Oxygen Production on the Lunar Materials Processing Frontier

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Abstract

During the pre-conceptual design phase of an initial lunar oxygen processing facility it is essential to identify and compare the available processes and evaluate them in order to ensure the success of such an endeavor. The focus of this paper is to provide an overview of materials processing to produce lunar oxygen as one part of a given scenario of a developing lunar occupation.

More than twenty-five techniques to produce oxygen from lunar materials have been identified. While it is important to continue research on any feasible method, not all methods can be implemented at the initial lunar facility. Hence, it is necessary during the pre-conceptual design phase to evaluate all methods and determine the leading processes for initial focus. Researchers have developed techniques for evaluating the numerous proposed methods in order to suggest which processes would be best to go to the Moon first. As one section in this paper, the recent evaluation procedures that have been presented in the literature are compared and contrasted.

In general, the production methods for lunar oxygen fall into four categories: thermochemical, reactive solvent, pyrolytic, and electrochemical. Examples from two of the four categories are described, operating characteristics are contrasted, and terrestrial analogs are presented when possible. In addition to producing oxygen for use as a propellant and for life support, valuable co-products can be derived from some of the processes. This information is also highlighted in the description of a given process.
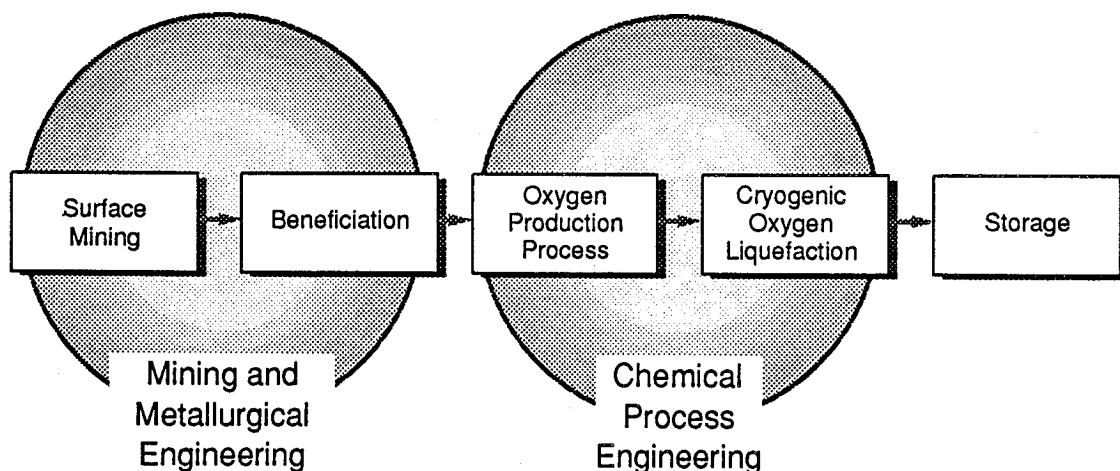
Introduction

This paper summarizes the points which were addressed at the plenary lecture for the session on Materials Processing at the Conference on Lunar Materials Technology which was sponsored by the University of Arizona/NASA Space Engineering Research Center for Utilization of Local Planetary Resources, held on February 20 - 22, 1992. The focus of the symposium was to present ideas related to an initial lunar outpost. With the scenario given, technology concerns in the areas of resource characterization, energy management, materials processing, environmental control, and automation and communications were presented. With the abundance of resources reported to be available in the lunar regolith, the potential for processing many different materials exists.

Recoverable lunar resources are classified as either volatiles or metals. The volatiles of possible interest include oxygen, hydrogen, helium, and nitrogen. These can be used for biosupport, as propellants, thermal fluids, processing reagents, purge gases and fuel for power. Various metals: iron, aluminum, silicon, magnesium, calcium, and titanium can also be retrieved from mining the Moon. These are useful as structural materials, cement additives, electrical conductors, thermal conductors, magnetic materials, refractories, ceramics and more. The focus of this paper is to look at lunar oxygen production as one part of a given scenario of a developing lunar occupation.

Overall Elements of Oxygen Production

A conceptual mining and processing facility on the lunar surface to produce oxygen for use as liquid propellant should contain the same elements as a terrestrial mining and processing facility. Part of the scheme should include excavation equipment, feed preparation facility, chemical processing plant for oxygen production, and facilities for purification, liquefaction, and storage. In addition, in support of such a facility, landing and transportation capabilities and power generation and transmission facilities are also required. The successful design, engineering , and construction of a lunar oxygen production plant will depend on the integration of all of these aspects of operation.

Figure 1 identifies five major elements of lunar oxygen production: surface mining, beneficiation, oxygen production, liquefaction, and storage. Minor, but noteworthy components of lunar oxygen production not shown in this figure include dealing with by-products and supplying energy. Later in this paper two processes for producing oxygen are described in more detail, but first it is necessary to discuss the environment on the lunar surface and some of the mining concerns.

The engineering challenges associated with oxygen production on the Moon are directly related to the harsh environment found on the Moon. The rocks and soil of the lunar regolith are very stable. It will not be easy to process such material. A major challenge in manufacturing lunar oxygen propellant from indigenous lunar resources involves understanding the lunar environment and knowing how to factor in these extreme conditions in the design of lunar facilities.

Indeed, when the first lunar base is constructed, it will be the lunar environment which will present the most difficult challenges. The extreme fluctuations in temperature may cause material embrittlement. The reduced gravity conditions on the Moon will greatly effect standard engineering practices such as material handling and process operation, i.e. gas-solids and liquid transport phenomena. The lack of atmosphere and near vacuum conditions also affect process operation by outgassing from lubrication used around the bearings and seals in mechanical equipment.

For the successful design of a lunar oxygen production facility it is essential that precursor studies take place now. Through remote sensing and ground truth exploration missions, one can identify a good location to mine. Recent work performed at the University of Arizona's Lunar and Planetary Laboratory has produced titanium oxide abundance maps [Johnson, et. al. (1990), (1991)]. Regions of highest titanium oxide concentrations are specified at greater than 8 weight percent in the Western Mare Tranquillitatis and the Oceanus Procellarum. Obtaining remote sensing data such as this will aid in finding the best mining site.

Using three-dimensional representation of the lunar surface in combination with a three dimensional model of a conceptual lunar oxygen production plant will facilitate the design of the lunar oxygen production facility. Engineers at Bechtel have constructed an image of the Taurus Littrow Valley from data brought back from the Apollo program. The simulation was developed with Bechtel's Walk-Thru® system and is accurate to a 10 meter contour interval.
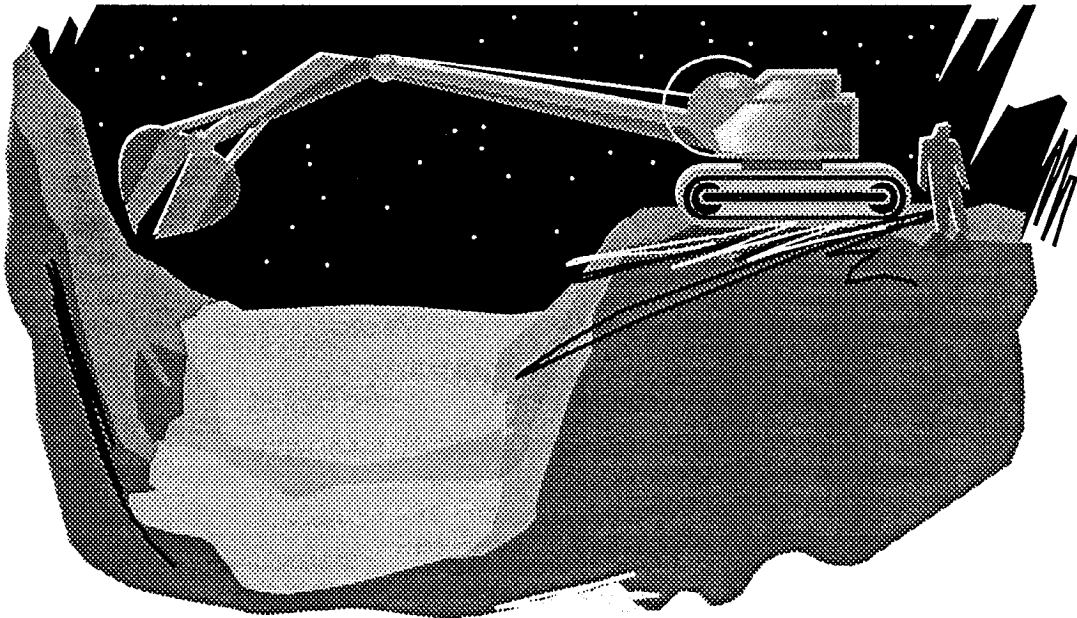

Figure 2: Surface Mining Using an
Opposing Claw Excavator

Determining the best excavating equipment will be essential to a successful mining operation. Terrestrial mines such as at the San Miquel Lignite Project in Texas use a backhoe and a dragline to mine lignite for use in a coal production process. It is not obvious how to dig the regolith. Perhaps an opposing claw excavator like the one shown in *Figure 2* will be able to successfully dig the regolith given the lunar surface conditions.

Once a feedstock location has been specified, it will be essential to prepare the feed for the selected oxygen production process. Examples of beneficiation schemes include grinding in a ball mill, separating by cyclone, by electrostatic, or by electromagnetic means. A simplified electromagnetic separator is shown in *Figure 3*.
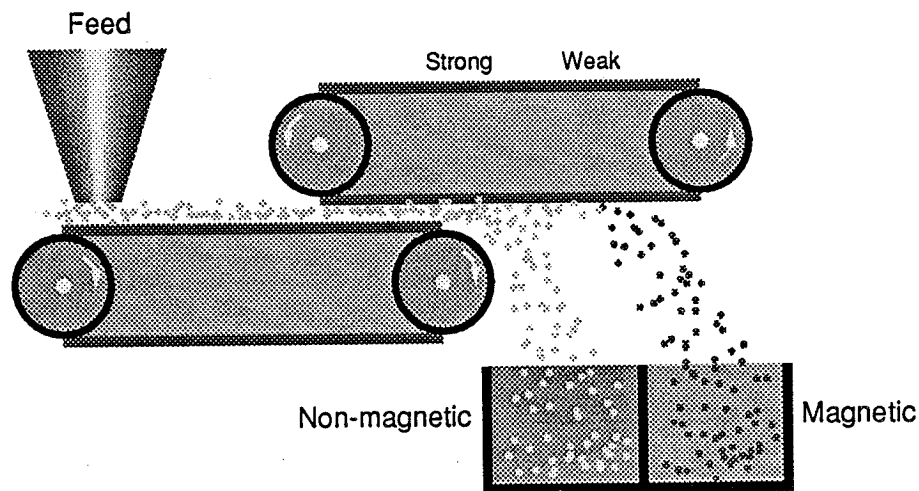

Figure 3: Dry Magnetic Separation

Oxygen production on the lunar surface will depend on the process selected. At least 25 different processes have been identified for the production of lunar liquid oxygen propellant [Altenberg (1990), Christiansen et. al. (1988), Taylor et. al. (1991), Waldron (1988, 1990)]. All of these processes have terrestrial analogs and generally fall into four categories of reaction: (a) thermochemical processes, such as solid/gas reaction in a fluidized bed (b) reactive solvent techniques, such as leaching and dissolution (c) electrochemical processes like those used in metal production processes and (d) pyrolysis techniques which can be considered advanced smelting methods. Once oxygen is produced it will be necessary to purify, liquefy, store, and transport the liquid oxygen product.

Producing Lunar Oxygen

In deciding to return to the Moon to set up a habitat suitable for occupation and for manufacture of useful products derived from indigenous resources, one realizes that it is an overall engineering challenge in which many aspects need to be integrated. It is valuable to tap into our terrestrial engineering experience in order to gain insight into making seemingly impossible projects happen.

Engineering construction firms have a history of success in the design, engineering, and construction of truly isolated production plants. For example, a successful lead and zinc mine and processing plant which processes 2250 short tonnes per day of ore is located in Canada 90 miles north of the Arctic Circle (600 miles from the North Pole) on Little Cornwallis Island. The mine is called the Polaris Mine and was built by Bechtel, Canada for COMINCO Corporation. Located in a very harsh, remote far away place, facilities for personnel are included where they grow plants, live, shop, and exercise in comfortable surroundings.

Techniques to Evaluate Lunar Oxygen Production Processes

There exist over 25 different techniques to obtain lunar liquid oxygen. How does one select a process to use for in-situ lunar oxygen production? It seems appropriate to evaluate all of the processes and determine which processes would be the best for use on the Moon.
Recent literature contains information about four methodologies which have been developed in order to sort through the numerous processes and determine which ones are the most feasible for implementation in a lunar oxygen production plant.

Taylor and Carrier (1992) have recently evaluated 20 processes and categorized them into 5 classes. For each of the processes information describing plant and mine characteristics (through-put, plant mass, energy, and ore required) was assembled. A technique for ranking the processes was presented which is based on technology readiness, number of process steps, process conditions, and feedstock. While the authors felt that the ranking was somewhat subjective, they also felt that the ranking did indicate that 8 of the 20 processes were more feasible for an initial lunar oxygen production plant than the remaining 12 processes. The top 4 processes as ranked by Taylor and Carrier were: (a) vapor pyrolysis (b) glass reduction with hydrogen (c) molten silicate electrolysis, and (d) ilmenite reduction with hydrogen.

Waldron and Cutler (1992) also looked at a large number (twenty-six) of different processes which could be used to make lunar liquid oxygen. A procedure to rank the processes based on benefit, cost and risk is described. The paper goes into detail explaining the methodology for evaluating the various oxygen production processes, and then concludes that sufficient information is not available to perform a reliable ranking of the proposed material processing and refining systems. It is recommended that reliable estimates of benefit, cost, and risk parameters for the proposed processes be obtained in part from a program to test processes in order to specify the parameters.

Cutler and Waldron (1992) propose another ranking method for selecting the most feasible processes to make lunar liquid oxygen. In this study the authors feel that comparisons among processes which are not in the same category of reaction can not be compared against one another. For example it is not a fair comparison to use the same criteria to rank hydrogen reduction of iron bearing feed to reduction of iron bearing feed by a reactive solvent such as sulfuric acid. Instead a preliminary ranking of processes within a single class is made. The processes studied ranked most feasible in the order given next: (a) hydrogen reduction of mixed feeds (b) hydrogen reduction of olivine (c) hydrogen reduction of pyroxene and (a) hydrogen reduction of ilmenite.

Altenberg (1990) examines sixteen processes for oxygen production and identifies the processes which would lend themselves well to producing oxygen on the lunar surface. An evaluation was performed which compiled existing quantitative information about feedstock quantities, oxygen yield, by-product production yields, number of major unit operations, operating temperatures, amounts of required reagents, energy requirements, and estimated weights of process units. A number of important parameters were considered, including: amount of research available, lab scale testing results, existence of terrestrial analogs, availability of feed material, reaction rate, number of

processing steps, oxygen yield, required reagents, catalysts, anodes, and /or fluxing material, energy required, temperature, materials of construction, amount of equipment required, ease of automation, potential for coproduct processing, and potential for a miniplant. A delphi survey of engineers (who were familiar with lunar materials processing technologies) was made in order to independently assign weighting factors to reflect their relative importance. Based on these factors, the processes were ranked. The results of the ranking show the top three most feasible processes for lunar liquid oxygen production are (a) vapor phase reduction, (b) magma electrolysis, and (c) hydrogen reduction of ilmenite.

Two processes: hydrogen reduction of ilmenite (which falls in to the first category) and vapor pyrolysis (which falls into the fourth category) are examined in more detail in the following.

Oxygen Production by Thermochemical Reduction

While there are many ways to engineer a process which uses the hydrogen reduction of ilmenite reaction, a simplified block flow diagram of a possible configuration is shown in *Figure 4*. Ilmenite feedstock $FeO-TiO2$ reacts endothermically with hydrogen gas to produce water. A reaction temperature of 700-1000°C has typically been reported as necessary to achieve rates of reaction. Product water vapor with excess hydrogen is then electrolyzed or thermally split to regenerate reactant hydrogen and liberate oxygen. Direct electrolysis of water vapor is shown in the figure; however, this type of electrolysis is not in current commercial use. Therefore, it may be necessary to condense the water vapor before electrolyzing it.
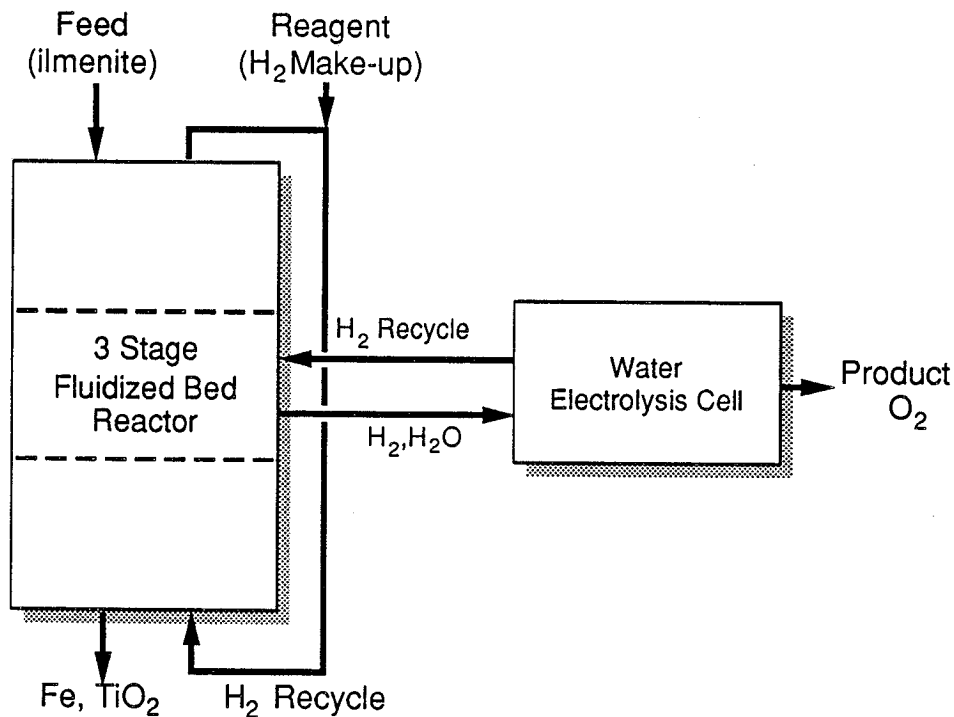

Figure 4: Hydrogen Reduction of Ilmenite

By performing Gibbs free energy minimization calculations , the effects of temperature and pressure were studied (Hernandez, 1992). It was important to find out if the reaction could be carried out practically at lower temperatures. If so a substantial savings in terms of energy to heat the process could be realized. *Figure 5* shows the effect of temperature (at a fixed pressure of 10 bar) on the conversion of hydrogen to water. A specified efficiency, also called figure-of-merit for the process was arbitrarily defined as the ratio of product water vapor to the amount of input hydrogen gas. It is evident that at temperatures less than 700°C, the conversion of hydrogen to water is very small. After that the conversion improves steadily and at 900°C the graph seems to level off. Higher than 900°C may improve the conversion, but there is the risk that the ilmenite will agglomerate and sinter.
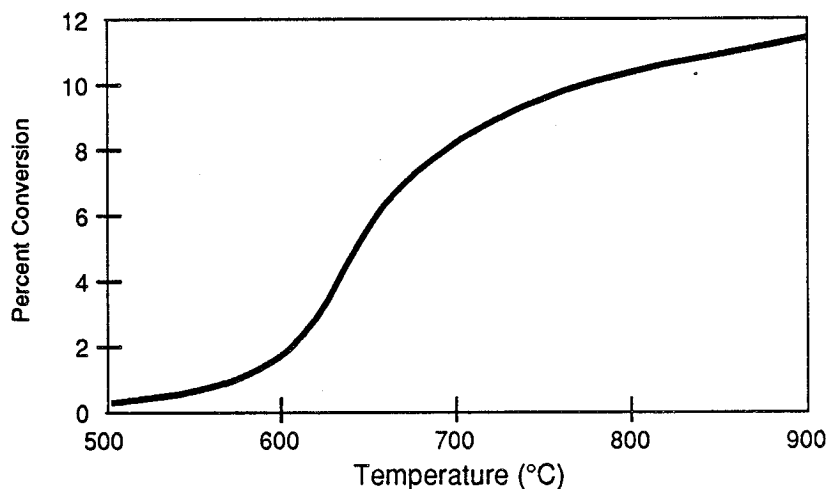

Figure 5: Conversion of H_2 to H_2O for HRI
Process as a Function of Temperature

For comparison purposes, a closed-loop, fluidized bed reactor which operates in batch mode was used to generate the data in Table 1. Calculations were performed to quantify the amount of energy required to produce 1000 metric tonnes/yr of O2 by the hydrogen reduction of ilmenite process. Analysis of the effects of operating pressure indicate that at lower pressures less feed, less reagent, and less energy are needed to produce a given amount of oxygen. However, a larger reactor is required translating to increased weight costs. Typical of fluidized beds on Earth, a superficial gas velocity of 1 ft/sec was used to determine associated reactor sizes for various operating conditions. The total energy required includes heat of reaction, heat loss, electrolysis, and energy for recycle compressor. While this analysis argues for lower operating pressure, a continuous fluidized bed operation in which water vapor is continuously extracted may favor higher operating pressures.

The phenomena of the effect of operating pressure on the hydrogen reduction of ilmenite reaction is very interesting. If one looks at the overall reduction reaction of ilmenite with hydrogen, there is the same number of moles of reactant gas present as there is product gas. This suggests that pressure should not affect the reaction. However, kinetics studies (Knudsen et. al., 1989) have shown that changes in pressure affect the rate at which the ilmenite reduction reaction occurs.

Table 1: Summary of Feed and Energy Requirements for the Hydrogen Reduction of Ilmenite Process

Operating Pressure (bar)	Required Ilmenite Feed (tonnes/yr)	Total Required Hydrogen (tonnes/yr)	Reactor Diameter (ft)	Total Energy Required (MWhr/yr)
1	50,540	626	7	14,285
10	90,981	1137	3	20,010

Thermodynamic equilibrium computer simulation studies using the HSC microcomputer code (Roine, 1989) have predicted that changes in pressure affect the equilibrium point of the ilmenite reduction reaction (Hernandez, 1992). In these simulations the functional conversion of hydrogen to water increased as operating pressure was lowered. This phenomena is now being investigated further.

The chemistry of the hydrogen reduction of ilmenite process is not complicated but lunar ilmenite could contain various amounts of chemical impurities such as sulfur, carbon, MgO, and Cr_2O_3. Impurities in a feed material such as ilmenite are of concern in designing a process to make lunar liquid oxygen, because they may induce side reactions and lower the desired conversion of hydrogen to water.

The thermodynamic equilibrium computer code was used to address the issue of potential impurities in ilmenite feed in the hydrogen reduction of ilmenite process (Hernandez, 1992). The effect of impurities on the conversion of hydrogen to water in the reduction of ilmenite process are summarized in *Figure 6*. The presence of Cr_2O_3 tends to enhance the conversion of hydrogen to water in the hydrogen reduction of ilmenite process. When small amounts of either sulfur or MgO are present in the system, the conversion of hydrogen to water is lower than the case in which no impurity is present; however, as the amount of impurity increases, the conversion shows an increase. Carbon impurity shows the most significant effect by lowering the conversion to less than 8 percent. As the amount of carbon impurity is increased the efficiency of the process decreases. The effect of these impurities on the process is important information to ascertain. Note that these examples are by no means considered exhaustive. If, however, one could conclude that the presence of these impurities do not severely poison the reaction, then it would be possible to use an "impure' feed. Assuming that this is just one of many process configurations, the fact that H_2S
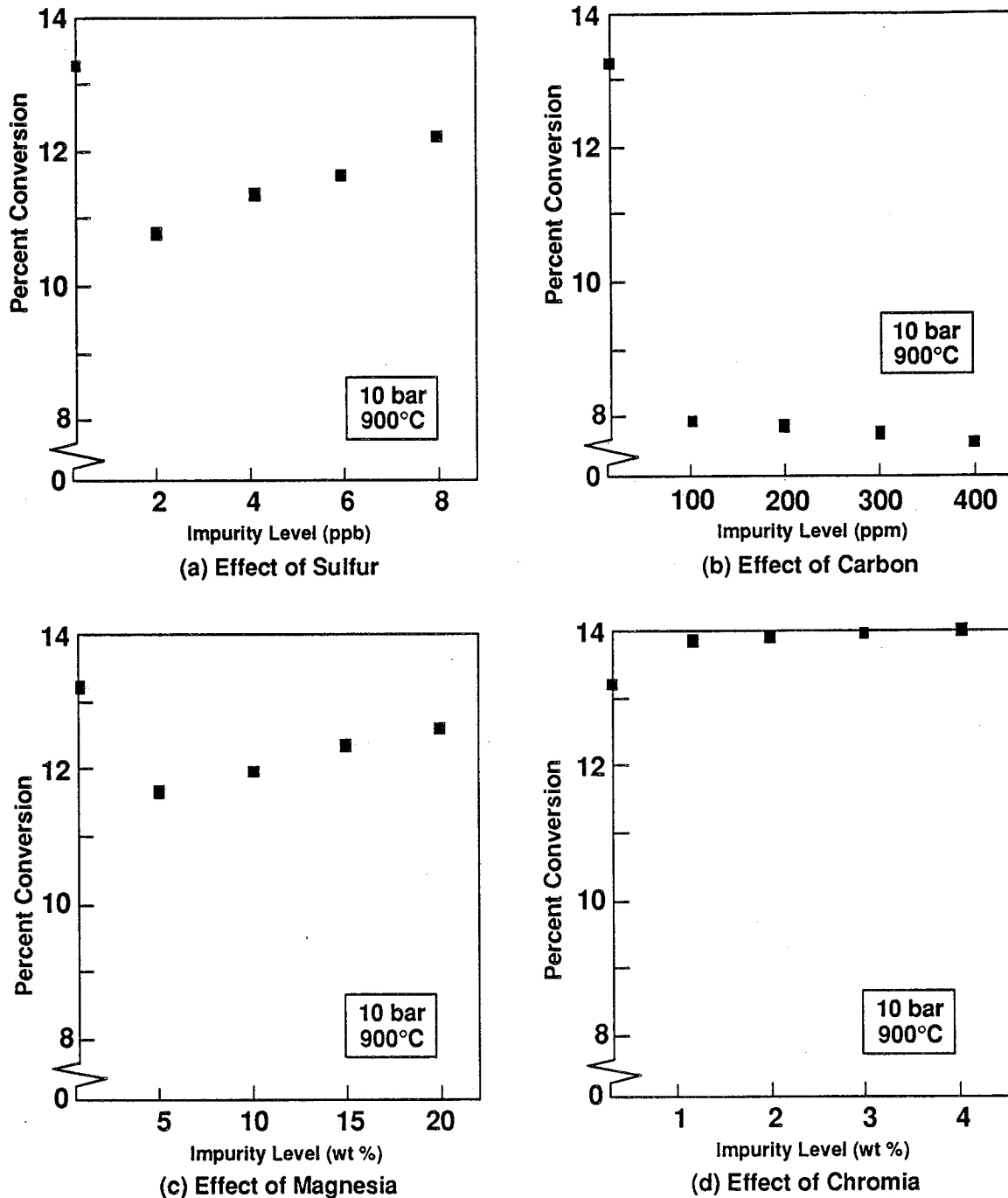
Figure 6: Effect of Impurities on Hydrogen Reduction of Ilmenite Process

and Mg may result in the product is an issue which needs to be addressed. In particular, what are the down stream requirements to purify the process?

In 1990 Bechtel completed detailed engineering, procurement, and construction management services to a new process plant capable of producing 45,000 tonnes per year of titanium dioxide pigment. The Tiofine plant in the Netherlands uses a process which consists of fluid bed chlorination

of rutile, followed by various unit operations including condensation, purification, oxidation, recovery of chlorine and raw pigment, finishing and packaging. This is an example of an existing plant which uses fluidized bed technology. This particular process is similar to the hydrogen reduction of ilmenite process which can be used to win oxygen from ilmenite in the lunar regolith.

Oxygen Production by Vapor Phase Pyrolysis

Another process which is feasible for the production of lunar liquid oxygen is vapor pyrolysis. This process consists of heating granulated lunar soil to a temperature of about 3000 K at very low pressure. At this high temperature the material is fully vaporized and the vapor dissociates into oxygen, sub-oxides, and free metals. Subsequent rapid cooling of the dissociated vapor to a discrete temperature causes condensation of the suboxides and metals, while the gaseous oxygen remains intact and can be collected downstream after some further purification. A schematic of this process is shown in *Figure 7*.
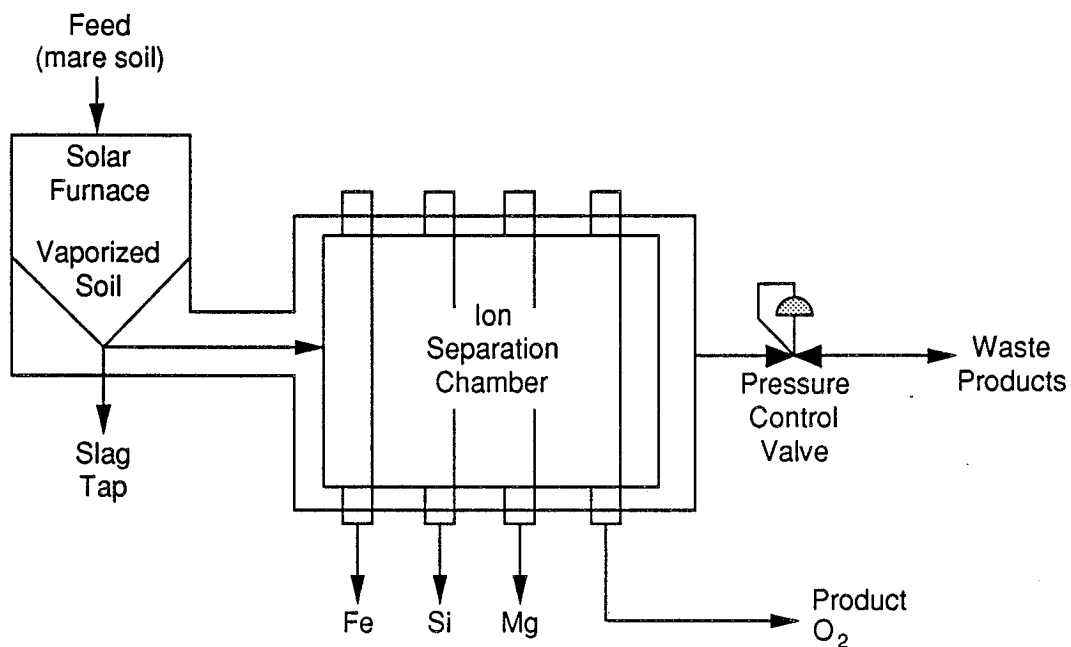

Figure 7: Vapor Pyrolysis

A solar furnace may be feasible to heat the regolith up to the desired reaction temperature. There exists a 1000 kw solar furnace on a mountain top in the Pyrenees in Odiello, France. The facility uses heliostats to track the sun and focus the sunlight into the parabolic reflector. The parabolic reflector concentrates the sun's rays onto a target area. Although a furnace such as this is vary large, the pyrolysis process lends itself well for a solar furnace.

Because the lunar soil composition can vary significantly from one site on the Moon to another, the amounts of oxygen, sub-oxides, and metals that are produced can vary. Therefore, the analysis of several bulk lunar regolith compositions is necessary to assess the raw material requirements as

well as energy requirements for the process. The types of regolith selected for analysis were mare, highland, low titanium mare, high titanium mare, and lunar basalt. From equilibrium calculation results, the amount of product oxygen was calculated for each of the lunar regolith compositions. Table 2 summarizes these results. Although the amount of oxygen produced varies from 27 gm /1000 gm regolith to 33 gm /1000 gm regolith doesn't seem dramatic, Table 3 shows that substantial differences exist in energy required to produce 1000 metric tonnes/yr of O2 by pyrolysis. Note that the type of regolith can have an effect on the energy requirements of the process. The difference translates to almost 4000 MWhr/year.

Table 2: Oxygen Production by Pyrolysis for Various Soil Compositions	
Lunar Regolith Type	Product Oxygen (gm/1000 gm regolith)
mare regolith	29.7
highlands soil	32.9
low titanium mare	30.0
high titanium mare	29.6
lunar basalt	27.6

Conclusions

It is important to continue studying processes which could be used to make liquid oxygen from feed materials which can be found on the lunar surface. Experimental data needs to be collected for a spectrum of processes which fall into different categories of reaction (thermochemical, reactive solvent, electrochemical, and pyrolytic). Data collection should include information about reaction chemistry, operating conditions, and energy requirements, as well as specifications on equipment. Understanding potential feed materials in terms of where ore deposits may be found, the soil mechanic characteristics of these feeds, and the necessary pre-treatment or beneficiation of the feed needs to be made. Equally important is the need to develop process design information based on computer models. Theoretical information, such as thermodynamic data which can be obtained from computer models, can be useful in specifying operating conditions as a function of required energy for a given process chemistry. These parameters can, for example, provide relative information about equipment vessel sizes. Downstream processes for oxygen purification, storage, and recovery need also be defined.

Table 3: Energy Required to Produce 1000 tonnes/yr Oxygen by Pyrolysis				
Type of Lunar Regolith	Required Heating Energy (MWhr/yr)	Required Cooling Energy (MWhr/yr)	Required Mechanical Energy (MWhr/yr)	Required Total Energy (MWhr/yr)
mare regolith	15,448	66,449	1,290	23,187
highlands soil	16,862	7,834	1,567	26,263
low titanium mare	15,627	7,893	1,579	25,100
high titanium mare	15,466	6,362	1,272	23,100
lunar basalt	14,999	6,362	1,272	22,633

To determine a way to make oxygen on the lunar materials processing frontier, it is valuable to rank the processes which have been identified as feasible methods. Several researchers have been doing this and the results indicate that a few processes appear to be more favorable than others. Hydrogen reduction of feed materials and vapor phase pyrolysis are two processes which at this point in time appear to be leading processes, even when the methods used to rank the processes are fundamentally different.

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