IDENTIFYING THE CHALLENGES OF A LUNAR MATERIALS PROCESSING PLANT

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Abstract

For frequent travel to and from the Moon, manufacture of liquid oxygen propellant on the lunar surface has been identified as a big "pay-back" technology. Production of other products from resources available on the Moon will also be valuable. The art of bringing together manufacturing with research, design, and development for application on the lunar surface is a chemical process engineering challenge. Given the extremes of the lunar environment, ideas for the structure and siting of a lunar pilot plant designed to manufacture useful products from lunar resources are presented and the unique challenges associated with designing operating plants based on three processes are described.

Introduction

In November 1964 Aerojet ran advertisements in aerospace trade magazines for its Carbothermal Process which recovers bound oxygen from lunar metal silicates (1). The idea to deploy a chemical plant to the Moon for the production of propellant and life support oxygen for advanced lunar bases, Moon-Earth transport, and planetary exploration has been considered plausible since at least the early 1960's. In 1978 the feasibility of rocket propellant production on Mars was proven with the publication of the paper by Ash, Dowler, and Varsi (2). Since the mid 1970's space manufacturing has been recognized as a plausible technology. Many studies have been performed addressing space industrialization, space colonization, lunar materials acquisition and processing, obtaining and using resources in near-Earth space, mining in space, and developing space factories (3-9). In support of the theory that significant advantages can be gained from the large-scale use of extraterrestrial resources, an extensive experimental program was performed in the early 1980's at the Jet Propulsion Laboratory (JPL) in Pasadena, California which studied a wide spectrum of potential extraterrestrial process and product concepts (10,11).

The primary focus of those studies was to identify construction materials easily obtained from raw materials available on the Moon, asteroids, and Mars. The scope was narrowed to looking at processes which lend themselves well toward the production of silicate products, metals, and oxygen from silicates found in extraterrestrial bodies. Analytical, theoretical, and experimental studies were pursued. It was found that depending on the specific starting materials and processing conditions, both polycrystalline and amorphous silicate products could be produced. With regard to derivation of metals and oxygen, it was found that many of the processes examined were impractical due to the required equipment complexity and need for large quantities of reagents to be supplied from Earth.

In two recent surveys regarding oxygen production from lunar materials, the same conclusions were reached about many of the proposed processes (12,13)- they are too complex and impractical for consideration as processes to use in the initial development of a facility to manufacture liquid oxygen propellant on the lunar surface. However, one conclusion which has prevailed, since the JPL work and including the recent surveys regarding lunar liquid oxygen production processes, is that the extraction of metals and oxygen by magma electrolysis and by pyrolysis appears to be both practical and cost effective. Hydrogen reduction of ilmenite is a third process that is simple and is being considered among the most feasible for lunar in-situ propellant production. One study has taken the hydrogen reduction of ilmenite process and developed it at the conceptual engineering design level (14). More such fundamental engineering design studies need to be performed to provide direction for and facilitate suggestions about additional development programs that need to be pursued.

The major challenges associated with process engineering of a lunar in-situ oxygen propellant production facility are identified. Overall challenges of deploying such a facility are described. With regard to the successful manufacture of liquid oxygen propellant from lunar resources, a review of the impact of the lunar environment on operations is provided. Ideas for the structure and siting of a lunar pilot plant designed to manufacture useful products, such as liquid oxygen, from lunar resources are presented. The lunar soils and rocks are very stable materials. Removing oxygen will be very difficult. The major challenges in manufacturing liquid

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**Manager, R&D Space Projects, Member AIAA oxygen propellant from the processing point of view are summarized. Understanding the lunar environment and knowing how to account for such extreme conditions in the design of lunar facilities are key to the success of a given process operation.

Lunar Process Plant Concepts

Overall Engineering Challenges

Imagine the complexity of building an operating pilot plant on the Moon. Ultimate construction of a base will require contributions from many different disciplines. Geologists and scientists will be characterizing the lunar surface through remote sensing techniques, geoscience studies, and by performing return missions to the Moon for prospecting and in-situ sampling. From their data cartographers will develop more accurate maps. The information about lunar soil types and locations of certain material deposits will aid the mining engineer in the quest for the best location to mine. Meanwhile biologists and medical professionals will be determining the essential components to sustain life on the Moon. All engineers: mechanical, chemical, electrical, computer, civil, structural, environmental, and those that specialize in power will contribute to the realization of a lunar outpost.

Numerous oxygen production schemes have been reviewed in the existing literature (12-14). Oxygen is one product that has been identified as being economical as well as feasible to produce on the lunar surface. Figure 1 shows an overall block flow diagram of the production of oxygen from lunar resources. Assuming a location for mining a suitable ore is selected, the first step in the in-situ production of liquid oxygen propellant is surface mining. Beneficiation (if required by the process) is shown as the second element of lunar oxygen production. The third element is chemical processing to produce oxygen followed by cooling and liquefaction of oxygen. The fifth and final element of lunar oxygen production shown in Figure 1 is storage of the liquid oxygen.

Logistics and transportation is an area of concern for any project involving the building of a processing facility in a remote location. How are construction materials, equipment, supplies, and crews delivered to a site? What support materials are needed to insure schedules are met? In the case of a lunar facility, the logic of how supplies reach the construction site is quite a bit different than in the case of a terrestrial facility. This concept related to the overall project planning is nontrivial and needs to be determined as a natural step in the mission to deliver a pilot plant to the Moon.

Another challenging aspect of a lunar materials processing plant is ensuring the health, safety, and environment of all persons and things involved. Planning must be careful such that there are no deleterious effects to the lunar environment, so that all operations of the facility (start-up, operation, shut-down, and maintenance) take place in a fail-safe manner, and that the health and safety of the people involved in such an operation is ensured.

The legal considerations associated with lunar resource developments are currently interpreted from the Outer Space Treaty (15), a multilateral treaty which was signed by the U.S. in 1967. Understanding this treaty has been attempted by many and was summarized by White (16) at the Space 1990 Conference. Six issues of particular

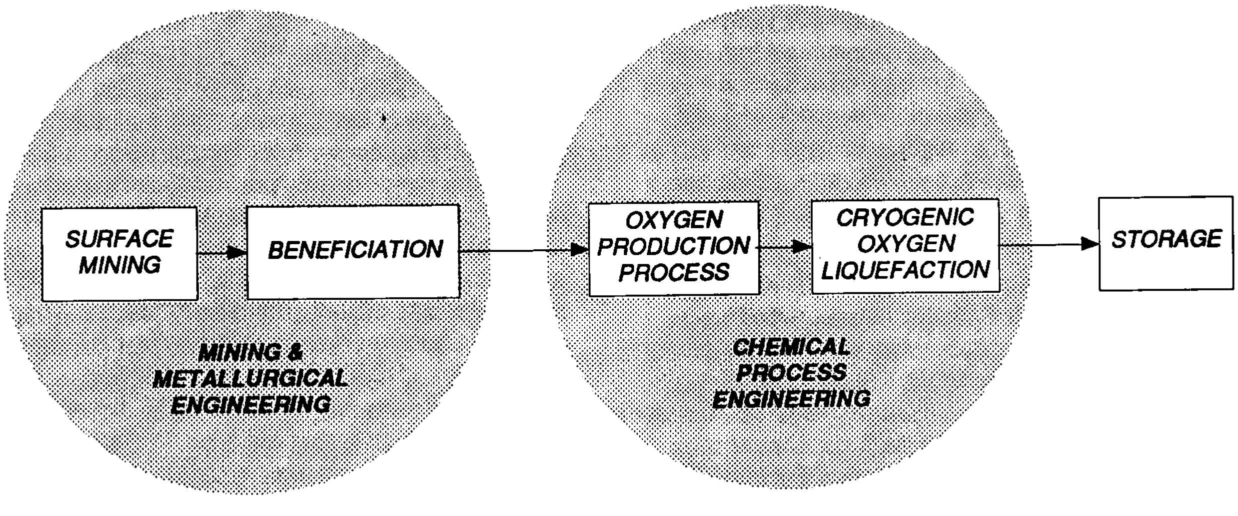

Figure 1: Elements of a Lunar Oxygen Production Facility

interest include (a) claims of sovereignty by occupation or other means is not allowed, (b) space objects occupy locations on a first-come, first-served basis, (c) nations have jurisdiction over space facilities and all personnel in or near the facility, irrespective of nationality, (d) personnel have the right to conduct their activities without the harmful intervention of other states, (e) entities may not claim ownership of mineral resources "in-place" but once they have been mined they are subjected to ownership, and (f) property rights cease when a facility is returned to Earth, destroyed or abandoned, or when activity is halted outside a facility.

This interpretation of current legal aspects presents some potential difficulties to resource developers whether the resource is ilmenite, or any other lunar or asteroidal resource. Is the provision of right-to-use limited to the immediate vicinity of a manufacturing plant and not give sufficient rights to allow mining of materials distributed over a wide area? Could activities, such as direct competition or scientific emplacements, be allowed to set-up around an ongoing mining operation, and as a result directly interfere with the mining plan? Applying the current legal structure to resource development requires careful understanding of all the issues involved. Future work by nations in this area should address some of the shortcomings of the existing framework and provide a straight-forward arrangement through which development can take place.

Impact of Lunar Environment on Plant Operations

Lunar Conditions Characteristics of the lunar surface are given in Table 1. The lunar environment is a near vacuum consisting of collisionless gas molecules (hydrogen, helium, nitrogen, argon and neon). The surface pressure varies from 10^{-9} torr during the day to 10^{-12} torr at night. The lunar day-night cycle is about equal to four Earth-weeks. The temperature varies with location. At the Apollo 17 landing site the surface temperature (due to solar radiation) varied from 110°C during the day to -170°C at night. In southerly polar regions temperatures down to -189°C were noted, and in permanently shadowed areas as cold as -233°C are suggested.

Since the lunar environment lacks atmosphere and has practically no magnetic field, the lunar surface is constantly being bombarded by radiation from galactic cosmic rays, solar flare particles, and solar wind. Micrometeorites are continually impacting the surface at very high velocities, pitting the surface rocks and any unprotected equipment that may be placed on the lunar surface.

Not much, if any, water is expected on the Moon (17); however, H_2O and other volatiles may have been brought to the Moon by cometary and carbonaceous chondrite meteorite impacts and made from solar wind hydrogen and other elements by means of surface reactions. The volatiles may have migrated to the lunar polar regions as part of the natural lunar atmosphere and may have been trapped in permanently shadowed regions of young small lunar craters at latitudes >60 degrees where the temperatures are <80 K. The water postulated to be stored in these shadowed craters is estimated by some scientists at 10^{11} mt. If true, then this is an amount that could have very significant impact on lunar surface operations.

Table 1
SUMMARY OF LUNAR CONDITIONS

condition	night	day	units
Time of single cycle	328	328	Hrs
Time with Sun 20° above horizon	- -	292	Hrs
Annual Time of sun 20°above horizon	- -	3910	Hrs
Temperature	-170°	110°	°C
Gravity (1/6 g)	162	162	cm/sec2
Surface Vacuum	1.00E-12	1.00E-09	torr
Solar Wind Flux (@ surface)	- -	1352	W/m2
Moisture	none	none	

Radiation The technical potential of an operational space system can be limited by environmental interactions. More energetic space radiation can cause bulk charging of components by becoming embedded on dielectric components and producing electrostatic discharges in cable insulation and circuit boards. Because of this a subsystem's signals or the operation of its devices may be disrupted. Microelectronic devices may experience single-event phenomena due to trapped particles in radiation belts, solar flare protons, and galactic cosmic rays. Microelectronic devices, solar arrays, and sensors may be degraded by the total dose effects of this high energy radiation. Radiation effects on materials is also a major concern. Shielding from radiation is an important aspect of plant design.

Vacuum There exists a near perfect space vacuum on the lunar surface. While the attractiveness of using the vacuum in separation technology is obvious, caution in designing a system that minimizes leaks is stressed. The vapor pressure of molten metal and vaporized metal species will undoubtedly be affected by the vacuum conditions; consequently, the operating system of a process will be different than terrestrial design would dictate. Careful theoretical consideration of the lunar vacuum conditions to transport phenomena needs to be made.

Further effects of vacuum on materials are mentioned in the subsection on materials of construction. Design of a processing plant can include locating the facility in a building that is has an atmosphere and temperature compatible with human activity, thus decreasing the direct effect of the surface vacuum on the process operations.

Reduced Gravity The lunar gravity is about one-sixth the gravity of Earth. Hence different dynamics for equipment movement and operation need to be considered. Stability of human and robot movements may be impaired and tall equipment could easily fall over when lateral loads are applied. The effect of gravity on lunar process operations is worthy of a thorough and separate study.

Reduced gravity effects on process operations result in major effects on gas-solids and liquid transport systems and related process equipment. Liquid and particulate flow systems will be greatly affected by reduced gravitational conditions. For a given process the transport of material through the process equipment needs detailed definition to assess its feasibility.

Earth based process operations can be modified for lunar operation using dimensional analysis and scaling arguments. Design of lunar process operating equipment is an area in which many alternatives will need to be considered in order to achieve an optimum design.

In considering flow through a column, gravity-driven buoyant forces are responsible for moving the fluid system. Net column area, net plate area within the column, and downcomer area will all need to be increased in a lunar environment. If a column for use on the Moon is designed for constant bubble mass, an increase in lunar plate efficiency will be realized. However, if the column is designed for constant hole diameter, a decrease in lunar plate efficiency will result (18).

Materials of Construction Carbon composite materials may be very desirable as materials of construction because they are light-weight and strong. Selecting the materials of construction is a nontrivial problem. Some materials must be able to withstand higher temperatures than those used in terrestrial glass processing. Based on observations during the Apollo missions and on somewhat limited research using simulated lunar environment and analog lunar materials, some effects of the lunar environment on materials used for space manufacturing facilities can be anticipated.

The low gravity field, lack of atmosphere and solar radiation cause significant effects. Outgassing of volatiles, such as H_2O, from equipment parts is an obvious problem. Synthetic materials used as seals or in bearings are particularly susceptible to outgassing due to the high vacuum in combination with the solar radiation. Material property characteristics will change due to thermal stresses caused by the extreme temperature differential and due to outgassing in the near vacuum conditions making the parts more brittle. Selection of materials for use in a lunar oxygen production facility will need to be determined in advance, such that they will be able to hold up to extreme operating conditions as well as the extreme environmental conditions on the lunar surface.

Process Equipment Process equipment will vary greatly, depending on which process is selected for use at a particular manufacturing facility. Process equipment for three key process technologies is discussed later in this paper. The equipment required for mining, beneficiation, liquefaction, and storage will also require careful design consideration. Gravity plays an important role in the design of similar sorts of terrestrial equipment. The reduced gravity conditions on the lunar surface will greatly effect the operating characteristics of surface mining equipment. For example, a dragline or back hoe may not have enough resistance to effectively dig regolith. Consequently, an opposing claw excavator may be more effective in the lunar mining scenario. Beneficiation, liquefaction, and storage equipment will have unique problems associated with adapting terrestrial equipment to lunar operations. Two major parameters that need to be minimized when designing process equipment are: (a) weight and (b) energy required to operate. The engineering design of appropriate equipment must be included in responding to the challenge of designing a lunar manufacturing facility.

Components and Instrumentation Numerous components will be used in a lunar manufacturing facility. Common miscellaneous components include filters, pressure transducers, temperature sensors, and valves. Many of these are currently in use in space applications. Experience from past and present space missions will be invaluable in the design of resource processing plants with regard to component selection and reliability of use. Component technology needs to be evaluated and applied to the lunar operating environment.

Control system and instrumentation is a needed research area in the design of processing systems for use in space.

According to Dowler (19), Ash at Old Dominion University is a proponent of using artificial intelligence (in which the system itself realizes that something has gone astray) for space manufacturing operations and has performed a small amount of research in this area. However, funding for this type of research has never been very abundant; therefore, the development of such components for use in lunar manufacturing facilities is not very advanced. The application of smart sensors to a lunar manufacturing plant's control system needs to be pursued under a technical development program.

Facility Design Considerations The principle components involved in the process engineering design of a manufacturing facility need to be combined with overall space mission analysis and design concepts. Plausible alternatives for a particular in-situ resource utilization problem need to be created and assessed. Once the system and associated subsystems can be defined, their interactions identified, design variables selected, the structure of the system can be evaluated. For example, researchers at the University of Arizona are evaluating the optimal energy supply sources needed for the hydrogen reduction of ilmenite process (20). They have developed energy load models for the overall process for lunar oxygen production.

Searching for optimum conditions may require a multilevel endeavor to tackle the overall problem. Careful analysis needs to be performed in order to optimize the overall space mission. As pointed out in the "figure-of merit" approach to extraterrestrial resource utilization developed by Ramohalli (21) at the University of Arizona, when the overall economics of the space mission are considered together, some less-than-the-best features prove to benefit the mission as a whole.

The task of designing a lunar materials processing plant is a prime example of engineering in the presence of uncertainty. Careful initial planning can facilitate easy accommodation to future developments. How to account for uncertainty in data, anticipate potential failure, and design around variations can often be better understood by detailed simulation of a given process operation. Economic design criteria and cost estimating are two additional areas incorporated into the mission to deliver a facility to the lunar surface to process in-situ resources.

While the concept of a completely remote-operated lunar in-situ propellant production facility is something for which to strive, it may not be completely feasible. Perhaps a human in-situ processing team needs to be available on the lunar surface to ensure continuous operation of the plant, particularly during plant start-up. Plant start-up is often the most difficult job of operating a new plant. Based on terrestrial experience, a lot of trauma is experienced by the plant and operators during plant start-up. Many people are needed, and process operation often remains in a state of quasi steady-state for a while during the start-up operation. The design of the process plant should be for the worst case- the transient control problem. Can the plant start-up and shut down by itself? The design needs to account for perturbations in the operating system- how does operation change under transient conditions? For space manufacturing applications, a facility must never approach a state of near failure- problems need to be identified long before a failure occurs. Can a processing plant be "smart" enough to identify a danger signal and turn off remotely before a failure occurs?

Process Plant Siting and Structures

Where a lunar materials resource processing plant should be located and the physical structure of the unit is another challenge to consider. Elements of how a process plant site may be selected and the current thinking about aspects related the physical structures required to house the operations are presented in the following.

Plant Siting Selecting the site for the lunar oxygen process plant will be dominated by the location of the mine providing the most attractive supplies of feedstock for the selected process. The physical and chemical beneficiation of the mine output, leading to the process plant feedstock or input, is of fundamental importance to the success of the process plant operations. This is the reason why extensive lunar precursor missions are recommended in order to assess the resources, both in quality and quantity. Finding the best regolith materials, meaning those regolith deposits that have the highest concentrations of the desired chemicals, will lead to highest efficiencies in the process plant and a reduction in the energy (due to reduced beneficiation needs and reduced waste streams handling). Observations of the Moon from Earth already indicate interesting and important variations in the ilmenite concentrations over the mare basins (22). A process plant that requires ilmenite as its feedstock would best be sited in those regions where the regolith has the highest concentrations. Likewise for those processes that require anorthites of selected compositions, precursor missions should prospect for future mine sites with the best compositions.

Even for those processes that promise to extract oxygen independently of the chemical composition of the regolith, there will be a need to site the plant where sufficient, well-graded reachable quantities of regolith exist. Thus the mine and plant site will benefit by being where relatively flat areas of deep regolith exist which have a minimum of boulders and rocks included. Having large quantities of well-graded regolith that does not require crushing operations and needs a minimum of separation operations also reduces the complexity and energy needs of the facility. The desired size of the mine area will be decided by the throughput and life expectancy of the mining operation. These features in plant site selection will also benefit the overall accessibility of the plant over the surface, since the product must be handled and delivered to storage and then to other surface facilities or orbiting vehicles.

It is likely that the early site selections will be constrained to the equatorial regions of the lunar near-side because of the convenience of easily achievable lunar orbits from Earth and because of the communications requirements. However this should not provide less than optimum opportunities for siting lunar oxygen plants. There is no evidence at this point that unusual concentrations of minerals may be expected on the Moon. This is a common feature of Earth's geology caused by the water, wind, weather and crustal plate movements that are not present on the Moon. If specific concentrations of minerals and chemicals are identified in future lunar missions then these could also influence the siting of a lunar oxygen plant subject to all of the above considerations.

Another important issue in process plant design and siting will be that of plant mobility. This is the question as to whether the plant should be mobile and move around to get the feedstock or whether the plant should be fixed and the feedstock brought to it. Too many technical considerations are involved to resolve this without specifics of feedstock, process and throughput requirements. However this can be expected to be a trade-off issue. Depending on production rates and process requirements and power demands, it will be useful to consider a small plant (or several parallel units) that moves along the surface, picks up and processes the regolith, deposits the processed waste back behind it, and periodically unloads the product oxygen. An interesting example of this is a lunar miner concept by the University of Wisconsin in which regolith is simply heated to drive off the solar-wind helium as the target product (23). Since there is so much process plant technology yet to be resolved for the lunar environment it is most likely that the entry designs will be for static plants that have the regolith brought to them as in a terrestrial operation. Conceptual sketches of such plants already appear in the technical literature (14, 24).

Plant Structure Practical process plant structures will be characterized by a high degree of modularity. This modularity will be enforced by the stringency of the transportation modes for delivery to the lunar surface. The diameter, length and mass of each module or plant component will be defined by the delivery vehicles. This might be the shuttle bay capacity to low Earth orbit (LEO) or the cargo capacity of a future heavy lift vehicle direct to lunar orbit. A small pilot plant will likely comprise several equipment packages that can be stacked and linked together. Linkages will be the various pipes, control systems, and power systems. Ideally the modular plant will be operated remotely so that it requires a minimum of shielding incorporated for human operators. However, the near presence of human operators is quite likely to be part of the plan along with suitable control system linkages. Other options for the plant are to excavate and provide a semi-buried arrangement or to provide complete burial. These options provide increasing difficulty of access by astronauts but with increased protection from the lunar surface radiation and micrometeorite flux. These choices will influence the plant structures and will be made in response to specific process and environmental criteria.

Elaborate foundations are not likely to be required at the selected plant site. All indications are that the regolith mantle is highly compacted, to almost 100% relative density, within a foot of the surface. This means that some site levelling and pad clearing may be all that is required to emplace the plant modules directly onto the lunar surface. In addition the structural frames of the plant modules will benefit by having adjustable screw support legs to allow independent levelling of each unit and thus avoid extensive levelling of the entire site. Even this can be disposed of if the process plant operations have no sensitivity to physical levelling of the components and if flexible connections can be made between modules.

Plant Feed Considerations

An average composition of the lunar regolith is understood from the information shown in Table 2. The most abundant resources on the Moon are oxygen, silicon, iron and aluminum. Table 3 reveals that the majority of oxygen is fixed in silicate form. This suggests that a process might be selected which can easily reduce silicate materials. If, however, a location on the Moon can be found which is rich in a particular mineral (for example ilmenite), then the ideal energy costs associated with oxygen extraction from the iron oxide in ilmenite combined with the cost of any required beneficiation may be less than processing bulk regolith at another mine site. Finding the regolith deposits that have the highest concentrations of desired chemicals will lead to the greatest efficiencies in the process plant. A reduction in energy due to reduced beneficiation needs and reduced waste streams handling can be realized. The quality and quantity of available resources needs to be assessed.

Table 2
Relative Lunar Resource Abundances

Major Resources		Minor Resources	
	wt %		PPM by wt
Oxygen	43.00	Carbon	104.00
Silicon	20.00	Fluorine	174.30
Iron	10.00	Nitrogen	95.40
Aluminum	10.00	Hydrogen	54.80
Calcium	9.00	Chlorine	25.60
Magnesium	5.00	Boron	4.78
Titanium	2.50	Berylium	2.63
Sodium	0.35	Helium	28.50
Potassium	0.08	Lithium	12.90
Sulfur	0.07	Neon	2.75
Total	100.00		505.66

Adapted from reference 25.

Table 3
Oxide Concentrations in Mare Regolith (wt %)

Oxide	Pyroxene	Olivine	Anorthite	Ilmenite	Total
SiO2	47.8	37.4	46.1	0.0	44.0
CaO	18.6	0.3	18.1	0.0	11.0
Al2O3	4.9	0.0	33.7	0.1	13.0
MgO	14.9	35.8	0.3	2.0	9.0
FeO	9.0	27.0	0.7	44.9	17.0
TiO2	3.5	0.1	0.2	53.6	5.0
Total	98.7	100.6	99.1	100.6	99.0

From reference 25.

Process Descriptions

In the following three processes are described: pyrolysis, magma electrolysis, and hydrogen reduction of ilmenite. Brief descriptions are provided and operating characteristics are contrasted.

Pyrolysis Process

Figure 2 summarizes a vapor phase reduction technique. Vapor phase reduction is a processing technology to be considered for obtaining oxygen, metals (silicon, magnesium, iron), and volatiles (He^3, CH_4) from lunar mare regolith. In this class of extractive metallurgy, mare soil is heated to a temperature sufficient to allow partial decomposition and vaporization. Currently an experimental program researching the pyrolysis process is being pursued by Senior (26, 27). Pyrolysis is of interest to some, because of theoretical arguments concerning vaporization of metal oxides. Many metal oxides vaporize via the formation of reduced oxide or metal atoms in the gas phase. If these reaction products are

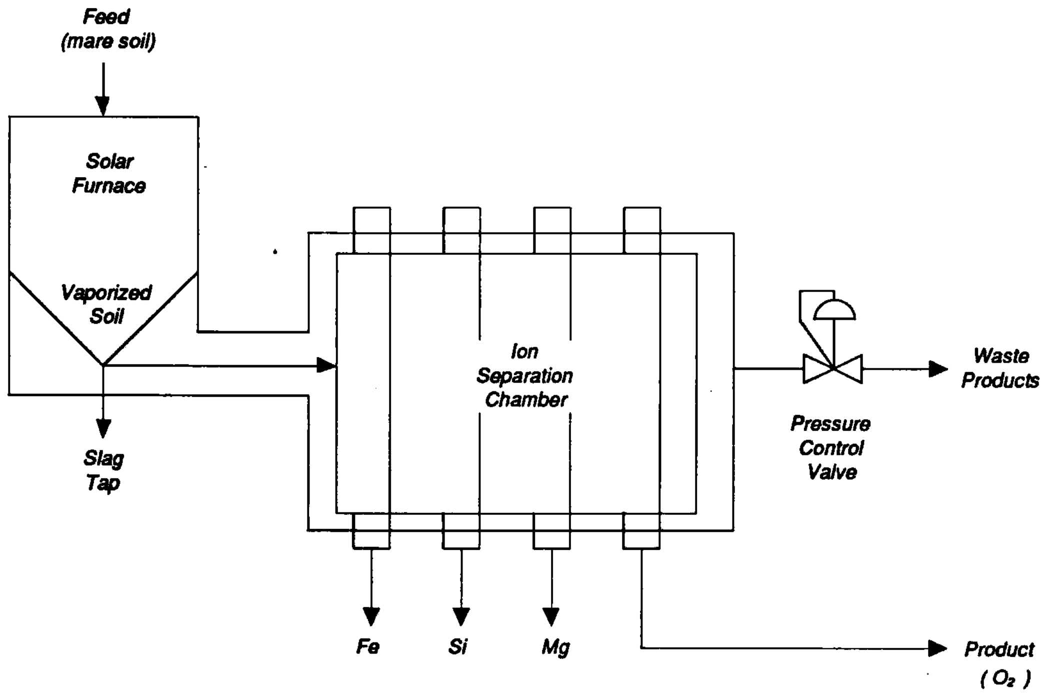

Figure 2: Pyrolysis Followed by Fractional Distillation

rapidly quenched, oxygen is easily generated.

The three major steps of the vapor phase reduction process: pyrolysis, condensation of metal species, oxygen recovery are revealed in Figure 2. In this technique powdered mare soil is heated to a vapor state and passed through an elevated pressure chamber. The pressure gradient moves the particles through the separation chamber where the products are condensed. Oxygen and metal products are recovered by fractional distillation. Selected products are cooled and collected. Melting points for some of the resources to be recovered are: oxygen (-219°C), iron (1535°C), silicon (1410°C), and magnesium (649°C).

Each resource will be extracted by a separate cooling (condensing) system. A cryogenic cooling system will be needed for oxygen storage. Recent work in the area of vapor phase reduction performed by Senior (27) used a concentrated solar heat source to achieve temperatures around 2700 K. The process ran at low pressure (0.15 to 0.2 torr). These conditions proved to be sufficient to apparently reduce lunar simulated ilmenite and anorthite to generate oxygen. A net pressure increase for both minerals was recorded during the course of heating the materials. Good oxygen yields are expected by achieving condensation of metal species without oxidation (i.e. without the recombination of metal with free oxygen).

The pyrolysis processing temperature can be selected to perform partial or complete vaporization of the metal oxides in the lunar regolith feed. At temperatures below 2500 K the more volatile elements Si, Fe, Mg will be vaporized and the remaining refractory slag will be rich in oxides of Al, Ca, and Ti. This scheme is amenable for use with mare soils which contain more iron than highland soils. Above 2500 K complete vaporization of all oxides in the regolith feed could be achieved with a higher oxygen yield (27); however, greater energy would be needed and adequate refractory materials of construction would need to be selected to withstand the very high temperatures.

Magma Electrolysis Process

Recent work has shown that electrolysis of silicate melt material similar to the composition of lunar soil can be used to produce oxygen and iron oxide (28, 29). The feed to the process is the iron and silica rich lunar regolith. Electrolysis of molten basalt is performed in an electrolytic cell in which gaseous oxygen is generated at the anode and molten iron and silicon form at the cathode. Absorbed volatiles in the feed are recovered and the lunar regolith is preheated by having the hot oxygen product flow counter-current to the feed in the input hopper. Figure 3 shows the magma electrolysis process.

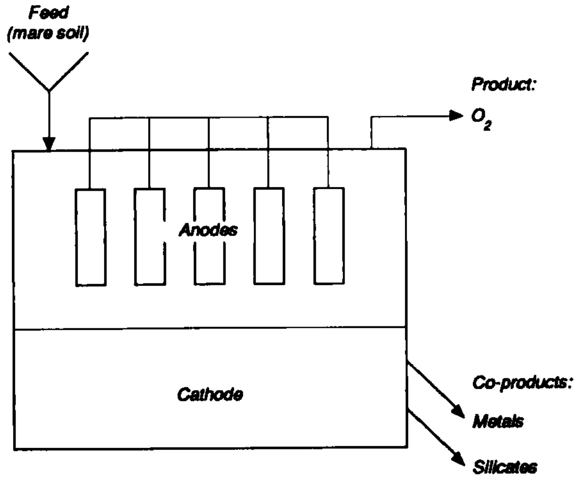

Figure 3: Magma Electrolysis Process

A lunar magma electrolysis cell could be operated in a batch or a continuous mode, at low feed rates, with resistance losses providing the thermal energy required to melt the solid feed. Operating temperatures are estimated to be in the range 1475 to 1875 K. The cell could in principle operate on solar power during the day, but for initial simplicity a nuclear power source is preferred. Energy requirements are expected to be about twice the theoretical minimum needed for chemical separation, or around 14 MWh/mt of oxygen (14, 25, 29).

Hydrogen Reduction of Ilmenite

This process accomplishes the goal of oxygen production by solid/gas reaction. Ilmenite is introduced and thermochemically reduced with hydrogen gas. An overall schematic of the reduction of ilmenite by reaction with hydrogen is shown in Figure 4. Numerous researchers have studied this technique to derive oxygen from lunar materials (14, 25, 30, 31). Various reactor designs would be feasible: fixed-bed and fluidized-bed are two potential reactor types. The following describes the fluidized-bed concept according to Gibson and Knudsen (30).

In this process cold ilmenite feed is preheated as it enters a three-stage continuous, fluidized-bed reactor. Hydrogen gas is pumped counter-currently through the beds and the ilmenite reacts with the hydrogen endothermically at around 950°C to produce iron, rutile (TiO_2), and water. The top bed primarily preheats the solid feedstock against the hot, recycle hydrogen. The temperature in this bed is determined by the solid feed rate and the rate of hydrogen recycle and is generally too low for reaction to take place. The center bed is where the solid ilmenite reacts with the gaseous hydrogen to

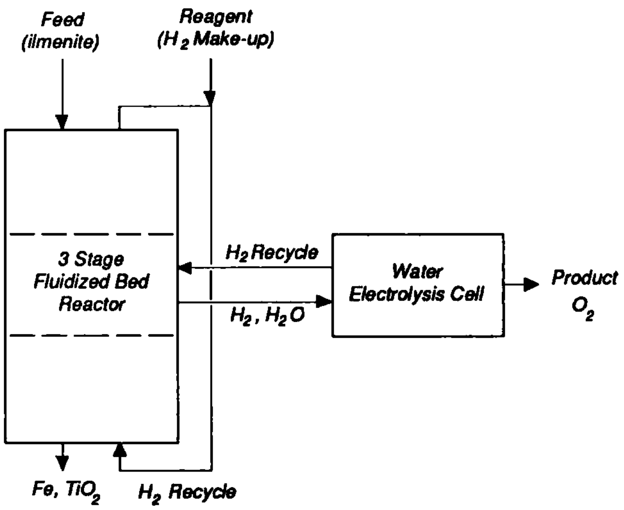

Figure 4: Hydrogen Reduction of Ilmenite

produce water vapor. Some make-up heat (electric heating) is added to this reaction bed to ensure the necessary temperature for reaction is achieved. The third bed located in the bottom portion of the reactor serves to preheat the recycle hydrogen reductant by extracting (otherwise wasted) heat from the spent solids.

The amount of product water vapor obtained by the reaction which occurs in the center bed is determined by the kinetics and thermodynamics of the reaction and by the diameter and depth of the fluidized bed. Hydrogen gas and water vapor comprise the product gas which exits this stage of the reactor. This stream is then electrolytically or thermochemically split to regenerate reactant hydrogen and liberate oxygen; the hydrogen is recycled back to the first stage fluidized bed. The corresponding electrolysis reaction reduces water to obtain oxygen and hydrogen.

Comparison of Process Parameters

Table 4 contrasts the operating parameters for the three processes described in the previous subsection. The information is based on existing quantitative data cited elsewhere in the literature (14, 25, 29).

Technical Development Needs

Pyrolysis

There are numerous areas of technical development required before a terrestrial pyrolysis process can be adapted for use on the lunar surface (27). Four major areas requiring development are:

a) Thermodynamic and transport properties of molten lunar regolith need to be defined. The prediction of liquid activity, heat capacity, viscosity, and diffusion coefficients need to be established.

b) The removal of molten slag from the pyrolytic extraction chamber prior to crystallization and without plugging slag traps will need to be optimized for the lunar operating scenario.

c) Characterization of how the reduced species of the pyrolysis reaction condenses in a lunar processing operation needs to be performed. Condensation of metal species must be achieved without recombination metal with free oxygen. The techniques of continuous condensation need to be investigated.

d) The interaction of the oxygen produced with the substrate material should be evaluated: the effect of surface temperature on the condensing plates and on oxygen content should be characterized. How well the reduced metal species adhere to the substrate needs to be determined.

Magma Electrolysis

Several technology development areas cited in the literature (14, 31) are summarized for the magma electrolysis process:

a) Anode oxidation and corrosion problems may be encountered with the high temperatures required for magma electrolysis. A corrosion resistant anode material needs to be found. Corrosion of the cathode is also a potential problem. Inert or thermodynamically stable container materials need to be identified. Using a composite refractory material derived from lunar materials should be explored.

b) The effect of reduced gravity needs to be determined. Cell productivity may be decreased under the lunar

Table 4

Operating Parameters for Three Lunar In-Situ Oxygen Production Processing Techniques

Process	Feed	Average Fractional Yield (g O2/g regolith feed)	Energy MWh/mt O2	Metal Coproducts	Operating Features			
					# Unit Ops	Pressure	Temperature	Comments
Pyrolysis	bulk soil	0.200	34	Fe, Mg	2	.01 to 1.0 torr	2000-2500 K	Solar Furnace
Electrolysis	bulk soil	0.008	14	Fe, Si	2	*	1475-1875 K	Reduction Potential -1.5V
Hydrogen Reduction	ilmenite	0.015	5	Fe	2	*	1225-1325 K	Earth supplied reagent.

* Not yet specified for lunar operations.

gravity conditions making complete separation of oxygen from molten silicates difficult.

c) Definition of the theoretical energy requirements of the electrolysis process needs to be made. Continued research in the areas of melt oxidation-reduction reactions and associated kinetics and reaction energies, production efficiencies, and melt resistivity characteristics is required. Actual energy requirements need to be determined and compared to theoretical values.

d) Characterization of the products of silicate melt electrolysis should be performed. Theoretical and experimental studies are needed. Optimum process conditions, feed rate, and feedstock requirements need to be specified. Expected oxygen efficiency needs to be studied and design parameters need to be identified.

Hydrogen Reduction of Ilmenite

The ilmenite reduction reaction has been studied theoretically as well as at the bench scale level (14, 25, 30, 31). It is a very attractive process because of its simplicity. Some areas of technical development include:

a) Verification of the required hydrogen recycle rate. Theoretical chemical equilibrium calculations need to be performed to specify the conversion of hydrogen to water under the conditions expected on the Moon. Additional thermodynamic calculations should be done to aid in specifying plant production ratios.

b) The feasibility to extract hydrogen needed for make-up from the lunar regolith needs to be explored in order to eliminate further requirements to import hydrogen from Earth.

c) The feasibility to use ilmenite as a feedstock should be verified. The energy costs associated with beneficiating ilmenite from a given ore deposit should be investigated.

Oxygen Liquefaction

The very important unit operation for recovery of liquid oxygen from the process and the storage of the finished product have been given very little attention in the design of a lunar in-situ oxygen propellant facility. The process design of these needs to be investigated in detail. Concepts such as the use a molecular sieve made of zeolite to adsorb oxygen at low temperature compared to pumping the oxygen could be tested to characterize the capture and regeneration of the oxygen.

Conclusions

This paper focused on identifying the challenges of designing a lunar in-situ liquid oxygen propellant manufacturing facility based on an overall mission concept. It becomes clear that a multidisciplined team will be required to ensure that the design and construction of a manufacturing plant is properly integrated with research, design, and development.

References

1. The Moon is Made of Oxygen: Advertisement in Aerospace Trade Magazines; November 1964.

2. Ash, R. L.., Dowler, W. L., Varsi, G., "Feasibility of Rocket Propellant Production on Mars", Acta Astronautica, Vol. 5, p. 705-724, (1978).

3. O'Neill, G. K., The Space Manufacturing Facility Concept", Space Manufacturing Facilities (Space Colonies), Grey, J. (ed.), Proceedings of the Princeton/AIAA/NASA Conference, May 7-9, 1975, p. 7-12 .

4. Criswell, D. R., "Lunar Materials", Space Manufacturing Facilities (Space Colonies), Grey, J. (ed.), Proceedings of the Princeton/AIAA/NASA Conference, May 7-9, 1975, p. 25-28.

5. Grodska, P. G., "Process Chemistry for L5", Space Manufacturing Facilities (Space Colonies), Grey, J. (ed.), Proceedings of the Princeton/AIAA/NASA Conference, May 7-9, 1975, p. 79-86.

6. von Puttkamer, J., "Developing Space Occupancy, Perspectives on NASA Future Space Program Planning", Space Manufacturing Facilities (Space Colonies), Grey, J. (ed.), Proceedings of the Princeton/AIAA/NASA Conference, May 7-9, 1975.

7. Mayur, R., "Space Industrialization: An International Perspective" Space Manufacturing III, Grey, J., Krop, C., (eds.), Proceedings of the Fourth Princeton/AIAA Conference, May 14-17, 1979, p. 63-66.

8. Kuck, D. L., "Near-Earth Extraterrestrial Resources", Space Manufacturing III, Grey, J., Krop, C., (eds.), Proceedings of the Fourth Princeton/AIAA Conference, May 14-17, 1979, p. 97-108.

9. Waldron, R. D., Erstfeld, T. E., and Criswell, D. R., "Overview of Methods for Extraterrestrial Materials Processing", Space Manufacturing III, Grey, J., Krop, C., (eds.), Proceedings of the Fourth Princeton/AIAA Conference, May 14-17, 1979, p. 113-127.

10. Steurer, W. H. (ed.), "Extraterrestrial Materials Processing", NASA-Jet Propulsion Laboratory, Pasadena, JPL Publication No. 82-41, April 1982.

11. Carroll, W. F. (ed.), "Research on the Use of Space Resources", NASA-Jet Propulsion Laboratory, Pasadena, JPL Publication No. 83-36, March 1983.

12. Altenberg, B. H., "Processing Lunar In-Situ Resources", Bechtel Technical Research and Development Project Job No. 90634-002, Final Report, December 1990.

13. Taylor, L. A., Carrier, W. D, "Oxygen Production on the Moon: an Overview and Evaluation", Resources of Near-Earth Space, University of Arizona Press, Tucson, AZ (submitted 1991).

14. Christiansen, E. L., et. al., "Conceptual Design of a Lunar Oxygen Pilot Plant", Eagle Engineering, Houston, NASA Contractor Report No. NAS9-17878, July 1988.

15. Outer Space Treaty: Treaty on Principles governing the activities of states in the exploration and use of outer space including the Moon and other celestial bodies, done Jan. 27, 1967, 18 U.S.T. 2410, T.I.A.S. No. 6347, 610 U.N.T.S. 205 (entered into force Oct. 10, 1967).

16. White, W. N., Jr., "The Legal Environment for Extraterrestrial Mining and Construction", ASCE Space '90 Conference, p. 9-18, April 1990.

17. Binder, A., "Lunar Data Base", Lockheed, Sunnyvale, Preliminary Release, May 1990.

18. Petit, D. R., "Fractional Distillation in a Lunar Environment", Lunar Bases and Space Activities of the 21st Century, p. 507-518, W. Mendell (ed.), Lunar and Planetary Institute, Houston (1985).

19. Dowler, W. L., personal communication, March 12, 1991.

20. Fazzolari, R., Wong-Swanson, B., "Energy Management and Analysis of Lunar Oxygen Production", Section IV, p. 17-22, NASA Space Engineering Research Center for Utilization of Local Planetary Resources, University of Arizona, Tucson, Annual Report (1989-90).

21. Ramohalli, K., Kirsch, T., "A Figure-of Merit Approach to Extraterrestrial Resource Utilization", Section IV, p. 1-16, NASA Space Engineering Research Center for Utilization of Local Planetary Resources, University of Arizona, Tucson, Annual Report (1989-90).

22. Johnson, J. R., Larson, S. M., Singer, R. B., "Determination of Lunar Ilmenite Abundances from Remotely Sensed Data", Section III, p. 3-15, NASA Space Engineering Research Center for Utilization of Local Planetary Resources, University of Arizona, Tucson, Annual Report (1989-90).

23. Kulcinski, G. L., Schmitt, H. H., "The Moon: An Abundant Source of Clean and Safe Fusion Fuel for the 21st Century", UWFDM-730, University of Wisconsin, Fusion Technology Institute, Madison (1987).

24. Covault, C., "NASA Technology to Support Synthesis Group Proposals", Aviation Week and Space Technology, March 18, 1991.

25. Teeter, R. R., Crabb, T. M., "Lunar Surface Base Propulsion System Study", Astronautics Corporation of America, NASA Contractor Report No. NAS9-17468, February 1987.

26. Senior, C., "Production of Oxygen and Other Products by Pyrolysis of Lunar Materials", PSI Technology Company, NASA Contractor Report No. NAS9-18102, August 1989.

27. Senior, C. L., "Lunar Oxygen Production by Pyrolysis", Resources of Near-Earth Space, University of Arizona Press, Tucson, AZ (submitted 1991).

28. Colson, R. O., Haskin, L. A., "Lunar Oxygen and Metal for Use in Near Term Space: Magma Electrolysis", ASCE Space '90 Conference, April 1990.

29. Haskin, L. A., "Oxygen Production by Electrolysis of Molten Lunar Regolith", Section I, p. 49-58, NASA Space Engineering Research Center for Utilization of Local Planetary Resources, University of Arizona, Tucson, Annual Report (1989-90).

30. Gibson, M. A., Knudsen, C. W., "Lunar Oxygen Production via Fluidized Bed Iron Reduction", AIChE Symposium Presentation, Washington, D.C., December 1988.

31. Briggs, R.A., Sacco, Jr., A., "Investigation of Ilmenite Reduction with Hydrogen and Ilmenite Oxidation with Oxygen", Worchester Polytechnic Institute, NASA Contractor Report No. NAG9-221, February 1989.