

Oxygen From the Lunar Soil by Molten Silicate Electrolysis

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p. 15

Introduction

In 1835, a lunar fantasy published as a factual account in the *New York Sun* (see French 1977) generated great economic interest in the Moon. This fantasy reported, among other things, the existence of huge gems on the Moon. Within a few weeks the story was shown to be a hoax, but the interest it generated remained. Now, the Apollo missions have dimmed hopes that such traditional treasures will be found on the Moon. These missions provided no evidence that the Moon ever experienced the plate tectonic processes or the major water and gas transport processes which have produced most gem minerals and ore deposits on Earth. Even if gem minerals and ore deposits had formed, they would probably have been destroyed or dispersed by meteoroids hitting the surface of the Moon. Besides, the cost of acquiring gems from the Moon will be prohibitive for the foreseeable future; if the most common lunar rocks were sold as souvenirs, they would carry a higher price than rubies.

Nevertheless, just as it was not the fantastic Fountain of Youth but rather the real land and plentiful natural resources that proved to be

the wealth of the New World, so the treasures of the Moon will be found in less romantic notions. "Water is worth more than gold to a parched desert wanderer," runs a trite statement. But the statement is true for the Moon, and for the Moon can be extended to include oxygen. In fact, production of lunar oxygen for life support and fuel in low Earth orbit and beyond is already seen as an economic incentive to build a Moon base (e.g., Mendell 1985).

In general, because of the high energy cost of launching material into space from Earth's substantial gravity well, materials already in space (on the Moon, for example) gain value for construction projects there. Such materials could be used "as found" or after only simple processing. Lava tubes on the Moon could serve as early lunar shelters (Hörz 1985). In near-Earth space, lunar basalt could be used as heat shielding for vehicles reentering the Earth's atmosphere and could provide built-in protection for orbiting platforms (e.g., Nozette 1983). More extensively processed bulk materials for space construction might include concrete (see Lin 1985 and also Lin's subsequent paper in this volume) and glass (Blacic 1985) from the Moon.

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Also because of the high cost of exporting materials from the Earth to the Moon, it is reasonable to imagine that a Moon base would, in the longer term, approach self-sufficiency, as eloquently proposed in the book *Welcome to Moonbase* (Bova 1987). What lunar resources make such a scenario feasible? The answer is found in the most common materials and conditions known on the Moon—the soil, the rocks, and the reliable supply of sunlight.

All the common soils on the Moon are rich in oxygen (about 45% by weight), silicon (about 21%), iron (6 to 15%), aluminum (5 to 13%), calcium (8 to 10%), magnesium (about 5%), and titanium (up to 6%). No ore bodies like those found on Earth have been proven to exist on the Moon, but some rock types have concentrated certain minerals; namely, ilmenite (rich in iron, titanium, and oxygen), anorthite (rich in calcium, aluminum, silicon, and oxygen), and olivine and pyroxene (rich in magnesium, iron, silicon, and oxygen). The chemical elements these soils and minerals contain are valuable in applications that range from construction to propulsion. And it may be economically possible to extract volatile elements present at low concentrations (such as carbon, hydrogen, and nitrogen) by heating the lunar soil (e.g., Haskin 1990).

The most promising early use for lunar resources is likely to be for energy. Energy for space transportation can come from lunar oxygen and hydrogen. Proposed energy exports include solar energy collected on the Moon and converted to microwaves (e.g., Criswell and Waldron 1985) and fuel in the form of ^3He for nuclear energy (e.g., Wittenberg, Santarius, and Kulcinski 1986) as well as chemical propellants (e.g., Thompson 1951, Arnold 1980, Mendell 1985). Considerable interest in chemical propellants has revolved around the extraction of oxygen (Mendell 1985), the most abundant and possibly the most immediately valuable of these lunar energy resources. It will be used as oxidant for fuel in the Earth-Moon system, and perhaps ultimately for flights to Mars if it can be provided at less cost than oxygen brought from the Earth (see, for example, Davis 1983 and Mike Simon's paper in volume 2, "Utilization of Space Resources in the Space Transportation System").

Oxygen From the Moon

Accepting, then, that oxygen, rather than gigantic gems or gold, is likely to make the Moon's Klondike, we have chosen to investigate the extraction of oxygen from the lunar soil. Unlike the Klondike, this strike will not be made by the prospector

who discovers the location of the oxygen ore, for it is everywhere on the Moon. This strike will be made by the inventor who discovers the robust, economical process for extracting the oxygen. We think the process that will pan

out will be electrolysis of molten soil. (See figure 21.) We are investigating it because it is conceptually simple and because its nontraditional character fits the nontraditional lunar materials and conditions.

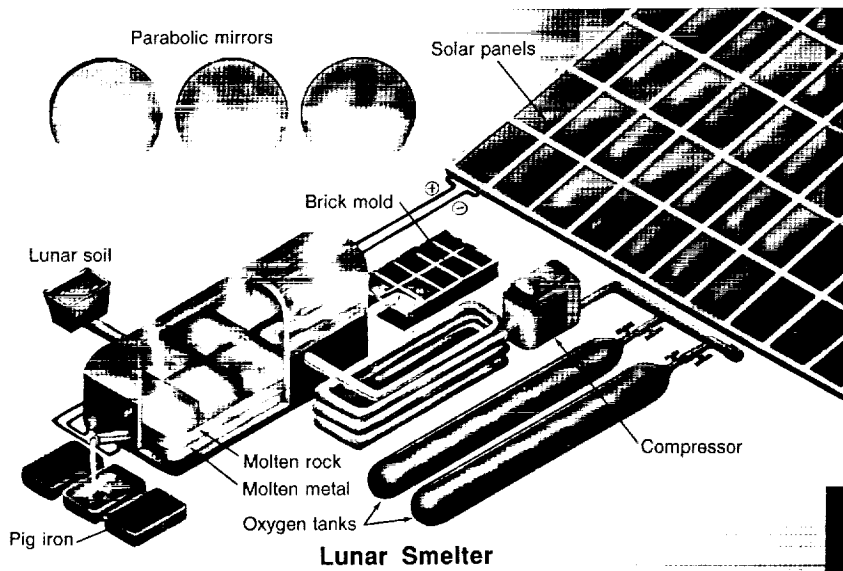


Figure 21

Electrolysis of Lunar Soil To Produce Oxygen and Iron (and Bricks)

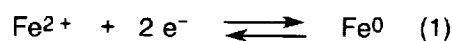
In this early concept of the direct (without a flux) electrochemical reduction of lunar silicates, solar heat is used to melt the initial batch of lunar soil. Solar energy is also captured by panels of solar cells and turned into electricity, which charges both the anode and the cathode of the electrolysis unit. (We now think nuclear power may be more practical. In the absence of an efficient solar energy storage device, nuclear power would be needed to continue the electrolysis during the lunar night.) The oxygen that evolves at the nonconsumable anode is compressed and stored as a liquid. The molten metal that gathers at the cathode (itself molten metal) is bled off to form pig iron and other alloys. The residual slag might be formed into bricks or beams for structural purposes.

Illustration: Washington University in St. Louis

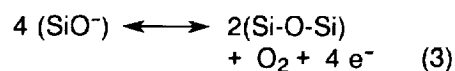
In our study of molten silicate electrolysis, we have taken the approach that the first step in developing the process is to understand its fundamental chemistry. This includes understanding the primary reactions that take place at the electrodes, the kinetics and energies of those reactions, competing reactions that might reduce the efficiency of oxygen production, and how melt resistivity changes with temperature and melt composition. The answers to these questions tell us whether the process is theoretically viable and competitive, presuming appropriate technologies can be developed to implement the process in real life and minimize dynamic problems arising during electrolysis (such as remixing of the product with the feedstock or insufficient mixing of the silicate melt). We have also begun investigating other specific questions about silicate melt electrolysis, such as durability of container and electrode materials and the nature and composition of the product. Our results are summarized here and are reported in more detail in Haskin et al. 1990, Colson and Haskin 1990, and Haskin and Colson 1990.

Process Theory

In molten silicate electrolysis, metal cations are reduced at the cathode to form metals, and silicate polymer chains are oxidized at the anode to form oxygen. The primary cathode reactions that produce metal are the following:

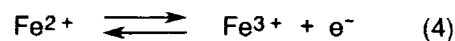


The primary anodic reaction producing oxygen is reaction (3).



The kinetics of these reactions are fast compared to the current densities expected in actual electrolysis, and reaction kinetics is not a serious constraint on the electrolysis process.

The efficiency of production is decreased and the energy required to produce a given amount of product correspondingly increased because of competing reactions at the anode and cathode. The most serious competing reaction at the anode in melts with high iron concentrations is oxidation of Fe^{2+} .



The efficiency of oxygen production (defined as moles O_2 produced/ 4 times moles electrons* passed through the melt) depends primarily on the concentration of Fe^{2+} cations, with efficiency of oxygen production decreasing as Fe^{2+} increases.

The electrical conductivity of the melt also has a significant effect on the power requirement of the electrolysis process. We investigated the dependence of melt conductivity on melt composition and found that conductivity increases in a predictable fashion as the proportions of the oxides of silicon and aluminum in the melt decrease and as the proportions of the oxides of iron, magnesium, and calcium increase.

Power Requirements

The power requirement for molten silicate electrolysis can be numerically related to the oxygen production efficiency, the melt conductivity, and the dimensions of the electrolysis cell as follows. Power to drive the electrolysis equals $E \cdot I$, where I , the current

required to get oxygen at the desired rate, is proportional to oxygen production rate/oxygen production efficiency. E , the potential required to drive the electrolysis, is roughly equal to $E_c - E_a - I(R_{cell})$, where $E_c - E_a$, the potential required to drive the reaction(s), is a function of the cation reduced (the absolute value of $E_c - E_a$ increases in the order $Fe < Si, Ti < Mg, Al < Ca$) and the concentrations of the cations in the melt. R_{cell} , the resistance of the electrolysis cell, is equal to $L/\kappa A$, where L is the distance between electrodes, A is the electrode surface area, and κ is the melt conductivity.

Calculated from this relationship and those above, the energy requirements expected for a realistic range of the variables L , A , O_2 eff, and κ are shown in figure 22. A comparison is made to energy requirements estimated for other processes. The estimated energy requirements for the molten silicate electrolysis process compare favorably with those for other processes even at the less favorable end of the range for the selected critical variables.

*A mole of electrons is Avogadro's number (6.023×10^{23}) of electrons.

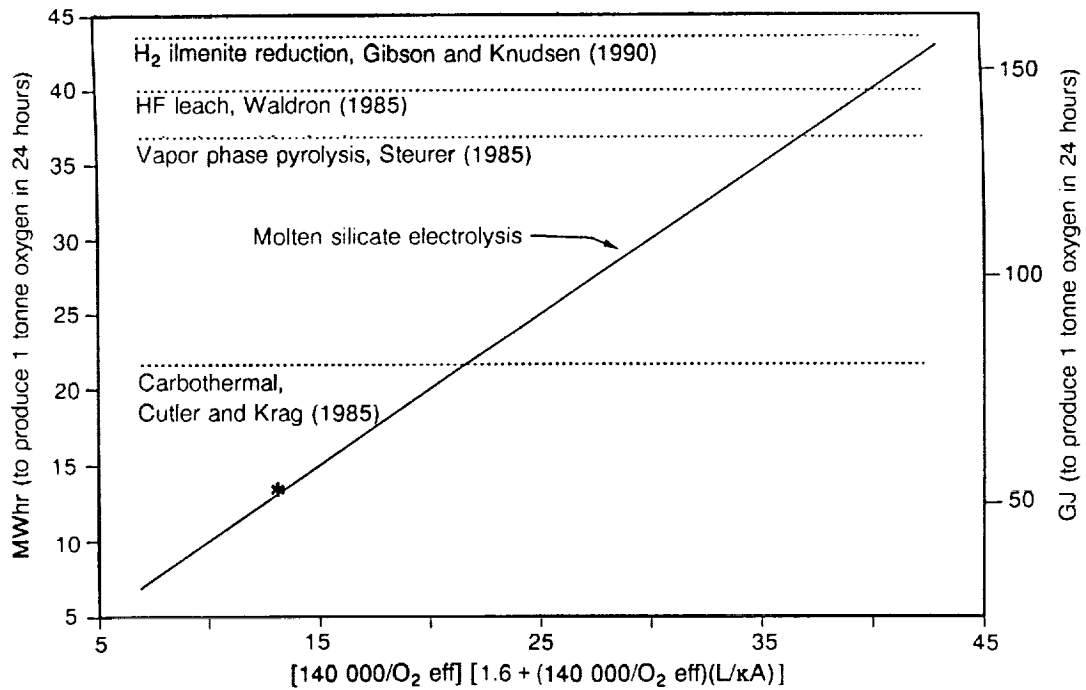


Figure 22

Energy Requirements for the Molten Silicate Electrolysis Process

The energy requirements for the molten silicate electrolysis process for extracting oxygen from lunar soil depend on the variables L (distance between electrodes), A (surface area of electrodes), O₂ eff (efficiency of oxygen production, defined in the text), and κ (melt conductivity).

The abscissa plots a term which numerically models the dependence of energy required for the electrolysis on these designated variables, as described

in the text and in more detail in Haskin et al. 1990 and Colson and Haskin 1990. It can be seen from the expression that the energy requirement increases as O₂ eff, κ, and A decrease and L increases. The range of values along the abscissa is a range we believe can realistically be achieved. The range is from O₂ eff = 90%, κ = 1 cm⁻¹ ohm⁻¹, A = 30 m², and L = 0.5 cm to O₂ eff = 50%, κ = 0.08 cm⁻¹ ohm⁻¹, A = 30 m², and L = 1 cm.

Presumably, an operating electrolysis cell could be maintained such that values for O₂ eff, κ, A, and L are the most advantageous (require the least energy).

The energy requirement calculated by Haskin et al. (1990) for a hypothetical electrolysis of a lunar soil is shown by an asterisk.

The term plotted along the abscissa has no bearing on the energy values reported for the alternative processes, which are shown for comparison purposes. These values are arbitrarily drawn as horizontal lines because they do not depend on the abscissa variables. It is seen that the energy required by the molten silicate electrolysis process compares favorably with that estimated for alternative processes.

Products of Molten Silicate Electrolysis

We have identified several products of silicate electrolysis, partly on the basis of our experiments and partly on the basis of phase diagrams for equilibrium processes. The main products are oxygen produced at the anode and a suite of metals and metal alloys produced at the cathode and consisting of iron, silicon, or iron-silicon alloys containing 0.2-1 percent titanium and chromium. The metal compositions vary as a function of imposed potential and magma composition. (Theoretically, but not yet observed in our experiments, aluminum, magnesium, and calcium could be reduced at increasingly negative potentials and at higher melt temperatures.)

The mineral spinel precipitates from the residual melt at sufficiently low temperature or with sufficient removal of silicon and oxygen. This material varies in composition from an iron- and chromium-rich spinel to a magnesium- and aluminum-rich spinel, depending on the composition of the magma and the extent of electrolysis.

The remaining molten silicate will be an important byproduct; it can be cast into bars, beams, and sheets, or its CaO- and MgO-enriched composition may make it suitable for use in cements. The so-called "waste heat" carried off

with the products or radiated by the cell is another potentially useful byproduct.

Electrode and Container Materials

The primary disadvantage of the molten silicate electrolysis process is that these high-temperature silicate melts are very corrosive, and suitable materials for containers and electrodes are yet to be tested. We discuss here four general types of possible electrode or container materials.

One type of material is simply inert to the silicate and its products. As an example, platinum has been used extensively in experimental petrology as an inert container for silicate melts at temperatures as high as 1650°C. However, although platinum does not react with silicate melt, it does combine with silicon to form an alloy that melts below 1000°C. Because silicon is expected to form at the cathode and accumulate in the container, platinum is unsatisfactory as a cathode or container. Platinum does appear to be a suitable anode material (Haskin et al. 1990).

The second type of material involves a steady-state equilibrium. An "iron skull" container or cathode could be formed by balancing the heat generated by the electrolysis with heat lost to

the surroundings to form a solid skin of product or feedstock enclosing the silicate melt and metal product.

The third type of material would be in thermodynamic equilibrium with the silicate melt and electrolysis products and would therefore not react with them. Because the product is Si-Fe metal, Si-Fe alloys might serve as the cathode material (Haskin et al. 1990). Similarly, the presence of spinel (MgAl_2O_4) on the liquidus of the residual silicate of the electrolysis process suggests the use of spinel as the containing material.

The fourth type of material would be destroyed by the process, but slowly. This option detracts from one of the intended advantages of unfluxed silicate electrolysis—the absence of any need to resupply reagents or other materials from Earth or to recover them from the products. Nevertheless, such an option may prove to be the most cost-effective.

Problems and Work Yet To Be Done

As discussed above, our first steps in the study of molten silicate electrolysis have been to investigate the fundamental chemistry of the electrolysis and to address some specific questions such as the product composition. We have not

addressed certain complexities of the process such as (1) problems that might arise in scaling up from our small experiments to a factory-size process, (2) the problem of designing a system that will effectively transfer the corrosive electrolysis products from the cell, (3) the problem of maintaining the cell at high temperature so that the silicate melt does not freeze and destroy it, (4) the problem of getting ore from the lunar surface to the cell, and (5) the still untested state of our proposed container and electrode materials. Our purpose thus far has been not to demonstrate that molten silicate electrolysis in its current state of development is the best process, but to determine whether, theoretically and experimentally, it might be the best process if certain technological hurdles can be overcome. As do all the proposed methods for extracting oxygen from lunar materials, the silicate melt electrolysis method requires considerable work before an operational factory can be built.

Criteria for Comparing Processes

Several other promising processes for extracting oxygen from lunar materials have been proposed and are being studied, including reduction of ilmenite by hydrogen gas (see the preceding paper by Knudsen and Gibson), reduction by carbon monoxide gas (see the paper by Rosenberg et al.

preceding Knudsen and Gibson's), extraction by processing with hydrofluoric acid or fluorine (e.g., Waldron 1985; Burt 1989, 1990), and electrolysis using a fluxing agent to reduce the melting temperature and increase the electrical conductivity of the melt (e.g., Keller 1989). Understanding which of these processes is the most convenient, reliable, and economical is one of the goals of current research efforts. At present, we are the primary investigators of the molten silicate electrolysis method (also called the "magma electrolysis" method) for extracting oxygen from lunar materials, and our work to date has increased our confidence in its promise. Here, we compare our method, as we now assess it, with other proposed technologies. We recognize the fine line between advocacy and objectivity (Johnson 1980), and we realize that only the test of time and adequate experimentation can determine which technology is the most appropriate.

Informed speculation and preliminary studies of these and other extraction processes have proceeded for over three decades, but slowly for the following reasons: (1) The exact characteristics of nonterrestrial resources are, in most cases, only poorly known, although our knowledge of lunar resources is at least based on experience on the

Moon's surface and materials collected there. (2) Conditions on the Moon (vacuum, intermediate gravity, extreme temperatures, and nontraditional ores) are foreign to Earth experience in mining and materials extraction. (3) Lunar conditions (with which we have little experience) and the uncertain future demand for lunar materials make significant investment of time and money in the development of specific processes seem risky. Thus, many studies have been of the paper, rather than the laboratory, variety.

Given the nontraditional ores and conditions on the Moon, it can be argued that nontraditional extraction processes may prove more practical there than transplanted terrestrial technologies (e.g., Haskin 1985). We form certain general criteria for judging the various processes as discussed below (and elsewhere in this volume).

The successful lunar process must rely on proven resources, preferably abundant ones. Especially in the short term, the cost of searching for specialized or superior ore bodies (which may or may not exist) could overwhelm the cost of extracting the desired material from less specialized ore. The use of a common material also requires that a process should accommodate a substantial range of feedstock compositions and

thus be relatively insensitive to the selection of a Moon base site. The process should use a feedstock that is easily mined and requires minimal processing. It should operate automatically or by teleoperation from Earth. Particularly in the early days of Moon base development, the process and accompanying mining, beneficiation, and other operations should not require a large fraction of the astronauts' time or of the available power.

The process should not be compromised by, and if possible should take advantage of, lunar conditions such as 2-week days (with dependable sunlight—there are no cloudy days), large temperature swings between day and night, vacuum, intermediate gravity, abundant unconsolidated lunar "soils," clinging dust, and the absence of traditional processing agents such as air, water, coal, and limestone.

The process should be simple, with few steps and few moving parts. It must be easy to install and robust against physical jarring during transport and installation. Initially, all operations on the lunar surface will be awkward and expensive. Thus, the simplest technologies that can produce crucial products will presumably be the first technologies developed (Haskin 1985). Keeping the process simple

will make it easier to automate, will require fewer replaceable parts, and should reduce operational problems, resulting in less downtime and fewer people needed to operate the plant. Simplicity can also decrease development time and cost. However, simplicity must be balanced against flexibility to yield more specialized products later on in the development of the Moon base. For example, some compromise should be reached between the ability to extract a single product from lunar soil and the ability to extract several valuable products by a more complex process or processes.

The process must require little or no continuing supply of reagents from Earth (such as fluorine, hydrogen, nitrogen, or carbon). One of the principal costs of setting up and maintaining a lunar factory will be the need to bring supplies from Earth (see Simon's paper in volume 2). If the process uses reagents that need to be recovered, their use raises power and mass requirements (in contrast to on Earth, where cheap reagents often need not be recovered) and increases the complexity of the process (since additional steps are required to recover them).

In addition to applying these first-order criteria, we can make rough comparisons of various processes for extracting oxygen by asking the

following questions. How much power is required to produce a given amount of oxygen? What fraction of the feedstock is converted into products? What are the products of the process? What technology must be developed before the process is viable? What plant mass is required to produce oxygen at a given rate? What must yet be learned about the theory of the process before any or all of the questions above can be answered? Exact answers to these questions cannot be obtained until much more research is done, but in the next section we describe a possible magma electrolysis operation, pointing out its advantages as judged by these criteria. Similar comparisons between various methods for extracting oxygen were made earlier by Eagle Engineering (1988).

A Proposed Lunar Factory

We envision a single-step, single-pot, steady-state electrolysis process using common lunar soil as feedstock with little or no preprocessing. As the soil is fed into the cell, it is melted by "excess" electrical heat released into the melt owing to resistance.

The total electrode surface area would be about 30 square meters each (because each electrode is divided into fins, as in a car battery), and the total cell volume about 1 cubic meter. The operating temperature would be between 1300°C and 1600°C depending on the type of container and electrode materials that are ultimately developed. The cell would produce 1.4 tonnes iron-silicon metal, 1 tonne oxygen, and about 3.5 tonnes slag in 24 hours, with an energy requirement of about 13 MWhr (or 47 GJ). The process would satisfy many of the criteria set forth above for early lunar technologies, including use of common and easily mined lunar soil as feedstock, absence of a need to supply reagents from Earth, and simplicity of the process combined with multiple products. Mass, size, and power requirements of the process are also competitive with alternative processes (table 9). The low energy and mass requirements of the process are particularly important because the major expense in establishing a lunar oxygen factory is the cost of transporting the plant materials (including the required power plant) to the Moon (see Simon's discussion in volume 2).

TABLE 9. Comparison of Proposed Processes for Producing Oxygen From Lunar Soil

	Electrolysis	Typical range for alternative processes*
Feedstock	Common soil	Common soil to beneficiated soil to ilmenite
Mass of mined material (per 1000 tonnes O ₂)	4 670 tonnes	4 600-120 000 tonnes
Reagents required	None	None to C, H, F
Temperature	1250-1400°C	700-3000°C
Plant energy (per tonne O ₂)	13 MWhr (47 GJ)	20-40 MWhr (72-144 GJ)
Plant mass (per 1000 tonnes O ₂ per year)	3-10 tonnes	5-80 tonnes
Product	Oxygen, Fe-Si alloy, slag	Oxygen with pure oxides or metals to oxygen plus slag
Primary advantage	Simplicity	E.g., good Earth analogs for process, many usable products, no consumables used, low-T operation
Primary disadvantage	Corrosive silicate, high-T operation, difficulty restarting after cooldown	E.g., complexity, high-T operation, low oxygen/reagent ratio, low product/ore ratio, high energy or mass required

*Values calculated from Eagle Engineering 1988 and references therein.

Conclusions

All the processes that have been suggested for extracting oxygen from lunar materials and probably many that haven't yet been suggested deserve our careful consideration in determining which is the "best" process to be implemented on the Moon. However, all the processes require substantial additional study before we are able to judge their relative worth for extracting lunar oxygen; and, before an operational plant can be built, even more study will be required.

We note that there is not much time (we hope) before the chosen process will be needed on the Moon. If we are to ensure that an oxygen production plant is included in the early planning and development of a lunar base, we need to progress quickly in assessing the various proposed processes so that the concept of a lunar oxygen plant can become a part of everyone's idea of what a lunar base should be.

Although it is certainly too early to decide which oxygen extraction process is the best one, our preliminary work with magma electrolysis has increased our confidence in its promise. We feel that its theoretical advantages listed above, including relatively

low energy requirements, low mass, simplicity, and versatility with respect to feedstock, are sufficient to warrant its consideration as one of the processes most likely to be used in the early mining of oxygen from the Moon.

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