Experimental reduction of simulated lunar glass by carbon and hydrogen and implications for lunar base oxygen production.

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Introduction: The most abundant element in lunar rocks and soils is oxygen which makes up approximately 45% by weight of typical lunar samples returned during the Apollo missions. This oxygen is not present as a gas but is tightly bound to other elements (mainly silicon, aluminum, iron, calcium, magnesium, and titanium) in minerals or glass. When people return to the moon to explore and live, the extraction of this oxygen at a lunar outpost may be a major goal during the early years of operation. It will likely be cheaper and more efficient to extract oxygen from local materials rather than bring it all the way up from earth, particularly when large quantities of oxygen are necessary. This oxygen will mainly be used for propellant to enable the lunar lander vehicle to go from the lunar surface to lunar orbit and return. It will also be used for life support and will likely be combined with extracted solar wind hydrogen to provide manufactured water to the outpost. In some scenarios, lunar-produced propellant would even be used to provide fuel for an expedition to Mars.

Because of the potentially large future cost savings which may come from the production of oxygen from local materials, it is very important to begin developing effective methods for extracting oxygen from lunar rocks and soil. Well over twenty different different chemical processes have been proposed for extracting oxygen from lunar materials. Only a few of these processes have had enough laboratory work performed to show that they really work. Among the most studied processes is the reduction of ilmenite by hydrogen gas to form metallic iron, titanium oxide, and oxygen. This process has recently been patented by Dr. Michael Gibson and Dr. Christian Knudsen of Carbotek, Inc. of Houston (patent number 4,948,477; August 14,1990). In this process, developed under NASA sponsorship, the hydrogen extracts the oxygen atoms bound to the iron in ilmenite. The patent also covers the reduction of lunar agglutinates which are small glass-bonded aggregates of lunar minerals formed by micrometeorite impacts. The hydrogen combines with the extracted oxygen to produce water which then removed from the reactor and electrolyzed. The oxygen can be collected and stored and the hydrogen can be recycled. The processing would take place in a fluidized bed reactor similar to those used in the chemical processing industry for many applications, including the processing of iron ore to extract iron metal. While this process has many advantages compared to some others, it also has some disadvantages. It requires an ilmenite-rich starting material, limiting the lunar site location to high-titanium mare regions. It requires that the ilmenite be concentrated by beneficiation methods, a process which is likely to be complex and possibly inefficient, particularly for mature lunar soils. Immature soils might permit easier concentration of ilmenite, but such soils may be much less abundant on the lunar surface than mature soils, and such soils also contain few agglutinates. Finally, the ilmenite process requires that considerable material be mined, transported, and processed in order to get a reasonable amount of the desired concentrated ilmenite feedstock.

Here we propose a related process which overcomes some of the disadvantages of ilmenite reduction. We propose that oxygen can be extracted by direct reduction of native lunar pyroclastic glass using either carbon, carbon monoxide, or hydrogen. One advantage is that no concentration of ilmenite or other phases may be necessary. Some areas of the moon are thought to be completely covered by thick layers of fine volcanic ash (pyroclastic material) from early lunar volcanos. This glass is thought to have been deposited during early fire-fountain eruptions. The famous orange glass, discovered by the Apollo 17 astronauts, Jack Schmitt and Gene Cernan, is thought to be an example of such deposits. A related version of this glass contains variable proportions of crystals and is known as the Apollo 17 black glass.

An oxygen plant which could use such volcanic ash as feedstock material without any preprocessing might be an efficient operation which would greatly reduce the need for mining and concentration compared to some other proposed processes. Another advantage of the proposed process is that mining of a uniform, fine-grained pyroclastic ash might be much easier than mining either basaltic lava flows or impact-produced regolith which usually has large rocks and even boulders scattered throughout the more fine-grained soils.

Experimental: In order to evaluate the feasibility of this proposed process we have conducted a series of new experiments on synthetic lunar glass. We exposed this powdered glass to reducing conditions (very low oxygen partial pressure in the flowing gas) in a controlled atmosphere gas mixing furnace through which various gases could be flowed, including carbon monoxide, carbon dioxide, and hydrogen. For some experiments, we also mixed the sample with carbon. The ratios of the gases could be varied to achieve the proper reducing conditions, under which oxygen bound in the samples would be extracted and combined with the gases, leaving behind the metal to which the oxygen was originally bound. The process is similar to that used by some commercial processes in the smelting of iron ore.

We conducted the experiments over a range of temperatures from 950 C at which the glass was still solid and remained as a powder to 1200 C at which the glass partially melted and behaved as a fluid. Initial glass composition (Table 1) was approximately Apollo 11 soil composition and was not too different from the Apollo 17 orange pyroclastic glass. The biggest difference between our experimental glass and the orange glass (Table 1) is that the orange glass contains more iron oxide and magnesium oxide and less silica, aluminia, and calcium oxide. Experimental conditions for the runs included reduction with carbon monoxide, reduction with elemental carbon, and reduction with hydrogen gas. After the runs, the solid samples were removed from the furnace, cooled and analyzed with Mossbauer spectroscopy to determine the relative amount of metallic iron produced.

Results and discussion: While we did not directly measure the production of oxygen from the simulated lunar glass, we measured the metallic iron produced in the sample after the run. As this metallic iron can only be produced by the extraction of oxygen from the glass, it is a direct indication of the amount of oxygen produced. Depending on the conditions of the experimental run, the oxygen extracted from the glass would combine with the added carbon to form carbon monoxide, or with the carbon monoxide/carbon dioxide flowing gas to form additional carbon dioxide, or with the hydrogen flowing gas to form water vapor. The proportion of iron in the glass which was converted to metal in the experimental runs ranged from none in the carbon monoxide runs to 11% in the 1000 C carbon run to 53% in the 1000 C hydrogen run.

The maximum conversion to metallic iron occurred for the hydrogen-reacted sample; in 24 hours, slightly more than half of the total iron was converted to metallic iron liberating its bound oxygen which presumably reacted with the hydrogen to make water vapor. The specific mechanism and kinetics of this process are not known in detail and must be the subject of additional experiments. This conversion occurs in temperature regime in which the glass is still solid and does not melt and flow. During the heating process, the glass, which initially contained no crystals, begins to crystallize and form minerals including ilmenite and pyroxene. It is not yet clear whether the metallic iron which we observed is produced directly from the glass or whether it is produced sequentially from newly crystallized ilmenite and pyroxene, both of which contain chemically bound iron. Regardless of the exact mechanism, these results are very encouraging and imply that these new experiments may be the basis for a viable process for producing oxygen from lunar glass.

Summary and Conclusions: In synthetic lunar glass samples, Reduction of iron to a metal occurred in experiments using both elemental carbon and hydrogen as reducing agents. When carbon was used, it formed cementite (Fe_3C) in the experiments; the production of this phase in a lunar oxygen plant would be detrimental because it would tie up the carbon and prevent easy recycling of this reducing agent . While additional steps might be developed to decompose the cementite and recover the carbon, this would add to the complexity of the process and likely significantly increase the mass and cost of the required systems. No measurable reduction occurred when the carbon monoxide/carbon dioxide mixture was used. Reduction with hydrogen was by far the most effective of the three processes.

These preliminary experiments suggest that reaction of lunar composition glass with hydrogen may be a viable process which should be considered for further technology development. The details of the mechanism are yet to be determined. If this process behaves similarly with Apollo 17 pyroclastic orange glass composition, (Table 1) and were 50% efficient at reducing the iron to metal (as demonstrated in our experiments for the 24 hour run), it would produce 24.5 kg of oxygen for each metric ton of lunar pyroclastic glass mined and processed. For comparison, a similar amount of unconcentrated high-titanium typical mature lunar soil contains only about 2% free ilmenite grains which, if concentrated and extracted with hydrogen at 100% efficiency,would yield about 2 kg of oxygen per metric ton of mined soil. If all of the ilmenite were concentrated by a magnetic or electrostatic process before chemical processing, the yield would go up to about 100 kg of oxygen per metric ton of processed ilmenite, but 50 tons of soil would have to be mined to provide the ilmenite. It seems clear that the reduction of lunar pyroclastic glass may have some advantages over lunar ilmenite reduction and should be studied in greater detail.

A practical, efficient, working process to produce oxygen on the moon would be an extremely valuable technology in the context of possible future lunar operations. Someday a small plant on the surface of the moon may be set up to process nearby volcanic pyroclastic ash deposits and produce tanks of liquid oxygen which can serve as propellant for rockets shuttling back and forth from the site and can also provide life support for the occupants of the lunar outpost.

Table 1. Composition of synthetic starting material and comparison with lunar materials

	Synthetic lunar glass	Apollo 11 soil 10084	Apollo 17 orange glass
SiO_2	44.65%	41.0%	38.57%
TiO_2	6.59	7.3	8.81
Al_2O_3	13.42	12.8	6.32
Cr_2O_3	0.14	0.31	0.75
Fe_2O_3	0.00	0.0	0.0
FeO	13.95	16.2	22.04
MnO	0.14	0.22	0.30
MgO	7.38	9.2	14.44
CaO	12.25	12.4	7.68
Na_2O	0.50	0.38	0.36
K_2O	0.02	0.15	0.09
P_2O_5	0.02		0.04
Total	99.06%	99.96%	99.40%