ANALYSIS OF LUNAR OXYGEN PRODUCTION METHODS UNDER VARYING LUNAR CONDITIONS

By:

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ABSTRACT

This research thesis compares the major, most feasible methods of providing the needed amounts of oxygen on the lunar surface for a future human mission. Past studies are combined to provide a comprehensive look at each process and their processing requirements (for example, the mass a processing plant requires, the speed at which the oxygen could be produced, and the cost of setting up such a processing system). There are three methods of in-situ oxygen production that will be researched: hydrothermal reduction, carbothermal reduction, and water/ice electrolysis. Transportation from the Earth is also noted as a basis of comparison. These three methods were chosen because they are the three simplest, most studied methods of regolith reduction to produce oxygen. There have been several studies done on these methods from which I base my research. Pure electrolysis is being studied because of the possibility of water ice at the lunar poles. All three processes are compared and analyzed under various lunar constraints. These constraints limit the feedstock of the system at different locations on the lunar surface.

It is found that the water ice concentrations estimated at the north-pole are significantly above that needed to make ice electrolysis the most beneficial method of extraction. However, in mid-latitudes and the south-pole such a definite conclusion is not yet seen. In the south polar regions if the water ice concentration is in the lower half of the bound estimated then ice electrolysis is not the most beneficial, yet if it is in the upper half it will be at least more beneficial than the hydrothermal process, if not the most beneficial. More research must be conducted on the carbothermal system to make definite analysis quantitatively conclusive.
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1. Introduction

For many years after the conclusion of the Apollo missions in 1972 there has been relatively little interest in or inspiration to return to the moon other than from a select group of lunar enthusiasts. The only missions since Apollo to study the moon were both unmanned probes sent in the 1990s – Clementine and Lunar Prospector. These two missions each showed very interesting evidence for possible water ice at the lunar poles. Clementine’s radar experiment showed a reflectance signature comparable to that of water ice [Nozette]. Several years later Lunar Prospector explored the poles with its neutron spectrometer. This instrument showed a significant reduction in epithermal neutrons which can be explained by the presence of water ice [Feldman]. These two experiments are not conclusive evidence for water ice at the lunar poles. Currently other explanations are still possible for the data seen from the experiments. For example, solar wind hydrogen has been proposed as a possible source of the epithermal neutron data count [Hodges, Crider]. Lunar Prospector was crashed into the southern pole in hopes of showing further evidence of ice, but none was seen. Further experiments are needed to determine the existence and concentration of ice at the pole. Since the end of the Lunar Prospector mission, no further experiments have been sent to the moon as of yet. However, there are several current missions in planning stages to be launch to lunar orbit including ESA’s Smart-1 craft, Japan’s SELENE, and a privately funded mission by Transorbital Inc. With luck these missions will help determine a more exact amount of water ice and the concentrations of usable resources on the lunar surface.
The discovery of possible water ice at the lunar poles has helped spark new enthusiasm for returning to the moon that is now apparent in the space community, as can be seen in the numerous new missions being planned to the moon mentioned above. China has also expressed interest in taking its new and developing space program to the moon. Within the next decade they plan to have launched a successful mission to the moon, and beyond that there are claims that China has plans for a manned lunar base. The recent NRC-NAS decadal survey determined a south-pole Aitken Basin sample return mission to be a high priority in the coming years in the NASA program. With this renewed interest in returning to the moon it is important to understand what resources can be used and how to use them. This study is one step in understanding the lunar resources that will become useful in future years.

1.1 Lunar water ice

Since the discovery of possible ice on the moon there has been much debate about the amount and concentration of this ice. Studies for and against its existence have battled back and forth. Figure 1 shows the epithermal neutron count with a clear lack of neutrons around the pole. Several studies claim that the solar wind itself is enough to account for the low count of epithermal neutrons seen by Lunar Prospector [Crider, Hodges], while others claim there must be at least some concentration of water at the poles. Hodges notes that simulations of Lunar Prospector data have shown that the neutron signature of simple mineralogical anomalies such as excess silicate could also account for the Prospector’s data [Hodges]. I will not address any debate over there being water or not being water in this paper. In order to conduct any analysis comparing water
electrolysis systems on the moon one must assume that there is some amount of water there. Several papers by Feldman et al claim that an analysis of the Lunar Prospector data shows there must be 1700 +/- 900 ppm hydrogen in lunar south-pole cold traps. This translates to 1.5 +/- 0.8% water. For the north-pole they were not able to make a realistic tally of the total amount of cold traps in the region. However, they were able to estimate this number by taking small regions and expanding the shaded area in those regions to the entire pole. Through this method Feldman et al estimated a water ice fraction in the north-pole cold traps to be ~10% by mass [Feldman].

1.2 Lunar base research and oxygen needs

The very notion of possible water ice on the moon sparked a renewed vigor in reviving the lunar program. More and more interest in returning to the moon for future exploration
and development has been expressed in both NASA and private enterprise. One of the main expenses of lunar missions is the cost of launching the mass into space. If the amount of mass launched from the Earth can be reduced by producing materials in-situ on the lunar surface the cost of future missions could be drastically reduced. There have been numerous research studies concerning various methods of processing lunar materials to create the needed resources for future missions. There are many resources that have been considered for in-situ lunar production including: structural materials from Iron Titanium and Aluminium, cement, solar cells, water, fuel, and of course breathable oxygen.

NASA itself has not made any plants for a manned lunar base; however, if cost is the only prohibitive item keeping such a base out of NASA’s eye new methods of building and running such a base could drastically aid in moving NASA toward such a mission. When concerning future human missions a main material need is oxygen. Humans need approximately 800 grams of oxygen per day [Sauer]. Any future lunar manned mission will most likely consist of at least three people. Assuming only a 10 day stay on the lunar surface this would require a total of:

\[
800\text{g/person} \times 3 \text{ people} \times 10\text{days} = 24\text{kg of oxygen.}
\]

This number assumes no recycling of Oxygen. Recycling methods have been well refined over many years of space missions and would drastically reduce the amount of oxygen production needed. Twenty-four kilograms of oxygen is much less mass than any
processing plant design proposed even after being scaled down. Therefore it would not be logical to launch a plant to produce this small amount of oxygen. It is only reasonable to launch a plant to process materials in-situ if the oxygen mass needed is greater than the plant mass needed to produce this oxygen. A study done by David Miller and several students researched this area from an engineering point of view and determined that it was not feasible to produce oxygen in-situ unless there was going to be a long-term, constant need for oxygen such as a human presence on the moon or the need to store oxygen for multiple future missions [Miller]. This study assumes that there will be a large continuous oxygen need – such as that required for a future lunar base.

The symposium on Lunar Bases and Space Activities of the 21st Century held in 1988 proposed and discussed many lunar base designs that varied in their specifics but kept one fact key to this paper fairly constant. Most bases require a minimum of 6-7 people to keep the base continually operational and conduct science experiments [Mendell]. For this study a base with a 6 person crew and an oxygen recycling system 99% efficient is used for analysis. Assuming it is desired to have enough oxygen on hand to last the crew for at least one month (30 days) the base would need an initial input of 144kg. At 99% efficient recycling 1.44kg of oxygen would be lost per day. Therefore the oxygen production plant would be required to produce at least this much oxygen in a day, or 525.6kg per year, to maintain lunar base self sufficiency.

It is important to study various methods of oxygen production in order to optimize the benefits for future lunar bases. The cost of constructing and maintaining a lunar base is
very high. A large portion of this cost stems from the launch costs of materials from the Earth. In general, if the amount of material needed from the Earth can be decreased, the running operational cost of the lunar base will also be cut. This paper focuses on cutting the amount of oxygen needed from the Earth, but oxygen is only one material that could be researched as an in-situ resource to reduce lunar base costs. When considering oneself with fully designing a lunar base it will be beneficial to research all possible resources to minimize the amount of mass taken from the Earth; however, working with oxygen alone allows for a more detailed analysis of the production processes.

2. Oxygen production methods

Numerous methods of oxygen production have been studied since the Apollo program. These processes range from very complex chemical reactions needing large complicated production plants, to a few relatively simple benefication and reduction steps. In the 1960s Rosenberg conducted several studies on propellant and oxygen production on the moon [Rosenberg, 1965] expecting the Apollo program to lead to a much larger manned presence on the lunar surface. More recently, many more studies have been conducted getting more specific on various different methods of oxygen and other lunar resource production. Taylor provides a fairly comprehensive comparison of the majority of the proposed processes and ranked them according to various criteria. He also made simple calculations of plant masses for a large-scale factory using various methods of oxygen production [Taylor, 1993]. Taylor broke down processing systems to include the best feedstock variables as well. He separated processes based on the reagent and the most
viable feedstock phase. However, on the lunar surface the various phases will often be
found mixed together in different concentrations. Therefore, for this study I will not be
separating processes based upon feedstock at all, but only based upon the reducing agent.
None of Taylor’s studies researched the possibility of water ice because there was, at the
time of his studies, no evidence for any lunar ice. Comparing the process of supplying
oxygen from water ice to the numerous other oxygen production methods is one of the
focuses of this study.

For this study I will be researching the two simplest methods of regolith reduction:
hydrothermal and carbothermal and comparing them with possible water electrolysis and
Earth supply methods of providing the needed amounts of oxygen to a lunar base. The
hydrothermal and carbothermal methods were chosen because they are the simplest and
are the only that will be feasible within the relatively near future. Other methods of
regolith reduction involve more complicated chemical processes. The more complicated
chemistry makes it much harder to create a processing plant on the moon based on these
processes.

In order to comprehensively study the best way to produce the needed oxygen for future
lunar bases, one must now also consider the possibility of ice at the lunar poles, as well as
supplying the oxygen from the Earth. Bringing oxygen from the Earth is generally
thought of as an antiquated way of providing needed resources to future bases, but it is
important to consider as a basis of comparison. Therefore, there will be a total of four
production methods researched in the study including two regolith processing methods:
hydrothermal and carbothermal reduction; one separating lunar polar ice, and one taking all needed resources from the Earth.

2.1 Carbothermal reduction

Carbothermal reduction simply implies taking carbon in some phase and using it as a reducing agent for regolith material. There are several different phases that can be used for this process. The two most useful are carbon monoxide, and methane [Taylor, 1993]. I have limited this study to considering only methane production methods because that is what is used in Rosenberg’s oxygen plant designs upon which I have based some research. The carbothermal reduction reaction of silicates and oxides with methane [Rosenberg] is noted below:

\[
[M]O + CH4 = [M]O + H2 + CO \\
3H2 + CO = CH4 + H2O \\
H2O + Q = H2 + 0.5O2
\]

In order to maintain the process, methane will need to be supplied to make up for any losses throughout the procedure. No laboratory studies have been conducted on the rate of methane supply needed for the reactions to be most efficient, or on how much methane might be lost in the system. For the carbothermal process this study will not worry about supplying this methane, but rather simply assume that it will be supplied as needed. Therefore no mass will be added to the production system for a methane supply system.

The carbothermal process reduces both oxides and silicates unlike the hydrothermal process which only reduces select oxides. Ilmenite (FeTiO3) is again the major oxide
phase reduced, while Olivine (Mg2SiO4) and pyroxene (MgSiO3) are two relatively easily reduced oxide phases. Using a bulk mare regolith composition Rosenberg determined that approximately 20 wt% of oxygen could be extracted using this carbothermal process. In other words, if 100kg of oxygen is required, 500kg of regolith must be mined and input to the system. It is also stated that this process could be used with anorthositic highland regolith, but that the resulting oxygen yield would be much lower (no actual figures were found) and would probably be less feasible in these regions than other processes [Taylor, 1993; Rosenberg]. Figures for feedstocks other than mare soil will need to be determined to completely analyze the system.

The carbothermal production method is the most complicated of the three in-situ processes being considered, having 3 processing steps rather than two (hydrothermal), or one (water/ice electrolysis). This method has been studied most notably by Sanders Rosenberg in which he designed a continuous carbothermal, and a batch carbothermal production system. It was calculated that the batch system worked best under lunar conditions. The plants that he designed were calculated to produce 5 metric tons of oxygen per year. The mass breakdown of his batch plant in kilograms is broken down as follows [Rosenberg]:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regolith Reduction Reactor</td>
<td>52.4</td>
</tr>
<tr>
<td>CO reduction reactor</td>
<td>75.1</td>
</tr>
<tr>
<td>Water electrolysis unit</td>
<td>91.7</td>
</tr>
<tr>
<td>Oxygen Liquefaction unit</td>
<td>393.0</td>
</tr>
<tr>
<td>Liquid Oxygen Storage unit</td>
<td>167.3</td>
</tr>
<tr>
<td><strong>Subtotal</strong></td>
<td><strong>779.5kg</strong></td>
</tr>
</tbody>
</table>
Rosenberg’s mass breakdown did not include a power system for such a plant, although he did provide the required amount of power needed for the subsystems. Assuming 125W/kg for a power system delivered to the lunar surface we are able to estimate the added mass to the entire system:

\[
\begin{align*}
\text{Regolith Reduction Power} &= \frac{25700\text{W}}{125\text{W/kg}} = 205.6\text{kg} \\
\text{Water Electrolysis Power} &= \frac{11600\text{W}}{125\text{W/kg}} = 92.8\text{kg} \\
\text{Oxygen Liquefaction Power} &= \frac{3700\text{W}}{125\text{W/kg}} = 29.6\text{kg} \\
\text{Total Power System Mass} &= 328.0\text{kg}
\end{align*}
\]

Therefore the total mass of the combined system is: **1107.5 kg**. Rosenberg does not provide a separate power figure for the CO reduction reactor. We can only assume that this figure is included in the Regolith reduction reactor power. In this paper I use the above Rosenberg plant mass breakdown as a basis for scaling the Hydrothermal, carbothermal, and water electrolysis systems. This is possible because the carbothermal system is broken down into component parts so that those not required by hydrothermal and electrolysis systems can be dropped while the rest kept. This plant is designed to produce 5 metric tons of oxygen per year. At the 20% conversion assumed by Rosenberg this amounts to a bulk regolith handling capacity of 25 metric tons per year.

### 2.2 Hydrothermal reduction

The hydrothermal system takes a regolith feedstock and reduces the oxide phases with hydrogen. Allen, conducted indepth studies of this process on numerous lunar samples. Through his studies he found that the major oxide phase reduced was iron-oxide with minor additions from TiO2 and MgO. The amount of oxygen released from his samples
depended heavily upon the amount of FeO contained in the sample. In lunar rocks most FeO is contained in the phase FeTiO3 (ilmenite). Therefore higher concentrations of ilmenite in the feedstock mean higher percentages of oxygen released. The chemical reaction assuming pure ilmenite feedstock is as follows [Allen 1996, Gibson]:

\[
\text{FeTiO} + \text{H}_2 = \text{Fe} + \text{TiO}_2 + \text{H}_2\text{O}
\]

\[
\text{H}_2\text{O} + Q = \text{H}_2 + 0.5\text{O}_2
\]

The hydrothermal reduction of ilmenite is the simplest known reaction feasible for producing oxygen from lunar regolith and has been studied theoretically by numerous researchers including Carleton Allen who conducted experiments on actual lunar samples and found the hydrothermal reduction process to yield between 1-4 wt% oxygen. He determined the process to be very dependent upon the feedstock of the system. Iron-poor highland soils yielded the smallest amounts of oxygen, 1-2 wt%. Mare soils produced up to 3.6 wt%, while pyroclastic glasses yielded as much as 4.7 wt% oxygen. Using pure ilmenite (FeTiO3) as feedstock, a stoichiometric yield of ~10 wt% oxygen can be achieved. With a fairly well sized benefication system a yield very close to this stoichiometric limit can be realized [Allen]. It was determined that the weight percent oxygen yield from this process follows the equation:

\[Y = 0.19X + 0.55\]
Where “Y” is the oxygen yield in weight percent, and “X” is the weight percent of ferrous iron in the form of FeO. For example, if one took pure ilmenite the weight percent of FeO in this phase is 47.4%, therefore, the expected oxygen yield is 9.56%.

Allen’s tests were conducted on very small (milligram size) Apollo samples. Each test was run for approximately 3 hours. However, Allen’s tests did not make any assumptions about the processing speed for large quantities. He did note that the majority of the weight loss occurred within the first 60 minutes for his trials [Allen, 1996].

Allen made no predictions concerning the mass of any production plant for processing large quantities of regolith. No actual plant designs for a hydrothermal plant were found through my research. However, because of the similarities in steps between the carbothermal and hydrothermal processes I was able to make a few assumptions and create a simple mass breakdown based on Rosenberg’s description of a carbothermal plant. There are several differences of note: a CO reduction reactor is not needed for the hydrothermal process. Carbotek inc. has patented a fluidized bed reactor for this processing method. In their studies they find that the hydrogen circulation through the feedstock must be fairly large compared to the oxygen production rates [Gibson, 1988]. This means that a fair amount of H2 must be supplied for the system. Hydrogen is conserved so it need not be continually supplied except for a small portion to make up for loses during the processing steps. In this study, as with the carbothermal process, we will not concern ourselves with re-supplying the hydrogen to the system, we will simple assume that it will be supplied and no mass will be added to the system for a hydrogen
replacement process. It is assumed that the hydrothermal regolith reactor will be similar in mass to the carbothermal reactor and to a first order approximation this is true. However, because the carbothermal reaction has a higher reacting temperature the reaction crucible and other materials will be more massive than that for the hydrothermal reaction. This difference in mass is not exactly known, yet it cannot be estimated at more than 10 kg (~20% of the mass of the regolith reactor of Rosenberg’s plant design). Taking the hydrothermal regolith reactor to be 10 kilograms less than the carbothermal one, the estimated mass in kilograms of the hydrothermal reduction plant based from Rosenberg’s carbothermal plant is:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Regolith Reduction reactor</td>
<td>42.4</td>
</tr>
<tr>
<td>Water Electrolysis Unit</td>
<td>91.7</td>
</tr>
<tr>
<td>Oxygen Liquification Unit</td>
<td>393.0</td>
</tr>
<tr>
<td>Oxygen Storage Unit</td>
<td>167.3</td>
</tr>
<tr>
<td><strong>Subtotal:</strong></td>
<td><strong>694.4</strong></td>
</tr>
</tbody>
</table>

Again, this mass does not include the mass of the power systems. We take these power system numbers again from the carbothermal plant designed by Rosenberg. However, there is a source of error here in that the power for the regolith reactor in this process will not include the portion needed for CO reduction. Therefore the mass calculation for the hydrothermal system is a high-end estimate. In the future this will have to be more precisely determined. The hydrogen reduction reaction takes places at a temperature of ~1000 C while the methane reduction reaction takes place at ~1600 C. Assuming a purely linear correlation we can scale the power system for the regolith reduction reactor using a scaling coefficient of 5/8th. The power mass figures for the hydrothermal plant are as follows:
Regolith Reduction Power = $25700\, \text{W} / 125\, \text{W/kg} \times \frac{5}{8} = 128.5\, \text{kg}$
Water Electrolysis Power = $11600\, \text{W} / 125\, \text{W/kg} = 92.8\, \text{kg}$
Oxygen Liquefaction Power = $3700\, \text{W} / 125\, \text{W/kg} = 29.6\, \text{kg}$
Total Power System Mass = $250.9\, \text{kg}$

Therefore the total mass estimate for a hydrothermal plant of the same size as Rosenberg’s carbothermal plant is: \textbf{945.3kg}. This is the basic plant mass breakdown used to scale hydrothermal plants to handle smaller amounts of bulk regolith. As it is, the plant is sized to handle the same amount of regolith as the Rosenberg plant – 25 metric tons, and will be scaled to smaller sizes as needed. The components of this system are taken from the carbothermal plant proposed by Rosenberg and need to be scaled based upon the amount of oxygen being produced.

\section*{2.3 Water/Ice electrolysis}

The notion that ice may exist at the lunar poles caused a flurry of excitement among lunar scientists. Many saw this as a new great source of lunar oxygen that could be easily tapped for future missions. The actual benefits of any polar ice depend highly upon the composition, and what types of missions are expected in the future. If a mission does not intend to go anywhere close to the pole, or you do not want to build a lunar base near the pole, the polar ice deposits may be less useful than reducing the regolith to produce oxygen. If ice exists, the process of getting out oxygen is simple electrolysis:

\[ \text{H}_2\text{O} + Q = \text{H}_2 + 0.5\text{O}_2 \]
This process eliminates the more complicated chemical steps in both hydrothermal and carbothermal regolith reduction. Given that the existence and concentration of lunar ice is not definitely known one thing to consider when comparing oxygen production methods and determining which may be the best for future missions is the possibility of large and small ice concentrations. The concentration will be very important in analyzing the benefits of an ice processing system. There is a lower concentration limit that below which, mining the ice is no longer more beneficial than regolith reduction. This study aims to determine that limit given various mission scenarios.

Through my research I have not been able to find any specific designs for a polar ice electrolysis factory per se. Therefore, the mass breakdown of such a plant is again taken from masses given from the Rosenberg carbothermal system. A water ice electrolysis system will need neither the regolith reduction reactor, nor the CO reduction reactor needed by the carbothermal process given by Rosenberg. However, it will require some sort of reactor to separate the water from the rest of the regolith unless there are large pure water ice crystals present which are not probable. As a first order approximation we will assume that such a separation system will be similar in mass to a benefication system noted the *Lunar base handbook* [Eckart] – 20kg. Therefore the mass breakdown of a water/ice electrolysis plant based from the Rosenberg plant is as follows:

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ice separation system</td>
<td>20.0</td>
</tr>
<tr>
<td>Water Electrolysis Unit</td>
<td>91.7</td>
</tr>
<tr>
<td>Oxygen Liquification Unit</td>
<td>393.0</td>
</tr>
<tr>
<td>Oxygen Storage Unit</td>
<td>167.3</td>
</tr>
<tr>
<td><strong>Total:</strong></td>
<td><strong>672.0kg</strong></td>
</tr>
</tbody>
</table>
The mass for the power system of this plant is that of the Electrolysis unit, plus the oxygen liquefaction unit plus the ice separation unit. I do not have any numbers for the power required by an ice separation unit. Therefore we will leave it out until a decent estimate is found. The power system mass of this system will therefore be a lower limit at:

\[
\begin{align*}
\text{Water Electrolysis Power} &= \frac{11600\text{W}}{125\text{W/kg}} = 92.8\text{kg} \\
\text{Oxygen Liquefaction Power} &= \frac{3700\text{W}}{125\text{W/kg}} = 29.6\text{kg} \\
\text{Subsystem total} &= 122.4\text{kg}
\end{align*}
\]

The total mass of the water/ice system is therefore: \textbf{794.4kg}. This plant is sized to handle 25 metric tons of regolith feedstock, and still needs to be scaled based upon the amount of oxygen being produced.

\textbf{2.4 Oxygen delivery from the Earth}

The last method of providing the needed oxygen on the moon being researched here is delivering it all from the Earth. This method was used by the Apollo program; however, it is now largely considered antiquated, and for future missions will likely be replaced by some sort of in-situ processing. There is no plant breakdown needed for this method because no in-situ mass is required. The costs of such a system will be singly based upon the cost of launching the needed mass to the moon. There will be one system required in addition to the mass of the oxygen itself: the oxygen storage unit. This unit will be necessary for any long duration mission or lunar base stay. Again we will take the mass of this storage unit from the Rosenberg plant. For 5 metric tons delivered from the Earth, the mass will be:
Oxygen Storage Unit (167.3kg) + 5000kg of oxygen

This mass is for a 5 metric ton per year production rate. These numbers are easily scaled depending upon the oxygen need. The only method of heavily reducing the cost of this system would be to reduce either the launch cost or the cost of the transport system. Any change in in-situ production costs or methods will not affect this system. For this reason it is good to use an oxygen delivery system from the Earth as a basis of comparison.

3. Scaling plant masses

In order to properly evaluate various systems of lunar oxygen production, one must be able to look at the various system masses required. The Rosenberg paper provided data concerning a carbothermal oxygen plant to produce 5 metric tons of oxygen per year. Using an oxygen conversion rate of 20 wt% this system took in 25000kg of feedstock during that time. The plant masses in the previous section have been taken directly from the Rosenberg mass breakdown; however, they have not yet been properly scaled. The oxygen liquefaction and storage subsystems of the plant and the associated power system can be estimated to scale linearly with the oxygen yield [Moulford]. For example, 500 kg of oxygen will need a smaller storage tank than 5000kg of oxygen by a factor of ten. Moulford estimates that the other subsystems will largely remain the same. Because only the processing method and not the amount of feedstock put into the process is being changed one can also assume that the other subsystem masses will not change for this scaling. The total mass of the plants will scale following this equation:
[non-storage associated mass] + [total storage mass]/5000 * kgO2 = total scaled mass

The total plant mass is dependant upon how much oxygen you are storing. For these plants, with the feedstock held constant, this makes the plant mass dependant only upon the composition of the feedstock and the weight % oxygen yield expected. Below is a table showing several plant masses scaled for various feedstock compositions relating to various areas on the lunar surface:

<table>
<thead>
<tr>
<th>Process</th>
<th>w% O2 yield</th>
<th>O2kg/yr</th>
<th>Unscaled Plant Mass</th>
<th>scaled plant mass(kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>H- anorthositic highlands [Allen]</td>
<td>1.2</td>
<td>300</td>
<td>945.3</td>
<td>390.79</td>
</tr>
<tr>
<td>H- Mare soil [Allen]</td>
<td>3.6</td>
<td>900</td>
<td>945.3</td>
<td>461.58</td>
</tr>
<tr>
<td>H- pyroclastic glass [Allen]</td>
<td>4.7</td>
<td>1175</td>
<td>945.3</td>
<td>494.03</td>
</tr>
<tr>
<td>H- pure ilmenite</td>
<td>9.56</td>
<td>2390</td>
<td>945.3</td>
<td>637.37</td>
</tr>
<tr>
<td>C- anorthositic Highland*</td>
<td>10</td>
<td>2500</td>
<td>1107.5</td>
<td>812.55</td>
</tr>
<tr>
<td>C- Mare soils [Rosenberg]</td>
<td>20</td>
<td>5000</td>
<td>1107.5</td>
<td>1107.50</td>
</tr>
<tr>
<td>E- SP high [Feldman]</td>
<td>2.05</td>
<td>512.5</td>
<td>794.4</td>
<td>264.96</td>
</tr>
<tr>
<td>E- SP avg [Feldman]</td>
<td>1.34</td>
<td>335</td>
<td>794.4</td>
<td>244.02</td>
</tr>
<tr>
<td>E- SP low [Feldman]</td>
<td>0.62</td>
<td>155</td>
<td>794.4</td>
<td>222.79</td>
</tr>
<tr>
<td>E- NP [Feldman]</td>
<td>8.9</td>
<td>2225</td>
<td>794.4</td>
<td>467.01</td>
</tr>
</tbody>
</table>

*no real data for this number

Table 1: Process plant masses

The last column represents the masses of plants scaled from the Rosenberg plant taking in 25000kg of feedstock. The second column displays the amount of oxygen produced. The third column of this table is noted as the unscaled plant mass. This means that it is the mass of the plant before the oxygen liquefaction and storage units have been scaled down to the size applicable for the given amount of oxygen produced. Having the scaled plant masses is important because they are more accurate masses for the production systems.
4. Initial Analysis of Production Methods

There are several different analyses that can be conducted in order to compare various oxygen production methods. This study conducts some simple numerical analyses of the given data to help rate production methods. An initial analysis of the scaled plant masses and oxygen yields above provides one method of comparing production systems – the ratio of O2 mass produced to the mass of the production system. Table 2 shows this ratio.

<table>
<thead>
<tr>
<th>Process</th>
<th>w% O2 yield</th>
<th>O2kg/yr</th>
<th>scaled plant mass(kg)</th>
<th>kgO2/kgSys</th>
</tr>
</thead>
<tbody>
<tr>
<td>H- anorthositic highlands [Allen]</td>
<td>1.2</td>
<td>300</td>
<td>390.79</td>
<td>0.77</td>
</tr>
<tr>
<td>H- Mare soil [Allen]</td>
<td>3.6</td>
<td>900</td>
<td>461.58</td>
<td>1.95</td>
</tr>
<tr>
<td>H- pyroclastic glass [Allen]</td>
<td>4.7</td>
<td>1175</td>
<td>494.03</td>
<td>2.38</td>
</tr>
<tr>
<td>H- pure ilmenite</td>
<td>9.56</td>
<td>2390</td>
<td>637.37</td>
<td>3.75</td>
</tr>
<tr>
<td>C- anorthositic Highland*</td>
<td>10</td>
<td>2500</td>
<td>812.55</td>
<td>3.08</td>
</tr>
<tr>
<td>C- Mare soils [Rosenberg]</td>
<td>20</td>
<td>5000</td>
<td>1107.50</td>
<td>4.51</td>
</tr>
<tr>
<td>E- SP high [Feldman]</td>
<td>2.05</td>
<td>512.5</td>
<td>264.96</td>
<td>1.93</td>
</tr>
<tr>
<td>E- SP avg [Feldman]</td>
<td>1.34</td>
<td>335</td>
<td>244.02</td>
<td>1.37</td>
</tr>
<tr>
<td>E- SP low [Feldman]</td>
<td>0.62</td>
<td>155</td>
<td>222.79</td>
<td>0.70</td>
</tr>
<tr>
<td>E- NP [Feldman]</td>
<td>8.9</td>
<td>2225</td>
<td>467.01</td>
<td>4.76</td>
</tr>
</tbody>
</table>

*no real data for this number

Table 2: Oxygen mass versus system mass

In this table H stands for the hydrothermal process, C for carbothermal, and E for water ice electrolysis. There are several items to note with this initial analysis. First, the hydrothermal process oxygen yield for anorthositic highlands, mare soil, and pyroclastic glass are taken directly from measurements made by Carleton Allen. The hydrothermal pure ilmenite oxygen yield is calculated using the equation in section 2.2. The electrolysis oxygen yields are taken from Feldman’s paper. The carbothermal mare soil row is taken directly from the Rosenberg paper using a high-end stoichiometric limit of
20% yield proposed in that paper. The carbothermal anorthositic row is not taken from actual data. The only thing currently known about a carbothermal anorthositic feedstock yield is that it will be significantly lower than that for carbothermal mare soils.

4.1 Carbothermal comparisons

Without having precise measurements on the amount of oxygen yield the carbothermal reduction process produces with non-mare feedstocks there is a limited amount of analysis that can be conducted. We can determine the amount of oxygen yield required to be better than an ice electrolysis production method. If we take as a variable the percent oxygen released from the feedstock of the carbothermal system, we can test what percent is needed to match the KgO2/KgSys ratio given by the high, average, and low ice yield estimates. The ice yield ratios are: 1.93, 1.37, and 0.70 respectively. Table 3 shows this data.

<table>
<thead>
<tr>
<th>Electrolysis O2/sys ratio</th>
<th>Carbothermal kgO2 needed</th>
<th>%yield O2 needed</th>
</tr>
</thead>
<tbody>
<tr>
<td>SP -- 1.93</td>
<td>1293.5</td>
<td>5.17</td>
</tr>
<tr>
<td>SP -- 1.37</td>
<td>845.8</td>
<td>3.38</td>
</tr>
<tr>
<td>SP -- 0.7</td>
<td>394.9</td>
<td>1.58</td>
</tr>
<tr>
<td>NP -- 4.76</td>
<td>5619.7</td>
<td>22.48</td>
</tr>
</tbody>
</table>

Table 3: Carbothermal comparison

Without knowing any specific data as to how the carbothermal system reacts to non-mare feedstock we cannot know exactly what percentage yields to expect, and there is no real way to estimate the expected yield. However, we can immediately see that a carbothermal reduction system based on the masses provided by Rosenberg cannot be more beneficial than an ice electrolysis system in the north-pole region of the moon. The maximum oxygen yield Rosenberg claims is 20 wt%, while what is needed to beat the
water ice electrolysis system is at least 22wt%. For the south-pole the yield percentages required for the carbothermal system to be more beneficial are much more reasonable to expect.

As an initial south-pole analysis one can consider the hydrothermal system to be a low end estimate for the carbothermal system. Both processes reduce similar oxides, although the carbothermal reduces more oxides and some silicates. The maximum FeO content Allen used for his anorthositic highland samples was ~8.5%. At this FeO concentration the hydrothermal system can produce ~2.17 wt% oxygen – well above the yield required for the low ice electrolysis system. Using this as a low end estimate we can safely say that the carbothermal system will at least be able to produce a kgO2/kgSys ratio better than that of the low end water ice electrolysis estimate. However, there is no way to make any further quantitative analyses on the carbothermal system without more data on how it reacts with highland soil samples.

5. Comparison of Hydrothermal and Ice Electrolysis Methods

Further analysis can continue on the hydrothermal and water ice electrolysis systems with a significant amount of accuracy assuming that we accept the figures of water concentration put forth by Feldman. If we take the minimum and maximum water ice concentrations provided by Feldman we can find the weight % oxygen yield required for a hydrothermal system to provide the same kgO2/kgsys mass ratio. This can then be converted into percentage of FeO required in the feedstock for the hydrothermal system.
by using the equation provided by Allen noted in section 2.2 of this paper. These data are shown in the table below.

**Table 4: Electrolysis versus Hydrothermal weight percent**

<table>
<thead>
<tr>
<th>Process</th>
<th>wt% O2 yield</th>
<th>KgO2/KgSys</th>
<th>Hydrothermal wt% O2 required</th>
<th>Correlating FeO wt %</th>
</tr>
</thead>
<tbody>
<tr>
<td>Electrolysis – SP</td>
<td>2.05</td>
<td>1.93</td>
<td>3.56</td>
<td>15.8</td>
</tr>
<tr>
<td>Electrolysis – SP</td>
<td>1.34</td>
<td>1.37</td>
<td>2.35</td>
<td>9.32</td>
</tr>
<tr>
<td>Electrolysis – SP</td>
<td>0.62</td>
<td>0.7</td>
<td>1.1</td>
<td>2.89</td>
</tr>
<tr>
<td>Electrolysis – NP</td>
<td>8.9</td>
<td>4.76</td>
<td>15.4</td>
<td>78.2</td>
</tr>
</tbody>
</table>

This table displays two important facts: first the hydrothermal weight percent oxygen yield required to meet the mass ratio given by the various electrolysis systems, and secondly the correlating percentage of FeO required to be in the feedstock of the material input to the hydrothermal system.

At the Lunar poles there are no mare basaltic areas available for use in any processing procedures. Therefore to properly compare the realistic production of oxygen between the electrolysis and hydrothermal systems we can only consider feedstocks that would be available around the permanently shadowed polar craters – highland soils and rocks.

Analysis of Apollo lunar samples has provided a compositional breakdown of lunar surface rocks and soils, however very few are from highland regions. The few highland samples we have are from Apollo 17. Excluding any possible iron ores or ejecta material from mare craters, the maximum weight % of FeO found in highland regions is approximately 10 wt% (from Apollo 17 soil samples) [Heiken]. Carleton Allen used highland samples with FeO abundances ranging from 3.6 to 8.5 weight percent [Allen].
On average, highland regions are very low in FeO abundance. For this study we will take a maximum FeO content for highland regions to be 8.5wt%.

From Table 4 it is obvious that a hydrothermal system will never be more feasible than a water/ice electrolysis system in north-polar regions of the moon. However, at the south-pole, hydrothermal production may be more profitable than ice electrolysis depending on the actual concentration of ice in the region. The Feldman ice concentration estimate of 0.7-2.3 wt% requires an FeO concentration in the feedstock to be 2.89-15.8 wt%. It is known that there are at least some soils and rocks in the highland regions with up to approximately 10 wt% FeO and Allen’s samples fell well above the minimum concentration required by the ice estimates. From these numbers one can deduce that if the actual ice content in the southern polar regions is within the lower half of the bound set by Feldman’s analysis – 0.7-1.5 wt% -- a hydrothermal production system would be more beneficial than the water/ice electrolysis system; however, an ice concentration in the upper half would make ice electrolysis more beneficial.

5.1 A hydrothermal benefication procedure

The hydrothermal system we have considered so far has not included any sort of regolith benefication system. If it is possible to beneficate the feedstock to greater than 15.8% FeO one can safely assume that the hydrothermal system would be more beneficial in the lunar south-pole region no matter what the water content so long as it is no greater than Feldman’s maximum bound. Taking Allen’s soil samples as minimum and maximum FeO contents for polar feedstocks we can calculate how much feedstock a benefication
system would have to process in order to produce the needed 25000kg/yr of feedstock for the processing plant at 15.8% FeO. This is done by the simple equation:

\[ X \times \text{FeO\%} = 25000\text{kg} \times \text{desired FeO\%} \]

Where \( X \) is the total kilograms of feedstock put into the benefication system. Therefore taking a low end estimate FeO concentration of 3.6% and a high end estimate of 8.5% a benefication system that could handle above 46500 kg feedstock low end, or 110000 kg of feedstock high end, would ensure that the hydrothermal system is more beneficial than the water/ice electrolysis system for the south-pole.

6. Fitting to a Lunar Base and Launch System.

The previous analysis of production methods has kept the major plan system the same size as the plant proposed in Rosenberg’s analysis of a carbothermal reduction plant. In this section we will look at the mass required to produce enough oxygen to supply a 6 person lunar base – which is the commonly proposed size for an initial inhabited base on the lunar surface. Also the mass of these proposed oxygen production plants are compared to modern launch capabilities. The Apollo missions were approximately three decades ago and we were able to launch on the order of 10 metric tons to the moon at the time. Today’s launch systems are not specifically geared toward launching material to the moon, but the ability is still there.
6.1 Lunar base fitting

Previously it has been shown that a six person base will require an oxygen supply of \(~525\text{kg}\) per year. To scale the plant masses to this sized oxygen production we assume that the entire plant mass scales linearly. In reality this will not be exactly true; however, we have no defined models for scaling plant masses. There will inevitably be a lower limit to the scaling as you reach the physical limit of how small you can make each component of the system (i.e. pipes and crucibles can only be made so small). A linear scale seems reasonable so long as you do not reach the lower physical limit of the scale.

Table 5 lists the plant masses scaled to 525kg oxygen production for the various processes we have been analyzing.

<table>
<thead>
<tr>
<th>Process</th>
<th>wt% O2 yield</th>
<th>scaled plant mass(kg)</th>
<th>Plant mass for 525kg/O2</th>
</tr>
</thead>
<tbody>
<tr>
<td>H- anorthositic highlands [Allen]</td>
<td>1.2</td>
<td>390.79</td>
<td>684</td>
</tr>
<tr>
<td>H- Mare soil [Allen]</td>
<td>3.6</td>
<td>461.58</td>
<td>269</td>
</tr>
<tr>
<td>H- pyroclastic glass [Allen]</td>
<td>4.7</td>
<td>494.03</td>
<td>221</td>
</tr>
<tr>
<td>H- pure ilmenite</td>
<td>9.56</td>
<td>356.53</td>
<td>140</td>
</tr>
<tr>
<td>C- anorthositic Highland*</td>
<td>10</td>
<td>637.37</td>
<td>171</td>
</tr>
<tr>
<td>C- Mare soils [Rosenberg]</td>
<td>20</td>
<td>1107.50</td>
<td>116</td>
</tr>
<tr>
<td>E- SP high [Feldman]</td>
<td>2.05</td>
<td>264.96</td>
<td>271</td>
</tr>
<tr>
<td>E- SP avg [Feldman]</td>
<td>1.34</td>
<td>244.02</td>
<td>382</td>
</tr>
<tr>
<td>E- SP low [Feldman]</td>
<td>0.62</td>
<td>222.79</td>
<td>755</td>
</tr>
<tr>
<td>E- NP [Feldman]</td>
<td>8.9</td>
<td>467.01</td>
<td>110</td>
</tr>
</tbody>
</table>

*no real data for this number

Table 5: scaling to fit estimated lunar base oxygen needs

6.2 Launch vehicle fitting

One can compare these masses to that of the Apollo Lunar Module – approximately 15000 kg. The masses needed for all of these systems are two orders of magnitude smaller than that of the Apollo module. This shows that the masses are far from unrealistic in terms of what can be delivered to the moon. However, we no longer have
the rockets designed to send missions to the moon on the scale of the Apollo missions. Therefore we must consider the launch capacity of modern rockets, and compare the production system masses to our current launch capabilities. Modern rockets are not designed to launch anything to the lunar surface or any lunar transit orbit without an additional transit stage. Richard Reifsnyder created a simple transit stage using a two-stage hydrazine/nitrogen peroxide fuel. He assumed the structural mass to be 15% of the fuel mass. Using a total delta V of ~6.3 km/sec he was able to estimate the total mass of a transit stage and therefore calculate how much mass could be delivered to the lunar surface using the launch

<table>
<thead>
<tr>
<th>Launch Vehicle</th>
<th>Cost (USD)</th>
<th>Payload (kg)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Atlas IIAS, escape</td>
<td>$158-162</td>
<td>665</td>
</tr>
<tr>
<td>Delta II-7925, escape</td>
<td>$72.25-74.25</td>
<td>315</td>
</tr>
<tr>
<td>Pegasus XL, escape</td>
<td>$17-18</td>
<td>28</td>
</tr>
<tr>
<td>Taurus (std), escape</td>
<td>$14.5-14.8</td>
<td>81</td>
</tr>
<tr>
<td>Titan III/TOS, GTO</td>
<td>$266-282</td>
<td>2020</td>
</tr>
<tr>
<td>Ariane 40, GTO</td>
<td>$95.67-98.67</td>
<td>380</td>
</tr>
<tr>
<td>Ariane 42P, GTO</td>
<td>$100.3-104.7</td>
<td>537</td>
</tr>
<tr>
<td>Ariane 44P, GTO</td>
<td>$105.3-110.3</td>
<td>620</td>
</tr>
<tr>
<td>Ariane 44LP, GTO</td>
<td>$143-148</td>
<td>765</td>
</tr>
<tr>
<td>Ariane 44L, escape</td>
<td>$169-175</td>
<td>725</td>
</tr>
<tr>
<td>Ariane 5, GTO</td>
<td>$161-171</td>
<td>1250</td>
</tr>
<tr>
<td>Proton D1e, escape</td>
<td>$99.0-108.7</td>
<td>1467</td>
</tr>
<tr>
<td>Zenit 3, escape</td>
<td>$102.7-107.3</td>
<td>717</td>
</tr>
</tbody>
</table>

Table 6: Fitting to launch vehicles

capacity of various modern rockets. The masses deliverable to the lunar surface are shown below. The Launch vehicle costs are taken from www.fas.org/spp/guide/launehmer.htm. This table shows that modern launch capabilities are well within that needed to launch any of the oxygen production systems analyzed in this study [Reifsnyder].
7. **Errors and future analysis.**

There are several key areas within this study that could use a significant amount of future research and that introduce a varying amount of error into the current calculations. Most of the error is insignificant; however there are some areas that amount to a significant amount of error that must be explained. To further improve upon this study these significant errors must be researched and reduced through further data analysis.

7.1 *Production plant design masses*

This study has based a large portion of its results from the plant mass breakdown provided from Rosenberg’s papers. These masses were then extrapolated to fit a water ice electrolysis and hydrothermal process. Although this should not introduce much error because the processes have similar components, it would be better if we actually had plant mass breakdowns for each individual process. This is something that can be researched in the future.

7.2 *Scaling errors*

When scaling plant masses to fit to the needed oxygen production size of a lunar base (525kg/year) we used a simple linear scale for this study. However, as noted these masses will not scale exactly linearly. There will be a minimum physical cutoff at some low end mass for the system. For simple analyses like those conducted in this study a linear scale estimate is suitable; however, if one desires to conduct more rigorous analysis on production methods or plant designs a better scaling method must be determined or
specific plant mass analysis data will have to be used. This scaling error does not lead to any major uncertainties in this study because the only thing it affects is the mass needed to be delivered to the moon. For these masses are all on the order of magnitude of the current launch capabilities of space programs and a couple orders of magnitude less than the Apollo system. The scaling errors are not expected to change the masses by an order of magnitude and therefore do not affect this analysis.

7.3 Carbothermal highland analysis

The analysis of the carbothermal process is severely lacking due to the fact that we have no data on how the process reacts with non-mare soils. This data is key to producing indepth analyses and comparisons with the carbothermal process. Without this data it is impossible to quantitatively see if the carbothermal method is better than either of the other in-situ methods being analyzed. Due to this limited data we are kept to only making any conclusions concerning the carbothermal process with the Mare soils as a feedstock for the system.

7.4 Statistical analysis

This study has not attempted to make any statistical analysis of the conclusions about which process is best for which area. A statistical analysis is important to making definitive conclusions about the best production process. However, more quantitative data on the exact nature of the carbothermal system is needed before conducting statistical analyses.
7.5 Processing time analysis

When comparing the carbothermal, hydrothermal and electrolysis production systems the time that it takes to do the processing was not analyzed. This begins by assuming each processing plant can handle 25000kg of feedstock per year. The amount of feedstock was taken directly from the Rosenberg design of the carbothermal plant. It is logical to say that a hydrothermal and electrolysis plant sized from the carbothermal plant could handle the same amount of feedstock per processing cycle as the carbothermal plant. However, we have not determined how long a processing cycle is for each system. For each method the processing cycle will be different. A processing cycle is defined as the amount of time it takes for one batch of feedstock to be treated and oxygen recovered. The carbothermal system will have the longest processing cycle because it has the most complicated reactions. The next longest is the hydrothermal system, and the shortest being the electrolysis system. Therefore plants similarly sized from the Rosenberg design for each process will in reality not each be sized to process 25000kg per year. The hydrothermal system will be able to process some amount larger than that per year, and the electrolysis system will be able to process even more than the hydrothermal. This introduces a significant amount of error into the current benefit analysis calculations; however, the extent of the error and whether or not it changes the most beneficial method for the varying lunar regions remains to be determined.

This is the most pressing area for further research. The difference in processing cycles for each method introduces the majority of the error into these calculations, and cannot be removed or precisely determined until the exact processing cycle times are calculated. With the cycle times one can then proceed to more accurately determine the
amount of feedstock processed – and therefore the amount of oxygen extracted -- by each
system per year.

7.6 Human factors and system maintenance

One last source of error in studying a complete oxygen production system is that this
study has neglected the input of any human maintenance needs. It has not analyzed what
type of maintenance will definitely be needed for such a system. However, previous
studies have determined that an oxygen production facility would only be useful if it was
for a permanent or semi-permanent human presence on the moon [Miller]. Therefore we
assume that there will be humans available to perform maintenance tasks as needed.

What is not known about the oxygen production systems is how much maintenance they
would require, and if this mount of man-power and time is feasible for an already heavily
worked lunar base crew. More research will need to be done in this region to precisely
determine if the amount of work required to keep an oxygen facility operational on the
moon is reasonable enough to make such a system more beneficial than oxygen delivery
from the Earth.

8. Conclusions

This study has produced several important conclusions concerning the production of
lunar oxygen and the feasibility of in-situ oxygen production plants. When comparing the
three methods in question we can split the results most easily into three lunar regions: the
north-pole, mid-latitudes, and the south-pole.
Water ice concentrations at the north-pole of the moon are capable of providing far more oxygen than either carbothermal or hydrothermal production could reasonably produce in the region. Feldman estimated a minimum of \(\approx 10\text{wt}\%\) ice in the lunar north-pole which creates a \(\text{kgO}_2/\text{kgSys}\) ratio of 4.76. This ratio is far above all others and only nearly reached by the carbothermal mare soil ratio of 4.51. However, in the north-polar regions there are no mare soils for feedstock. Therefore, the actual carbothermal ratio for this region will most definitely be significantly lower than this. With this data it is safe to say that in the north-pole region of the moon, water ice electrolysis will be the best method of oxygen production.

The middle latitudes of the lunar surface contain both mare and lunar highland crusts. However, they do not contain any water ice. For this reason one can only consider using either carbothermal or hydrothermal reduction. From the data that we have used in this study the carbothermal system will be considerably better suited for oxygen production in both mare and highland soils unless a significant benefication system is introduced to the hydrothermal processing plant. Unfortunately we do not have precise data on the masses required for such a benefication system, or proper data for the carbothermal O2 yield from the highland soils. Therefore we cannot say anything more concerning the mid-latitudes other than this: a carbothermal reduction system will be better suited for oxygen production than a completely unbeneficated hydrothermal system.

The south polar region of the moon is slightly more complicated when considering which process is best for oxygen production. The amount of water ice estimated does not allow
for an immediate assertion that water ice electrolysis will be more beneficial than the other processes as the north-pole did. Because of the range of ice concentration estimates we cannot be certain that one method will be better than another. However, it is shown that if the ice concentration is in the upper half of the bound defined by Feldman then ice electrolysis has the highest kgO2/kgSys ratio and is therefore the most beneficial – excluding the introduction of a benefication system to the hydrothermal plant. If a benefication system were introduced it would have to be able to process 110000kg/yr of feedstock to ensure that the hydrothermal system was more beneficial than ice electrolysis. If the concentration of ice in the south-pole region falls in the lower half of the Feldman bounds then the hydrothermal system will have a higher KgO2/KgSys ratio unbeneficated and it is safely said that the water ice concentration cannot provide enough oxygen to be better than a hydrothermal oxygen production system.

The last conclusion to be made by this study shows the feasibility of any one of these systems sized to produce oxygen for a lunar base. Each processing system was scaled to produce the 525 kg of oxygen per year that is needed by a lunar base. The masses of these plants falls well within the deliverable mass to the moon with current launch technology as calculated in this study. It is also two orders of magnitude smaller than that of the Apollo module. Therefore it can safely be said that the launch of any oxygen production system for the support of an initial lunar base is well within our current capabilities and is a reasonable endeavor to undertake.
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MISSING PAGE(S)

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