

LUNAR OXYGEN PRODUCTION BY VAPOR PHASE PYROLYSIS

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Abstract

The vapor phase pyrolysis process is designed exclusively for the production of oxygen by means of thermo-physical rather than chemical reactions. Raw material such as lunar soil is vaporized and dissociated; the free oxygen gas is then isolated by condensation of all other gas species. The process does not require any consumables and makes extensive use of direct solar (thermal) energy.

A detailed thermodynamic evaluation of the process is presented for individual oxides as well as for an oxide mixture representative of the lunar soil. The gas composition as related to temperature is measured by the partial pressures of the individual species and the oxygen yield by the oxygen weight fraction of the total gas weight. Optimum processing temperatures are in the 2500-3000°K regime which is well within the limitations of direct solar heating.

Data are further presented on energy requirements, facilities mass and the overall process efficiency in terms of the facility investment write-off per ton of oxygen, which is in the order of 1.5% (payback ratio 63:1).

Process feasibility has been demonstrated experimentally.

Introduction

It is generally accepted that oxygen will be the prime near-term product in any endeavor on the utilization of space resources. The reason for this is threefold: First, oxygen is of universal use in all space activities since liquid (O_2/H_2) propulsion will be dominant for the foreseeable future. Second, oxygen represents by far the largest single mass fraction of space systems and, therefore, the largest cost item in space transportation. Third, oxygen is abundant at readily-accessible near-space resource sites, particularly on the Moon and on Earth-approaching asteroids of the ordinary chondrite type; the surface minerals of the Moon, for example, have an oxygen content of 43 percent (Ref. 1). It is further favorable that in the case of oxygen the end-product is in bulk form, precluding expensive secondary processing.

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This paper addresses itself to lunar oxygen production, even though the discussed process is equally adaptable to asteroidal conditions. The Moon offers the advantage of easy accessibility, particularly with regard to launch opportunities as well as flight and signal time. Another advantage is the availability of reliable data on mineral composition and terrain conditions. Furthermore, in the case of the establishment of a manned lunar base, the production of oxygen on the Moon is a necessary and integral part of base operations.

The oxygen of the Moon is exclusively in the form of metal oxides which account for 99.8% of the lunar surface material (Ref. 2). (The postulated presence of oxygen in the form of ice at the polar regions is disregarded at this time, since it is highly speculative.) The production of free oxygen calls, therefore, for processes for the extraction of oxygen from metal oxides.

Oxygen Production Processes

Several processes for the extraction of oxygen from metal oxides have been proposed and investigated to various degrees. Generically, they may be divided into chemical, electrolytic, and pyrolytic processes.

The most viable chemical process is the reduction of ilmenite, using hydrogen as a reducing agent and producing water and free metals. The oxygen is then extracted from the water by electrolysis and the simultaneously recovered hydrogen recycled into the reduction phase. This process has been discussed in detail in the preceding paper.

The production of oxygen by electrolysis directly from the lunar soil consists of melting of the raw material and separation of oxygen and metals by electrolysis of the molten silicates. It has first been investigated experimentally by Kesterge (Ref. 3). Production-oriented development and experimental demonstration were carried out at JPL over the past years (Ref. 4).

Both these process concepts require a certain - even though modest - supply of consumables from Earth: Replenishment of hydrogen losses in the first, and anode refurbishment in the second. In the attempt to eliminate the need for consumables completely, JPL pursued the development of pyrolytic processes, in which the separation of

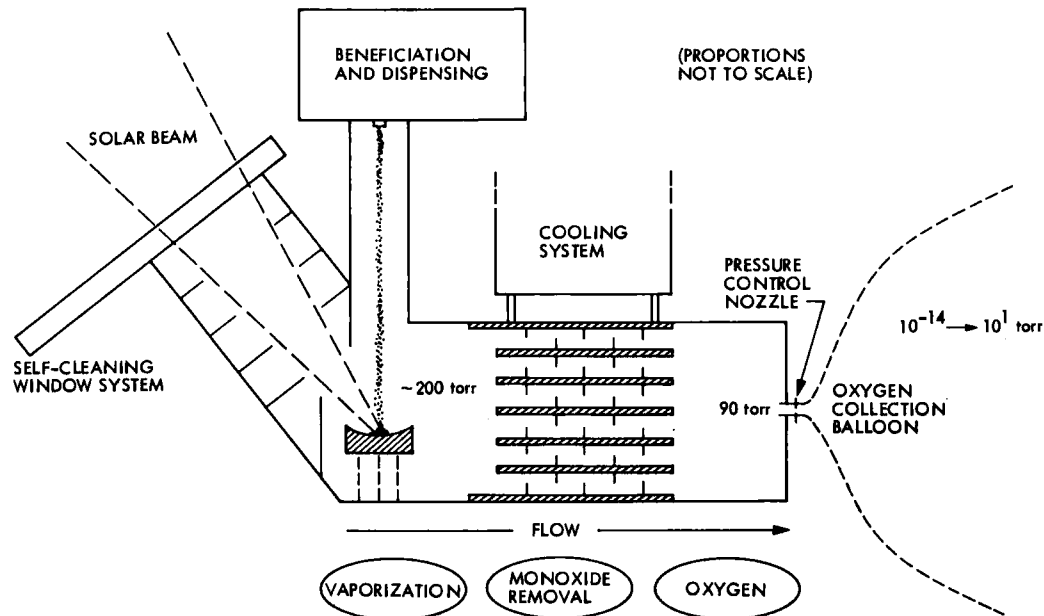


Figure 1 Conceptual Processing Facility (Schematic)

oxygen and metals is exclusively achieved by thermal energy. This led to the definition of two specific processes designated as "Vapor Phase Pyrolysis," which is the subject of this paper, and "Plasma Separation by Selective Ionization" which is discussed in detail in Ref. 4.

Principles of Vapor Phase Pyrolysis

In this process, granulated raw material (soil) is fully vaporized and the vapor raised to a temperature where it dissociates into oxygen, sub-oxides and some free metals. Subsequent rapid cooling of the dissociated vapor to a discrete temperature causes condensation of the sub-oxides and metals, while the gaseous oxygen remains intact and can be collected downstream. The gas flow path and flow rate are maintained at an optimum level by control of the pressure differential between the vaporization region and the oxygen collection system with the aid of the environmental vacuum.

Theoretical and design studies indicate that the optimum operational temperature is in the order of 3000°K. While this temperature may appear high, it is still low enough to permit extensive use of direct (concentrated) solar energy, which reduces the overall facility mass substantially as opposed to the use of all solar-electric energy.

The process is illustrated in Figure 1 in the form of a conceptual facility (schematic). The particle feedstock is dispensed from a vacuum-sealed feeding unit to a crucible by gravitational free-fall. There it is vaporized and dissociated by means of thermal energy supplied from a solar concentrator whose focal point is at the crucible. The beam enters the sealed unit through a self-cleaning window at a distance where the concentration is still low enough to preclude overheating of the window.

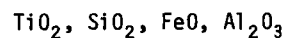
The dissociated gases pass then through a rapid-cooling system at a yet to be determined optimum flow rate and flow pattern. The cooling column will, in reality, be considerably longer than shown in the sketch. The produced oxygen may be collected as gas in a balloon (with a shadow/micrometeoroid protection shield), or liquified. The problem of oxygen storage and liquification is common to all oxygen-producing processes and is, therefore, not addressed here.

Process evaluation, reported in the following sections, consisted of (1) the identification of the dissociation species; (2) the thermodynamic determination of the gas composition as related to temperature for single oxides and a representative oxide mixture; (3) the definition of the oxygen yield and its experimental verification for a single oxide (SiO₂). The studies, further, included an assessment of energy requirements, facility mass and overall production efficiency (pay-back ratio).

Dissociation Species and Vapor Pressures

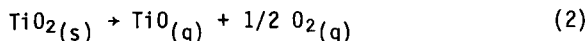
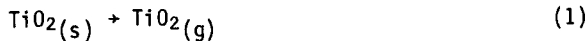
Single Oxides

The increasing degree of vaporization and dissociation as related to temperature was measured by the vapor pressure of individual species vs temperature. Four oxides, predominant in the lunar basalt (soil) were selected for this analysis:



The approach taken is best illustrated by an example (TiO₂). In examining the JANAF tables (Ref. 5), the possible vaporization products of

TiO₂ are TiO₂(g), TiO(g) and O₂(g).^{*} To determine the equilibrium vapor pressures at a given temperature, the following equations were introduced:



The equilibrium constants (K) for these reactions are:

$$K_1 = \frac{\gamma_{\text{TiO}_2(\text{g})}}{\gamma_{\text{TiO}_2(\text{s})}} \quad (3)$$

$$K_2 = \frac{\gamma_{\text{TiO}(\text{g})} \cdot \gamma_{\text{O}_2}^{1/2}(\text{g})}{\gamma_{\text{TiO}_2(\text{s})}} \quad (4)$$

where γ is the "activity". These equilibrium constants can be simplified by noting that the activity of a gas, if ideality is assumed, is equal to the partial pressure. Furthermore, the activity of a solid is defined to be 1 (unity). Therefore:

$$K_1 = P_{\text{TiO}_2(\text{g})} \quad (5)$$

$$K_2 = P_{\text{TiO}(\text{g})} \cdot P_{\text{O}_2}^{1/2}(\text{g}) \quad (6)$$

Equation (2) further indicates

$$P_{\text{TiO}(\text{g})} = 2P_{\text{O}_2(\text{g})} \quad (7)$$

We now have three independent equations (5, 6, and 7) with three unknowns, $P_{\text{TiO}_2(\text{g})}$, $P_{\text{TiO}(\text{g})}$, and $P_{\text{O}_2(\text{g})}$.

Using the free energy (ΔG) data from the JANAF tables and the thermodynamic relationship

$$\Delta G = -RT \ln K_{\text{eq}} \quad (8)$$

the temperature dependence of the vapor pressures can be determined. For example, at 500 K, the free energies of the individual species are:

$$\text{TiO}_2(\text{s}) : \Delta G = -203.692 \text{ kcal/mole}$$

$$\text{TiO}_2(\text{g}) : \Delta G = -61.801 \text{ kcal/mole}$$

$$\text{TiO}(\text{g}) : \Delta G = 8.230 \text{ kcal/mole}$$

$$\text{O}_2(\text{g}) : \Delta G = 0.000 \text{ kcal/mole}$$

Thus, the equilibrium constants at 500 K are

^{*}The subscripts (s), (l) and (g) denote the solid, liquid and gaseous state, respectively.

$$K_1 = \exp [(\Delta G_{\text{TiO}_2(\text{s})} - \Delta G_{\text{TiO}_2(\text{g})})/RT] \quad (9)$$

$$= 9.43 \times 10^{-63}$$

$$K_2 = \exp [(\Delta G_{\text{TiO}_2(\text{s})} - \Delta G_{\text{TiO}(\text{g})} - \Delta G_{\text{O}_2(\text{g})})/RT] \quad (10)$$

$$= 2.30 \times 10^{-93}$$

From Equations 5 and 9 we find

$$P_{\text{TiO}_2(\text{g})} = 9.43 \times 10^{-63} \text{ atm} = 7.16 \times 10^{-60} \text{ torr}$$

To calculate $P_{\text{TiO}(\text{g})}$ we use Eqs. (6), (7), and (10). Substituting Eq. (7) in Eq. (6) we find:

$$K_2 = P_{\text{TiO}(\text{g})} (1/2 P_{\text{TiO}(\text{g})})^{1/2} \quad (11)$$

$$= P_{\text{TiO}(\text{g})}^{3/2} / \sqrt{2}$$

$$\text{Thus } P_{\text{TiO}(\text{g})} = (\sqrt{2} K_2)^{2/3} \quad (12)$$

$$= 2.20 \times 10^{-62} \text{ atm} = 1.67 \times 10^{-59} \text{ torr}$$

$$\text{and } P_{\text{O}_2(\text{g})} = 1/2 P_{\text{TiO}(\text{g})} \quad (13)$$

$$= 1.10 \times 10^{-62} \text{ atm} = 8.35 \times 10^{-60} \text{ torr}$$

For SiO₂, the calculation of the partial pressures of the individual vapor species (SiO₂, SiO, O₂) followed the same procedure as outlined above for TiO₂. The vaporization products of Al₂O₃ consist of Al₂O₂, Al₂O, AlO₂, AlO and O₂; thus, the calculations involve 5 independent equations. For FeO(s), the work is trivial, as the sole vapor species present is FeO(g).

The results of the calculations for the four selected oxides (SiO₂, TiO₂, Al₂O₃, FeO) are presented in Table 1. The temperature dependence of the partial pressures of the individual dissociation species is further illustrated in Figure 2 in the form of the customary ln P (atm) vs 1/T plot. While the Clausius-Clapeyron equation postulates straight lines for ideal gases and constant enthalpy changes vs temperature, the calculated data produce slightly bowed lines due to the non-constant ΔH over the entire temperature range.

An examination of these data indicates relatively high partial pressures at temperatures above 2,500 K which permit high throughput and production rates. A quantitative assessment of the oxygen yield is presented later in this paper.

Oxide Mixtures

To approach the conditions of the processing of lunar soil by vapor phase techniques more accurately, the theoretical analysis was extended to the prediction of the vapor composition of a mixture of oxides. The model mixture consisted (as

Table 1 Vapor pressure of oxide dissociation species vs. temperature

Oxide	Vapor Species	Vapor Pressure of Species (torr) at $^{\circ}\text{K}$		
		2000	2500	3000
SiO_2	SiO_2	1.92×10^{-4}	1.77×10^{-1}	1.53×10^1
	SiO	7.13×10^{-3}	3.26	1.80×10^2
	O_2	3.57×10^{-3}	1.63	9.00×10^1
TiO_2	TiO_2	8.22×10^{-7}	1.23×10^{-3}	1.20×10^{-1}
	TiO	4.78×10^{-5}	5.36×10^{-2}	4.71
	O_2	2.39×10^{-5}	2.68×10^{-2}	2.34
Al_2O_3	Al_2O_2	8.13×10^{-11}	1.50×10^{-6}	5.46×10^{-3}
	AlO_2	5.72×10^{-9}	7.30×10^{-5}	2.84×10^{-2}
	Al_2O	4.63×10^{-8}	2.99×10^{-4}	6.43×10^{-2}
	AlO	2.24×10^{-7}	9.42×10^{-4}	2.11×10^{-1}
	O_2	1.01×10^{-7}	5.17×10^{-4}	1.09×10^{-1}
FeO	FeO	2.56×10^{-3}	5.81×10^{-1}	1.92×10^1

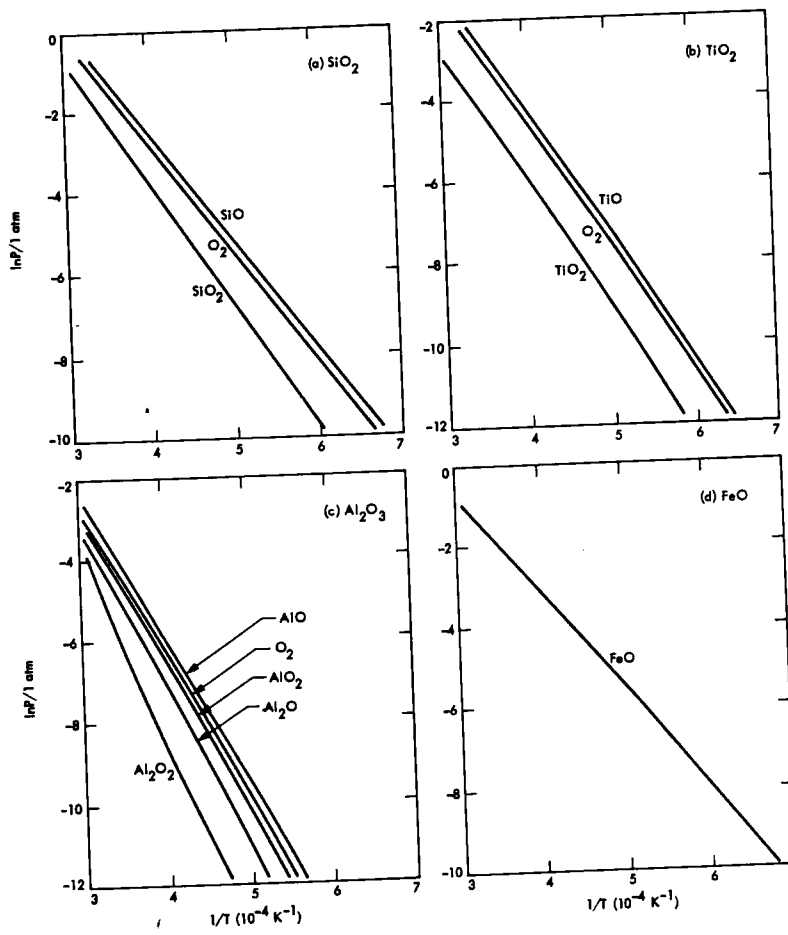


Figure 2 Partial Pressures of Dissociation Species vs. Temperature

in the preceding treatment of individual oxides) of SiO₂, TiO₂, FeO and Al₂O₃, representing major constituents of the lunar soil. The vapor composition was again expressed in terms of partial pressures.

Assuming an ideal mixture of these oxides, i.e., that the activity of all solids is equivalent to the mole fraction, and the activity of the gases is equal to their respective partial pressures, the thermodynamic data of the JANAF tables (Ref. 5) can be used to calculate compositional vapor pressures.

The thermodynamic procedure is somewhat complex and, therefore, omitted here; details may be obtained from Ref. 4 (pp. 4-13 to 4-18). It involves nine equilibrium equations and leads eventually to an eighth-power equation for the determination of the compositional vapor pressures. Solving these equations was accomplished by a computer program for the temperature range from 1000 to 3000°K and the following model composition of the starting material representative of major constituents of lunar basalt:

Oxides	% (Weight)
Al ₂ O ₃	15
SiO ₂	50
TiO ₂	10
FeO	25

The results in terms of computational vapor pressures are presented in Table 2 for the temperature regime between 2000 and 3000°K. The table shows that the pressures rise sharply with temperature, as expected. The oxygen pressure at 3000°K in the order of 0.1 atm is more than adequate for practically useful production rates.

Table 2 Compositional vapor pressure (atm) of a mixture of Al₂O₃, SiO₂, TiO₂ and FeO.

Species	2000 K	2500 K	3000 K
O ₂ (g)	3.2 x 10 ⁻⁶	1.5 x 10 ⁻³	8.1 x 10 ⁻²
AlO(g)	7.3 x 10 ⁻¹²	5.6 x 10 ⁻⁸	1.8 x 10 ⁻⁵
Al ₂ O(g)	2.5 x 10 ⁻¹⁶	1.6 x 10 ⁻¹¹	1.6 x 10 ⁻⁸
AlO ₂ (g)	2.9 x 10 ⁻¹¹	2.0 x 10 ⁻⁷	5.8 x 10 ⁻⁵
Al ₂ O ₂ (g)	6.8 x 10 ⁻¹⁷	3.7 x 10 ⁻¹²	3.2 x 10 ⁻⁹
SiO(g)	6.5 x 10 ⁻⁶	3.0 x 10 ⁻³	1.6 x 10 ⁻¹
SiO ₂ (g)	1.4 x 10 ⁻⁷	1.4 x 10 ⁻⁴	1.1 x 10 ⁻²
TiO(g)	4.8 x 10 ⁻¹⁰	9.3 x 10 ⁻⁷	1.0 x 10 ⁻⁴
TiO ₂ (g)	8.4 x 10 ⁻¹¹	1.4 x 10 ⁻⁷	1.3 x 10 ⁻⁵
FeO(g)	8.1 x 10 ⁻⁷	2.0 x 10 ⁻⁴	5.9 x 10 ⁻³

Oxygen Yield

Individual Oxides

The oxygen yield is defined as the oxygen weight fraction of the total gas weight or

$$O_2 = \frac{\text{Weight of Gaseous Oxygen}}{\text{Weight of Total Gas}} \quad (14)$$

For the example of TiO₂ the oxygen yield (in percent by weight) is

$$\% O_2 = \frac{M_{O_2} p_{O_2}}{M_{O_2} p_{O_2} + M_{TiO} p_{TiO} + M_{TiO_2} p_{TiO_2}} \times 100 \quad (15)$$

where M is the mole weight and p the partial pressure of each species. The calculated oxygen yield data for the four selected oxides and various temperatures are listed in Table 3.

Table 3 Oxygen Yield (% by Weight) of Oxides vs Temperature

Oxide	Temperature				
	1000K	1500K	2000K	2500K	3000K
TiO ₂	20.0	19.9	19.7	19.6	19.5
SiO ₂	26.6	26.4	25.9	25.3	24.5
FeO	0	0	0	0	0
Al ₂ O ₃	-	17.7	19.6	20.1	18.2

It may at first glance appear surprising that the yield is insensitive to temperature. It should be remembered, however, that the overall gas pressure which determines the throughput and output rate drops drastically with temperature; the lower temperature values are, therefore, only of academic interest.

To place the data of Table 3 further in perspective, it may be useful to compare the oxygen yield with the total oxygen contained in each oxide. In the 2000-3000°K temperature range in every case, except FeO, nearly half of the oxygen is extractable, as evidenced by the following data (in % by weight):

Oxide	O ₂ Yield (% of Oxide)	Total O ₂ (% of Oxide)	O ₂ Yield (% of Total O ₂)
TiO ₂	19.6	40.1	49
SiO ₂	25	53.2	47
FeO	0	22.3	0
Al ₂ O ₃	19.3	47.1	40

Mixed Oxides (Lunar Soil)

The ultimate measure for the effectiveness of the process is, of course, the single figure for the oxygen yield of the entire raw material, i.e., the lunar soil feedstock. For the earlier defined model mixture of oxides it was computed from the partial pressures and molecular weights of the

various gas species (Table 2). For the 2500-3000°K regime, a yield value of 19.6% (by weight) was obtained. It was, further, independently computed from the yields of individual oxides (Table 3) and their weight fraction of the lunar soil. Introducing the following weight fractions (Ref. 2, Table III-3)

SiO ₂	40%	
FeO(Fe ₃ O ₄)	19%	
TiO ₂	13%	of lunar soil (wt)
Al ₂ O ₃	10%	
CaO	9%	
MgO	9%	

an oxygen yield of 17.0% was obtained for the 2500-3000°K temperature regime.

These figures are based on the use of unrefined lunar soil as feedstock which contains a substantial amount of FeO (Fe₃O₄). As indicated in Table 3, the oxygen yield of FeO by this process is zero. It will, therefore, be beneficial to remove the iron-rich particles from the soil prior to processing. The enhancement of the oxygen yield by such beneficiation - in terms of vapor pressure - is identified in Table 4 for the earlier defined model mixture of oxides. In the 2500-3000°K temperature of interest, this enhancement increases the oxygen yield by approximately 20%. Soil beneficiation would, therefore, increase the yield values of 19.6 and 17%, above, to 23.5 and 20.4%, respectively. For the ensuing evaluations of process efficiency, the more conservative figures were adopted as base values for the oxygen yield:

Unrefined Soil	17.0% (wt)
Beneficiated Soil	20.4% (wt)

Table 4 Oxygen Vapor Pressure of the Model Mixture With and Without Prior Beneficiation.

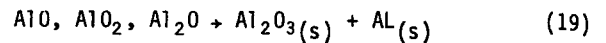
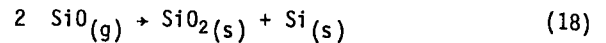
Temp. (K)	Without (atm)	With (atm)	Enhancement (%)
1000	5.43 10 ⁻²⁰	6.50 10 ⁻²⁰	19.7
1500	9.25 10 ⁻¹¹	1.11 10 ⁻¹⁰	20.0
2000	3.23 10 ⁻⁶	3.87 10 ⁻⁶	19.8
2500	1.51 10 ⁻³	1.81 10 ⁻³	19.9
3000	8.12 10 ⁻²	9.73 10 ⁻²	19.8

Metal Yield

Even though the objective of the process is the production of oxygen, the potential generation of free metals has been evaluated merely for completeness.

As stated initially, the envisioned technique of suboxide removal is rapid cooling of the gas to a temperature in the order of 500 K and at a rate which prevents reaction with the free oxygen and recombination to the original oxide. In the rapid cooling process the condensing vapors, such as TiO,

SiO, TiO₂, SiO₂, AlO, etc., will in some instances disproportionate to form the original oxide and free metal, according to the following equations:



As can be seen from Eqs. (18) and (19) the condensation of the suboxides of Al and Si may be associated with the formation of free metals. Tentative calculations of the metal yield indicate the following maxima (in % by weight of the original oxide):

Oxide	Metal	1000K	1500K	2000K	2500K	3000K
SiO ₂	Si	23.4	23.2	22.7	22.2	21.5
Al ₂ O ₃	Al	-	19.9	21.1	22.6	20.5

The data represent close to half of all metal contained in the oxide (SiO₂ = 46.8% and Al₂O₃ = 52.9%).

Experiments

The objective of the experiments carried out to date was the verification of process feasibility, i.e., the capability to generate free/recoverable oxygen which hinges on the effective condensation of other species.

The experimental facility is illustrated in Figure 3, which is self-explanatory. Except for the heating mode (induction heating via a susceptor instead of radiant heating) it simulates the conditions in the envisioned processing column. Of particular importance is the cooling loop ("cold finger") for condensation (re-solidification) of suboxides and free metals.

For feasibility verification it was considered permissible to use only a single oxide as raw material. Silica was selected since it is predominant in the lunar soil. In a first series of experiments it was attempted to verify the generation of recoverable free oxygen by the presence of condensed material at the cooling loop. Upon completion of each experiment run at a temperature of 2650°K, substantial deposits of free metal (silicon) and suboxides were found at the cooling loop. This permitted two conclusions: (1) free oxygen was generated, and (2) the cooling rate is not as critical as anticipated.

In a second series of experiments with a modified apparatus, the gas past a condensation path was sampled and analyzed. Even though free oxygen concentrations in the order of the predicted values were found, the results are not yet considered conclusive and have to be further verified.

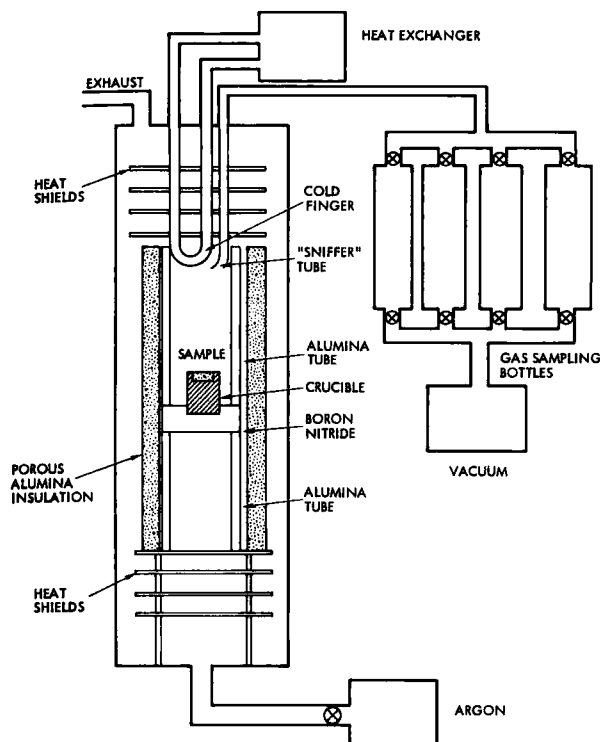


Figure 3 Experimental Apparatus

Energy Requirements

Energy Consumption

The assessment of the energy required for oxygen production by the vapor-phase pyrolysis process involves the two major consumers:

- (1) The vaporization and dissociation of the raw material.
- (2) The quenching of the vapors for the condensation of the sub-oxides.

For (1) reasonably accurate calculations were carried out using thermodynamic data from Refs. 5 and 6. Energy data for the quenching phase (2) were merely estimated since they depend extensively on the not yet defined design of the cooling system.

Since thermodynamic data for oxide mixtures are not available, the energy requirements for the vaporization phase (1) were calculated for each individual oxide from data on the heats of formation, vaporization and dissociation. The resulting figures were then adjusted commensurate with the raw material fraction of each oxide. The energy requirement of the starting mixture was determined as the sum of the individual adjusted data. It amounted to 4.8 kcal/g or 5,100 kWh/ton. Interactions in the vapor, which may alter this figure slightly, were disregarded, since at this time only a first approximation was required.

For the cooling phase a conservative estimate of 1700 kWh/ton was introduced, and 300 kWh/ton for various mechanical devices. Assuming the use of beneficiated raw material with the earlier defined oxygen yield of 20.4%, the total energy required per ton of oxygen is

$$E_{O_2} = \frac{7,100}{0.204} = 34,800 \text{ kWh/ton}$$

This total energy is provided in the form of direct solar energy (heating phase) and electric energy as follows:

	Thermal	Electric
kWh/t (Raw)	5,100	2,000
%	72	28
kWh/t (O ₂)	25,000	9,800

Mass of Energy Facilities

The mass of the energy facilities is determined by required installed energy E_i (kw) which, in turn, is computed from the energy consumption per ton of oxygen e_{O_2} (kWh/t), the yearly oxygen production P_{O_2} (t/yr), and the operations time per year t_y (hrs/yr):

$$E_i = \frac{e_{O_2} \times P_{O_2}}{t_y} \quad (\text{kw}) \quad (20)$$

For a production rate of 100 t/yr, a net production time of 3,800 hrs/yr (0.43 yr) and the thermal/electric breakdown, above, the required installed energy is

E_i (Thermal)	658 kw
E_i (Electric)	258 kw

Introducing further the mass factors projected for the 1990's of 2 kg/kw for solar concentrators (including heliostatic drive) and 8 kg/kw for photovoltaic systems, the following mass values for the energy supply system of a 100-ton plant are obtained:

Direct Solar	1.3 tons
Solar-Electric	2.1 tons

Lunar Production Plant

It would be premature to attempt a specific design of the lunar production plant at this time. However, a conceptual definition of the required facilities is necessary in order to assure operational feasibility and to obtain reasonably valid mass data for the assessment of the overall efficiency of the process.

In the envisioned plant lay-out, actual processing is carried out in a series of individual and identical "columns", each with its own solar concentrator. The number of individual columns depends on the overall plant size in terms of output. The reason for this modular arrangement is

threefold: (1) It minimizes the effect of any down-time for maintenance, repair or removal of the condensed suboxides and metals; automated schemes for such removal are presently under study. (2) The modular approach permits a gradual increase of plant output by added standard-size columns. (3) Smaller-diameter columns are more efficient and exhibit a higher assurance of complete feedstock vaporization. Based on best engineering judgement, a column with a 20 ton/year oxygen output appears to provide optimum conditions.

To perceive a mental picture of the operational load on such a column, it is useful to visualize the throughput rates at short intervals which are as follows:

(20-ton Column)

Interval	Throughput (Mass)	Throughput (Volume*)	O ₂ Output (Mass)
Per hour	25.8 kg	15.5 ℓ	5.26 kg
Per minute	0.43 kg	260 mℓ	88 g
Per second	7.16 g	4.3 mℓ	1.46 g

*Bulk volume (including voids) of lunar soil.

Actual facilities which serve all modules comprise the external part of the cooling system with radiator, the electric power plant (photovoltaic or nuclear), the oxygen collection system, and several ultra-lightweight sun shields. As stated initially, provisions for oxygen liquification are excluded since they are common to all oxygen production processes and may not be mandatory.

Tentative mass data for these facilities and the entire plant were obtained from preliminary design studies. The mass summary for a 100 t/yr plant with 5 modular columns is presented in Table 5.

Table 5 Mass Summary of an Oxygen Production Plant with a Yearly Output of 100 Tons

FACILITIES	MASS (kg)
5 Processing Columns	4,500
5 Solar Concentrators	1,500
Photovoltaic Power Plant	2,100
Power Conditioning	500
Cooling System	2,600
Oxygen Collection System	1,400
Solar Shields	300
All Facilities	12,900
Contingency (10%)	1,300
Plant Total	14,200

Production Efficiency

In the deployment of hardware to the Moon, the cost of transportation exceeds the cost of the hardware itself, including development, by 1 to 2 orders of magnitude, at least until such time when lunar oxygen is routinely supplied to LEO. It is, therefore, permissible to neglect the hardware cost and to express the cost of the lunar installation by the delivered mass.

This mass investment has to be written off against the total product mass accrued over the expected facility life. The investment "mass burden" b_i which has to be imposed on each ton of product is defined by

$$b_i = \frac{M_i + m_c \times t_p}{(1-f_l) \times m_p \times t_p} \quad (t/t) \quad (21)$$

where M_i is the installed mass, m_c the yearly mass of consumables supplied from Earth (= zero for vapor phase pyrolysis), m_p the yearly production rate, t_p the life of the facility in years, and f_l a product loss factor. For the plant discussed above with a production rate of 100 t/yr, a conservative lifetime of 10 years, a loss factor of 0.1, and a total plant mass of 14.2 tons (Table 5), the mass burden per ton of deliverable oxygen is then:

$$b_i = \frac{14.2}{0.9 \times 100 \times 10} = 1.56\%$$

This value is well within the acceptable limit of 3% postulated in Ref. 7.

The production efficiency is also often expressed by the inverse relationship (deliverable product mass/total invested mass), designated as payback ratio, which in our case is a very attractive 63:1.

Conclusions

For the production of lunar oxygen, the vapor-phase pyrolysis process appears particularly attractive for the following reasons: (1) It does not require any consumables; (2) It makes extensive use of direct solar (thermal) energy; (3) it is a continuous process confined to a single enclosure. The predicted oxygen output is in the order of 20% of the raw material throughput mass. The facility write-off per ton of deliverable oxygen is very favorable and in the order of 1.5%, equivalent to a payback ratio of 63:1.

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