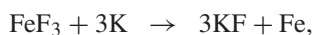
Since the titanium fluoride is separated in vapor form at the initial fluoridation stage, the product from this reaction will be potassium fluoride salt plus a mixture of aluminum and iron in metallic form. The metal can be separated from the salt by melting.

There are roughly two atoms of iron for every three atoms of aluminum in the lunar soil. The lowest temperature liquid phase of metallic aluminum and iron mixtures is liquid aluminum plus iron aluminide (Al_3Fe). Since the average composition of lunar soil is on the iron-rich side of this eutectic, the aluminum/iron resultant phase will be primarily iron aluminides.

If the main goal of the processing sequence is oxygen production, then once the oxygen has been separated out, the iron aluminide can be discarded as an unused byproduct. For applications as a structural metal, the intermetallic iron aluminide can be used directly. Iron aluminide is a weldable [19] intermetallic ceramic with properties similar to stainless steel, although lower density and somewhat more brittle [20–22].

If metallic aluminum is required, purifying the aluminum can be done by a number of processes. One method would be to use a high-aluminum/low-iron soil as the initial feedstock. For example, from the Apollo 16 soil (27% Al_2O_3, 5% FeO), metallic aluminum will be a product along with Al_3Fe. Aluminum can also be separated out after processing. Chemical separation can be done by conventional chemical refining methods, such as exploiting the high solubility of aluminum fluoride compared to other fluoride salts. Physical separation can be done by separating out the aluminum from the iron by vacuum distillation; this may be a preferable method for lunar application since it requires only heat and vacuum. This process exploits the higher vapor pressure of aluminum over iron; it requires heating the alloy mixture to a temperature at which aluminum vapor is evolved, and then exposing a cooled surface for the vapor to condense upon. The relatively pure film of aluminum produced is then removed for use by heating the condensing surface to melt the aluminum.

Vacuum distillation could also be used to separate the aluminum fluoride from the fluoride salt mixture in the same way, first subliming aluminum salt AlF_3 away from the iron salt at 1291 °C. This has the disadvantage that, since the fluorine must be recovered to be reused as reactant, the distillation cannot allow any wasted material. Loss of aluminum metal, on the other hand, is of little concern, since aluminum is abundant on the Moon. Thus, if high-aluminum soil cannot be easily found to use as feedstock, vacuum distillation will be used to separate the aluminum from the alloy mix.

2.5. Calcium and magnesium

The calcium and magnesium fluorides are not reduced by potassium, and will remain in the form of salts. The fluorine can be recovered by direct electrolysis of the salts, but since direct electrolysis may require an electrolysis temperature as high as the calcium fluoride melt temperature of 1423 °C, electrolysis presents a difficult materials problem. A preferable alternative is to return the fluorine to the potassium fluoride form by

oxidation of the potassium followed by a substitution reaction:

$$CaF_2 + K_2O \rightarrow 2KF + CaO,$$

$$MgF_2 + K_2O \rightarrow 2KF + MgO.$$
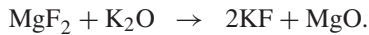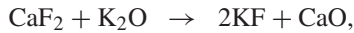
This is possible because potassium has a higher chemical exchange potential for the oxygen/fluorine substitution reaction than any of the metals that are not directly reduced by potassium. Fluorine can be recovered in this way from the trace sodium and lithium salts as well. The nominal temperature of this reaction is $520\,°C$. The metal fluorides are returned to the metal oxide and the potassium converted to potassium fluoride. This can likely be done in a single step of adding oxygen to the mixture of metallic potassium with magnesium and calcium fluoride.

The net result of all these steps in sequence is that FeO and Al_2O_3 are reduced to metals with the accompanying production of oxygen, while the CaO and MgO are separated from the Si, Fe, Al, and Ti, but not from each other, and remain in the form of oxides.

Calcium and magnesium oxides make up about 20% of typical lunar soil, and leaving these unreduced results in about 15% reduction in oxygen production compared to a process which reduces these oxides. These metals are not significantly valuable in reduced form. Calcium will be required in oxide form for glass manufacture (discussed in a later section). It has also been proposed to make concrete out of lunar material; this also requires calcium oxide. Thus, it is not of great significance that the process does not reduce calcium and magnesium. It may be desirable to be able to separate the Ca oxide from the Mg oxide in order to produce an optimum mixture for glass production, however, this is not discussed here.

At the end of this step, all the fluorine is in the form of potassium fluoride, therefore, only a single salt needs to be electrolyzed to recover the initial reactants, instead of a mixture of salts.

2.6. Other products

The fluorine processing of regolith may produce some quantities of other volatile fluorides, including fluorides of hydrogen, phosphorus, boron, arsenic, germanium, carbon, some platinum group elements, sulfur, tungsten, antimony, bromine, iodine, vanadium, uranium, niobium, and others. All of these boil (at 1 bar) below the processing temperature for the fluoridation step. While the abundances of these elements are rather low ($\ll 0.01\%$ for all except sulfur, $\sim 0.07\%$, and carbon, 0.01%), production of rare-element fluorides must be

taken into account for three reasons: the volatile fluorides will clog the plumbing or contaminate the product output if the process sequence is not designed to account for their production, they will represent a sink for fluorine if not recycled, and finally, many of these represent important resources which are in scant supply, and may have other processing uses.

3. Process sequence

3.1. Eutectic fluoride salts for electrolysis

The potassium fluoride is electrolyzed to recover the original reactants potassium and fluorine.

It might be argued that fluorine is extremely reactive, and it will be difficult to find materials in which to do the initial electrolysis. However, electrolysis of molten fluoride salts is a high-throughput industrial process, used in the production of many materials. The most well-known fluoride electrolysis process is the Hall process for production of aluminum, in which molten sodium–aluminum fluoride ("cryolite") is electrolyzed at $1000\,°C$. Seboldt and co-workers [5] discussed some of the materials issues involved in the electrolysis of fluoride salts.

It is desirable to reduce the electrolysis temperature below the $858\,°C$ melting point of KF by as much as possible. Lower temperatures result in less corrosion of the electrodes, and it is desirable to avoid the need for frequent replacement of electrodes. Likewise, lower temperatures allow a wider range of materials for the crucible, and decrease the frequency of replacement of the crucible.

Reducing the electrolysis temperature is done by performing the electrolysis in a eutectic salt with a lower melt temperature than that of pure KF. The choice of salt is limited by the requirement that the electrolysis products are to be potassium and fluorine, and so the salt to be added to the KF to form a eutectic must not be electrolyzed more easily than KF. Since fluorine is the most electronegative element on the electromotive series, there is no choice available to replace fluorine as the anion. Because K is extremely low on the electromotive series, only a few cation choices are available which will reduce potassium at the cathode. Na, Ca, Sr, and Ba are lower on the electromotive series at $700\,°C$ [23], and will not be reduced from the salt. Hence, the possible choices are NaF, CaF_2, SrF_2, and BaF_2. In small quantities, other components may also be possible.

Na, Ca, Sr, and Ba fluorides all form eutectics with KF. The NaF/KF eutectic salt mixture at a molar ratio 60:40 NaF:KF, with a melt temperature of $710\,°C$,

seems to be the best choice. An admixture of LiF will lower the temperature further, although a significant Li component will result in lithium instead of potassium electrolysis. A maximum of 5% (molar) admixture of LiF, which will lower the temperature to 700 °C, should be possible.

Ternary eutectics have even lower melt temperatures. A potassium/sodium/calcium fluoride eutectic mixture, with molar ratio approximately 0.6:0.3:0.1 $KF:NaF:CaF_2$, will have a melt temperature as low as 676 °C.

The electromotive series in molten salts has a dependence on temperature and on the composition of the salt [23]. Further research may make it possible to find a temperature and a salt mixture with a lower electrolysis temperature.

A 676 °C molten salt electrolysis temperature is assumed here. A solar dynamic ground-test demonstration demonstrated melting a LiF/CaF_2 eutectic salt at 800 °C [24], well above the 676 °C electrolysis temperature. This test operated for extended period without corrosion. This design serves as a demonstration of the materials compatibility of fluoride salts at temperatures of interest.

An alternative reduction strategy is to use lithium fluoride. Lithium can be separated from fluorine by electrolysis in a KF/LiF eutectic salt mixture at a temperature of 492 °C. Lithium metal will reduce magnesium, sodium, and potassium fluoride to metal, but will leave calcium fluoride unreacted. By the use of LiF, the temperature is reduced, but the fluorine recovery now includes both lithium and calcium fluoride. If lithium oxide can be used to drive the reaction $CaF_2 + Li_2O \rightarrow CaO + 2LiF$, the electrolysis required is reduced to a single electrolysis. However, this reaction exploits only a small difference in chemical potential, instead of the large difference exploited in the potassium substitution reaction. It is worth exploring to see whether the calcium/lithium oxide exchange occurs at a fast enough rate, and with a high enough recovery of lithium fluoride, for use as a production reaction.

The use of gaseous fluorine presents some materials compatibility issues for the chemical engineer; however, fluorine chemistry is used industrially, and a body of work exists on materials handling properties, as summarized by Grannec and Lozano [25]. Nickel and Monel crucibles, using copper gaskets, are compatible with the fluorine gas. Teflon is appropriate for gaskets and tubing at lower temperatures. Quoting from Grannec and Lozano, "Fluorine handling at low pressures is not very dangerous, provided that a few precautions are taken" [25].

3.2. Candidate process summary

The process sequence is divided into seven steps.

1. Fluorine is brought to Moon in the form of potassium fluoride/sodium fluoride/calcium fluoride salt mixture. Two moles of fluorine is required for each mole of oxygen in regolith.
2. Potassium fluoride is electrolyzed from eutectic salt to form free fluorine and metallic potassium at a temperature of 676 °C.
3. The fluorine reacted with heated lunar regolith to form SiF_4, oxygen, and metal fluorides at a temperature of 500 °C. Electrical power required: none.
4. Gaseous SiF_4 is separated from oxygen by condensation at a temperature of −95 °C.
5. SiF_4 is reacted with plasma to form silicon at a temperature of 300 °C.
6. Potassium metal is added to metal fluorides to produce metallic aluminum, titanium, and iron at a temperature of 500 °C. Required electrical power: none.
7. Oxygen is added to a mixture of potassium metal with calcium fluoride to produce potassium fluoride and calcium oxide at a temperature of 520 °C. Required electrical power: none.
8. The KF is returned to step 2 to electrolyze potassium fluoride back to fluorine gas and metallic potassium.
   The overall processing plant will require:

(1) electrical power;
(2) solar furnace with capability of 676 °C operation;
(3) condenser stage with capability of −95 °C refrigeration;
(4) crucibles, gas chambers, and plumbing.

The solar dynamic ground-test demonstration, based on a power system originally designed for the Space Station Freedom, demonstrated the technology for melting fluoride eutectic under simulated space conditions [24]. This design could easily be adapted to serve as the solar furnace required to produce the temperatures required for this process.

For the fluorination step, there may be some unreacted oxide if the reaction is done at the lowest temperatures. As long as these do not contain fluorine, these can be considered slag and discarded.

The primary output products are:

1. oxygen;
2. silicon;
3. aluminum/iron mixture;
4. calcium and magnesium oxides (unseparated mixture).

4. Lunar glass

4.1. Glassmaking

Glass is needed as the radiation-protecting cover, as the structural substrate or superstrate for solar cell deposition, and may also be used as a structural material in the form of glass–fiber composite material. It may also be usable to make Fresnel lenses or to make mirrors, if a solar concentration system is required. Glassmaking is considered such a low technology, bulk thermal process that it is hard to realize that it may be difficult on the Moon. It is desirable to design a process that can use unbeneficiated regolith.

Glass is an amorphous mixture of silicon dioxide with typically alkaline and alkaline-earth oxides. The silicon dioxide forms the structural network of the glass; the other oxides modify the properties to the desirable form. On Earth, the most commonly produced glass is soda-lime glass. "Soda" indicates sodium, in the form of Na_2O; lime indicated calcium oxide, in the form CaO. The typical proportions are SiO_2 75%, Na_2O 15% and CaO 10%, plus 2–3% other materials. Soda lime glass is produced in large amounts on Earth because its low melt temperature makes it easy to work with. Unfortunately, sodium is not a common material on the Moon. A second disadvantage of soda-lime glass is that it has a very high thermal expansion coefficient, making it vulnerable to the temperature excursion of the lunar day–night cycle.

An alternative glass to use would be fused silica, which consists of silicon dioxide plus trace components. While silicon is abundant on the Moon, the melt temperature of fused silica makes it extremely difficult to work with. Typically, laboratory silica is mixed with other components to lower the working temperature.

A useful laboratory glass is borosilicate glass, such as Pyrex, where boron oxide B_2O_3 is the primary additive, however, boron is also not a commonly available material on the Moon.

4.2. Lunar glass

Based on materials availability, an aluminosilicate composition is selected as the baseline for lunar glass. (Similar considerations led to choice of aluminosilicate glass by Tillotson and co-workers [10].) A typical aluminosilicate glass formula is 57% SiO_2, 20% Al_2O_3, 12% MgO, 5% CaO, 4% B_2O_3, 1% Na_2O, and 1% trace oxides. Of these constituents, silicon, aluminum, magnesium, and calcium are common on the Moon (in fact, calcium–magnesium aluminosilicate is virtually the definition of the anorthositic material that is the primary constituent of the Moon, with some iron substituting for magnesium). For the lunar glass composition, the boron and sodium oxides will be left out. This will have the effect of raising the softening temperature of the glass, but will allow it to be made from the bulk lunar material without requiring the less common components of the soil.

Aluminosilicate glasses have an intermediate melt temperature, typically around 1130 °C, which is well above the 860 °C melt temperature of soda-lime glass, but well below the almost unworkable 1710 °C of fused silica. In terms of working temperature, it has an annealing temperature of typically 715 °C, and softening temperature 915 °C (although note that the boron-free formulation discussed here will probably have a slightly higher temperature). It also has a low thermal expansion coefficient, comparable to borosilicates.

A second difficulty is that for most uses the glass will have to be transparent. This turns out to be a significant difficulty. Glass darkening is primarily due to transition metal oxides, in particular, iron oxide (FeO). FeO is a significant component of lunar rock, ranging from roughly 3% to 23% of the rock weight fraction. This is why lunar rock is black. Producing a transparent glass will require reducing the iron content to nearly zero. On Earth, this is done by selecting iron-free source materials; however, this is not likely to be an option on the Moon, and removal of the iron will probably have to be done by chemical or physico-chemical means. Another step used on Earth is to add manganese dioxide to neutralize some of the green color of the iron, however, on the Moon, manganese is a low abundance mineral (<0.25%), and is found typically in exactly the same rocks that contain Fe, with a Fe:Mn ratio of ~ 80:1. Thus, this is not a good option.

In principle, in the procedure outlined here, most (if not all) of the iron is segregated in the form of an iron/aluminum/titanium mixture by potassium reduction. Of this, only the aluminum component is needed as a raw material for the glassmaking. Thus, the question of removal of the iron is equivalent to the problem of purifying the aluminum, discussed in the aluminum section.

Thus, there seems to be no real barrier to production of glass from lunar materials. Once the raw oxides have been refined, the glassmaking process requires melting the component materials, producing the required form (plate, cast ingots, etc.), and, for stress-free glass, holding the glass at the annealing temperature for an extended period to allow internal thermal stress to relax. Conventional glass plate produced by the "float glass"

method is done by spreading the melt on a bed of liquid tin; this may not be the optimum process for lunar production. The melting temperature for the aluminosilicate glass, on the order of 1130 °C, is significantly higher than the temperatures required in any other parts of the solar cell production process. This is an incentive for refining of boron, sodium, and lithium oxides despite the relatively low-mass fraction of these materials in lunar soil, to lower the glass melting temperature.

An alternative approach to lunar glassmaking, discussed by Mackenzie and Claridge [26], is to form glass out of anorthite purified from the lunar plagioclase. They note that anorthite (calcium aluminosilicate) is naturally low in iron, and hence can be used as a material to form a transparent glass. Their approach requires purification of the feedstock to separate out essentially pure anorthite, then melting this to make glass. The melting point of anorthite, approximately 1550 °C, is relatively high, making it difficult to work with. They suggest addition of calcium oxide, to form a composition of roughly 46% CaO, 42% SiO_2, 11% Al_2O_3, and 1% trace, to reduce the melting point to 1350 °C, and sketch a design for an electric furnace for processing the glass into both sheet and fiber. Even this modified composition results in a very high melt temperature of the glass, though, which will make it difficult to work. Nevertheless, if beneficiation of the input material to purify anorthosite proves to be easy, this may be a good approach.

5. Conclusions

There seems to be no insurmountable barriers to producing from lunar materials the main raw materials required for basic manufacturing, including semiconductor-grade silicon and structural materials. A candidate process sequence is presented. Silicon, aluminum, and glass can be refined directly from the regolith using fluorine, and a multi-stage reduction process can separate out and purify the required materials. This refining process also produces oxygen, and possibly other refined materials of possible economic value.

Acknowledgment

References

[1] L.A. Taylor, W.D. Carrier, Oxygen production on the Moon: an overview and evaluation, in: J.S. Lewis, M.S. Matthews, M.L. Guerrieri (Eds.), Resources of Near Earth Space, U. Arizona Press, Tucson, AZ, 1993, pp. 69–108.

[2] S.D. Rosenberg, R.L Beegle, G.A. Guter, F.E. Miller, M. Rothenbert, The onsite manufacture of propellant oxygen from lunar resources, in: M.F. McKay, D.S. McDay, M.B. Duke (Eds.), Space Resources: Materials, NASA SP-509, vol. 3, NASA Johnson Space Center, 1992, pp. 162–213.

[3] A.F. Hepp, D. Linne, G.A. Landis, M. Wadel, J. Colvin, Production and use of metals and oxygen for lunar propulsion, Journal of Propulsion and Power 10 (6) (1994) 834–840.

[4] E. McCullough, C. Mariz, Lunar oxygen production via magma electrolysis, in: Proceedings of Space-90 Engineering, Construction, and Operations in Space, Albuquerque, NM, 1990, pp. 347–356.

[5] W. Seboldt, S. Lingner, S. Hoernes, W. Grimmeisen, R. Lekies, R. Herkelmann, D. Burt, Lunar oxygen extraction using fluorine, in: J.S. Lewis, M.S. Matthews, M.L. Guerrieri (Eds.), Resources of Near Earth Space, U. Arizona Press, Tucson, AZ, 1993, pp. 129–148.

[6] Y. Zhao, F. Shadman, Production of oxygen from lunar ilmenite, in: J.S. Lewis, M.S. Matthews, M.L. Guerrieri (Eds.), Resources of Near Earth Space, U. Arizona Press, Tucson, AZ, 1993, pp. 149–178.

[7] G.K. O'Neill, The High Frontier: Human Colonies in Space, William Morrow & Co, 1976.

[8] G.A. Landis, Lunar production of space photovoltaic arrays, in: Proceedings of the 20th IEEE Photovoltaic Specialists Conference, Las Vegas, NV, 1988, pp. 874–879.

[9] G.A. Landis, M.A. Perino, Lunar production of solar cells: a near-term product for a lunar industrial facility, in: Space Manufacturing 7: Space Resources to Improve Life on Earth, AIAA, New York, 1989, pp. 144–151; available as NASA Technical Memorandum TM-102102, 1989.

[10] B. Tillotson, P. DuBose, H. Kelso, R. Kendrick, E. Liening, Near-term nonterrestrial materials usage in solar power satellites, in: Space Manufacturing 7: Space Resources to Improve Life on Earth, AIAA, New York, 1989, pp. 152–157.

[11] D.R. Criswell, P.A. Curreri, Photovoltaics using in situ resource utilization for HEDS, in: Space 98: Proceedings of the Sixth International Conference and Exposition on Engineering, Construction and Operations in Space, Albuquerque, NM, ASCE, Reston, VA, 1998, pp. 286–289.

[12] D.R. Criswell, R.D. Waldron, International lunar base and the lunar-based power system to supply Earth with electrical power, Acta Astronautica 29 (6) (1993) 469–480.

[13] A. Ignatiev, A. Freundlich, Solar cell development on the surface of the Moon, Paper IAC-98-IAA.13.2.0, in: 49th International Astronautical Congress, September 28–October 2, 1998.

[14] A. Ignatiev, A. Freundlich, M.B. Duke, S.D. Rosenberg, The fabrication of silicon solar cells on the Moon using in-situ resources, Paper AIAA 2002-0465, in: 40th AIAA Aerospace Sciences Meeting and Exhibit, 14–17 January 2002.

[15] B. Hidding, Untersuchung der Eignung von Silanen als Treibstoffe in der Luft- und Raumfahrt, Ph.D. Thesis, Universität der Bundeswehr, Munich, Germany, 2004.

[16] D. McKay, et al., The lunar regolith, in: G. Heiken, D. Vaniman, B. French (Eds.), Lunar Sourcebook, Cambridge University Press, Cambridge, 1991, pp. 285–356, (Chapter 7).

[17] K. Lodders, G. Fegley Jr., The Planetary Scientists Companion, Oxford University Press, Oxford, 1998 p. 179.

[18] E.B. Jenson, J.N. Linsley, Waste heat rejection system for a lunar oxygen production plant, in: Proceedings of Space-90 Engineering, Construction, and Operations in Space, Albuquerque, NM, 1990, pp. 378–388.

[19] T. Zacharia, P.J. Maziasz, S.A. David, C.G. McKamey, Weldability of Fe_3Al based iron aluminide alloys, in: 6th Annual Fossil Energy Materials Conference, Oak Ridge, TN, 12–14 May 1992.

[20] C. Posišil, P. Kratochvil, M. Hanzal, Iron aluminides as a high temperature structural material, Paper no. 177, in: METAL 2002: 11th International Metallurgical and Materials Conference, Ostrava, Czech Republic, 2002.

[21] C.G. McCamey, Physical Metallurgy and Processing of Intermetallic Compounds, Chapman & Hall, London, 1996.

[22] Panel on Intermetallic Alloy Development, Intermetallic Alloy Development: A Program Evaluation, National Academies Press, Washington, DC, 1997.

[23] A.F. Alabyshev, M.F. Lantratov, A.G. Morachevskii, Reference Electrodes for Fused Salts, Sigma Press, Washington, DC, 1965 pp. 32–39.

[24] R.K. Shaltens, R.B. Boyle, Initial results from the solar dynamic (SD) ground test demonstration project at NASA Lewis, in: 30th Intersociety Energy Conversion Engineering Conference, IECEC-95-421, Orlando, FL, July 31–August 4, 1995; available as NASA Technical Memorandum TM-107004, 1995.

[25] J. Grannec, L. Lozano, Preparative methods, in: P. Hagenmuller (Ed.), Inorganic Solid Fluorides, Vol. 2, Academic Press, NY, 1985, pp. 17–76.

[26] J.D. Mackenzie, R. Claridge, Glass and ceramics from lunar materials, in: Space Manufacturing Facilities 3, AIAA, NY, 1979, pp. 135–140.

[27] G.A. Landis, Solar array production on the Moon, in: SPS-97: Space and Electric Power for Humanity, Montreal, Canada, 1997, pp. 311–318.

[28] G.A. Landis, Materials refining for structural elements from lunar resources, in: M.B. Duke (Ed.), Workshop on Using In-situ Resources for Construction of Planetary Outposts, Lunar and Planetary Institute Technical Report 98-01, 1998, pp. 43–46.

[29] G.A. Landis, Technology for solar array production on the Moon, in: Proceedings of the 29th IEEE Photovoltaic Specialist's Conference, New Orleans, LA, 2002, pp. 796–798.