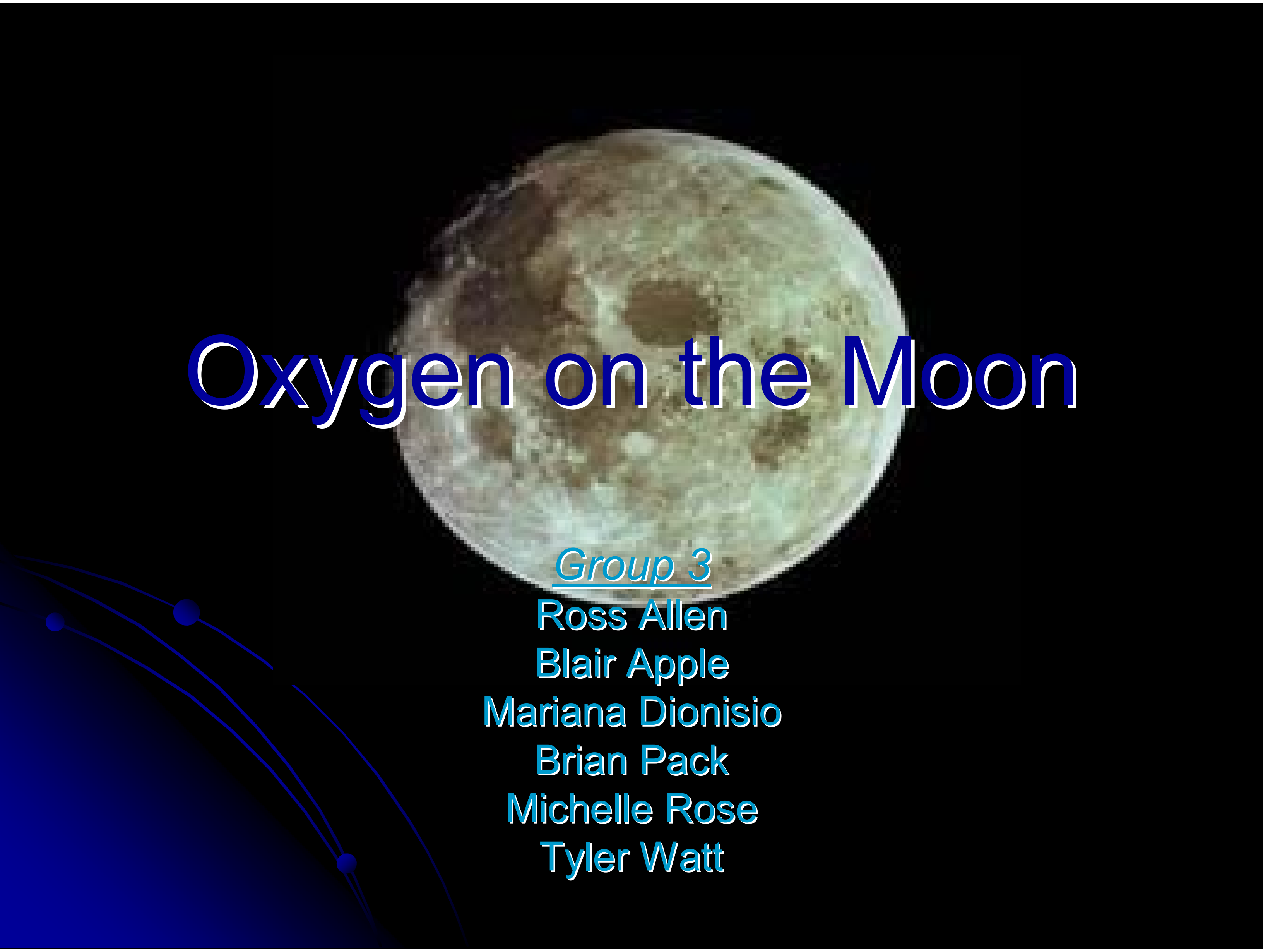

Oxygen on the Moon

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Introduction

Humans venturing into space have generally relied solely on equipment and supplies that were transported directly from earth. While this strategy has proven to be suitable for brief exploration trips to the moon or operations in earth orbit, new technology will be necessary for the recently proposed, long-term lunar exploration missions. Transporting material from the earth to the moon costs approximately $25,000 per pound. The ability to effectively utilize local lunar resources will be critical to long-term human occupancy of the moon, as well as other planetary explorations. This project is focused on the extraction of oxygen to directly support early human habitation on the moon.

Background

A strong renewal of interest in space exploration has begun since President George W. Bush announced on January 15, 2004 that the United States would begin to develop a new space exploration vision. President Bush announced that the US would begin the development of the technologies required to return to the moon by 2015 and maintain a permanent lunar outpost. The new lunar landing missions will be used as a spring board into a series of manned Mars missions.

This new vision of space exploration is currently being studied and developed by The President's Commission on Moon, Mars, and Beyond. The goal of the commission is to develop an exploration plan that will be not only technically feasible but also economically attainable. Both of these goals are considered throughout this report as the lunar oxygen production process is designed.

There are numerous technological goals that must be accomplished before any large missions can be launched to the moon, for example a new generation of heavy launch vehicles must be designed and constructed. The Saturn V rocket which launched the Apollo missions can no longer be built. The redesign and construction of these new launch vehicles is expected to cost on the order of $50 billion. Until this new generation of heavy launch vehicles is built it is not expected to be able to launch any manned lunar missions; thus, no permanent lunar colony could be built until the design and construction is completed. The available cargo lift capability of the new launch vehicle is a major constraint on the construction of the proposed lunar outpost. The maximum cargo mass constrains the maximum size of many components of the outpost. Since the new generation of launch vehicles has not be designed some assumptions must be made to aid in the design of this oxygen production unit, namely that the new launch vehicle will at minimum match the Saturn V in launch capability both in maximum launch mass and frequency of launches.

Reaction Options

In order to properly address the problem of creating oxygen from resources on the moon, it is necessary to understand the materials and reactions behind the production process. Over twenty different processes have been proposed for the production of oxygen on the Moon, most of these processes involve the removal of bound oxygen from various metals in the lunar regolith. The most developed processes include the reduction of the lunar regolith using hydrogen gas at high temperatures. A few of the process that have been considered will be outlined briefly below.

Lunar Soil

The reduction of lunar soil with hydrogen is the most well documented series of reactions that has been proposed for the production of oxygen on the moon. This process was studied in the early nineties, using lunar soil returned by the Apollo missions, by Gibson and Knudsen. From these studies it was determined that the main constituent of the lunar soil that is reduced is ilmenite ($FeTiO_3$). During the reduction of the ilmenite the FeO was shown to be completely reduced yielding solid iron and TiO_2. This complete reduction of the iron is one benefit of using this process because the solid by-products could be used in the future as building materials after additional processing.

Reduction of Volcanic Glass with Hydrogen

Another reduction reaction that has been proposed is the selective reduction of volcanic glass with hydrogen. While this process has not been studied to the same extent as the reduction of lunar soil, it is believed that this selective reduction process will provide higher oxygen yields. While this expected higher oxygen yield is attractive for this process it must be noted that high oxygen yield is not the only parameter that should be considered when comparing different processes. Another process consideration is the availability of feedstock. While volcanic glass is found in relatively high concentrations in some areas of the lunar surface it is not as widely available as the lunar soil. This constraint on the availability of feedstock was the reason that this process was not selected for further study because it is not certain if the volcanic glass will be available in the area selected for the lunar outpost.

Water Splitting

Recent spectrographic scans provided by the Clementine satellite missions have provided some evidence of frozen water ice near the lunar poles. If these preliminary findings can be confirmed it would be expected that the simple electrolysis of the frozen water would be the most efficient method for producing oxygen on the moon; however, until more concrete evidence is provided confirming the existence of lunar ice and some idea of the quantity of ice available this process remains highly uncertain. This process was not chosen for further study because of the uncertainty in the availability of the feedstock for the process.

Pyrolysis

The process of pyrolysis is the thermal the decomposition of species at very high temperatures. There are many benefits associated with using pyrolysis as the process to produce lunar oxygen, the biggest expected benefit of this process is that it is not strongly dependent on the feedstock to the process. Also pyrolysis, depending on feedstock, could theoretically give very high yields of oxygen. But there are two significant drawbacks to using pyrolysis as the primary method of producing lunar oxygen. First pyrolysis has very large energy requirements because of the temperatures that must be achieved and maintained in the pyrolysis reactor, these high energy requirements are a significant difficulty for lunar processing because of the expected dependence on solar power as the primary energy source on the moon. The second reason that pyrolysis was not selected for further study was the relatively large number of technological developments that would be required to make this process feasible, this high level of technological development required makes it highly unlikely that this process could be implemented in the timeframe of this project.

Reaction Information

The reaction that was chosen to study in detail was the hydrogen reduction of lunar soil. This method of oxygen production offers many benefits over the other reactions considered. First this reaction has very limited constraints on feedstock because this process utilizes the easily obtainable lunar soil which is available in abundance in most locations on the moon. The only real constraint on the feedstock of this reaction is that there must be adequate iron content in the soil; studies have definitively shown that there is high iron concentration in the soil across the lunar South Pole region. Second the technology required to implement this process is relatively well understood, this means that this process can be ready for operation within the proposed project timeline. Finally this reaction does not require extreme reaction conditions and is relatively energy un-intensive. After evaluating this process based on the above benefits it was chosen for further study and process design.

The reduction of lunar soil (ilmenite) proceeds following this reaction path:

$$FeTiO_3(s) + H_2(g) \longrightarrow Fe(s) + TiO_2(s) + H_20(g)$$

$$H_20(g) \longrightarrow H_2(g) + \tfrac{1}{2} O_2(g)$$

This reaction sequence shows the initial reduction of the solid ilmenite to form solid iron and titanium dioxide waste and product gaseous water. The second reaction shown above is the electrolysis of the product water to form hydrogen gas, which is recycled to the process, and oxygen which is sent to the habitat for consumption.

Reaction Kinetics

This reaction was studied by Gibson and Knudsen in the early nineties and their results were published in 1994. From their experimental work it was found that this reaction must be carried out at temperatures above ~700°C but below 1000°C to avoid sintering of the ilmenite. Their experiments determined that the reduction of the ilmenite was complete in approximately 20 minutes at 900°C. Their experimental work also resulted in the development of a kinetic model of the reaction. This reaction model is shown here:

$$\frac{d\eta_c}{dt^*} + \left[1 - 6\sigma_s^2(\eta_c^2 - \eta_c)\frac{d\eta_c}{dt^*}\right]^n = 0$$

The model that was proposed includes terms that account for both diffusion and reaction resistances to reaction. This model provides information regarding the required time to complete the reaction and dependence on hydrogen concentration. *(A detailed explanation of this model is provided in the full technical document prepared for this process.)* This model was used during the process design to determine optimum operating conditions.

Reaction Optimization

The reaction model described in the above section was used to determine the optimum reactor operating conditions. The reactor conditions that were investigated using this model were the operating pressure and the volume of the reactor. The pressure dependence of the reaction is based upon the increase in hydrogen concentration resulting in an increase in reactor pressure. The reactor volume affects the reaction time based on the change in hydrogen concentration, the larger the reactor volume the smaller the decrease in hydrogen concentration during the reaction time. Four pressures were studied at varying reactor volumes. There was a significant decrease in reaction time as pressure was increased to 20 atm beyond which increasing the pressure had a minimal effect of reaction time. Similarly increases in reactor volume up to ~1250 liters greatly reduced reaction times, after which further increases in reactor volume caused very small decreases in reaction times. From these results the optimal reactor conditions where found to be 20 atm in a reactor with a total volume of 1250 liters. These results can be observed in the following graph.

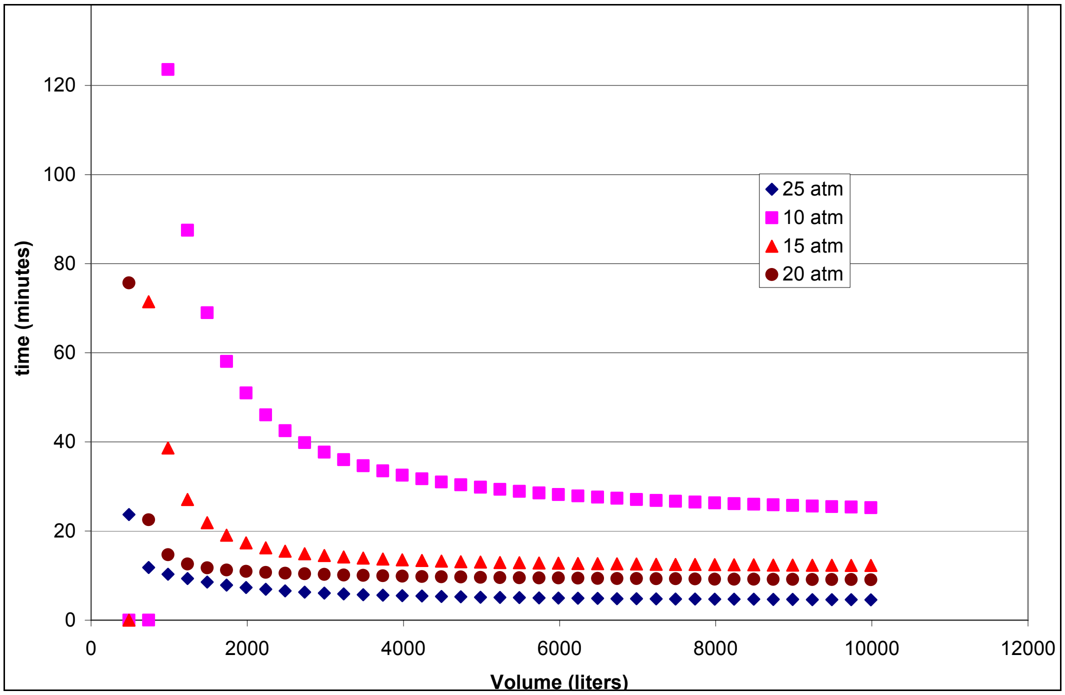


Figure 1: Reaction time at varying reactor operating pressures and volumes

Process Design

After selecting the reaction to be used and studying the kinetics of this reaction the process design operation could begin. The process design included determining the best design to produce the oxygen in a simple effective manner. There were a number of options investigated during each phase of the design process, a complete report of all options considered can be found in the full technical document prepared for this part of the project, and a few of the major options will be discussed in the following sections along with the final equipment design.

General Process Considerations

Before the final process design could be completed the oxygen production demands had to be determined. The process is to provide enough oxygen to support respiration for ten people. The amount of oxygen required for this was found by looking at average amounts of oxygen consumer by a human over the course of a year. An average human consumes ~305 kg of oxygen per year. For ten people this works out to 39 moles of oxygen per hour. The process was designed to produce this amount of oxygen in half of a lunar month because of possible limitations on the amount of solar power available to run the process. Half a month was chosen as a conservative estimate because most locations receive more than fourteen days of sunlight per month, by making this conservative estimate the design allows more freedom in picking the location of the lunar outpost.

Another consideration when designing this process was to minimize the amount of supply missions that would be required to maintain the functionality of the process. To accomplish this goal the process was designed to minimize the amount of hydrogen which would be lost during operation. To prevent hydrogen from escaping the process must never be open to the lunar atmosphere. Preventing the process from being open to the atmosphere must include air locking all entrances and exits to the process. This requirement of air locking would make running the process continuously very difficult; therefore, a batch process was designed to minimize the complexity of the process.

Design Process Flow Diagram

Shown below is a simplified PFD of the design chosen to produce the lunar oxygen. The following sections will provide a more detailed explanation of each step in the process as well as details of the equipment design.

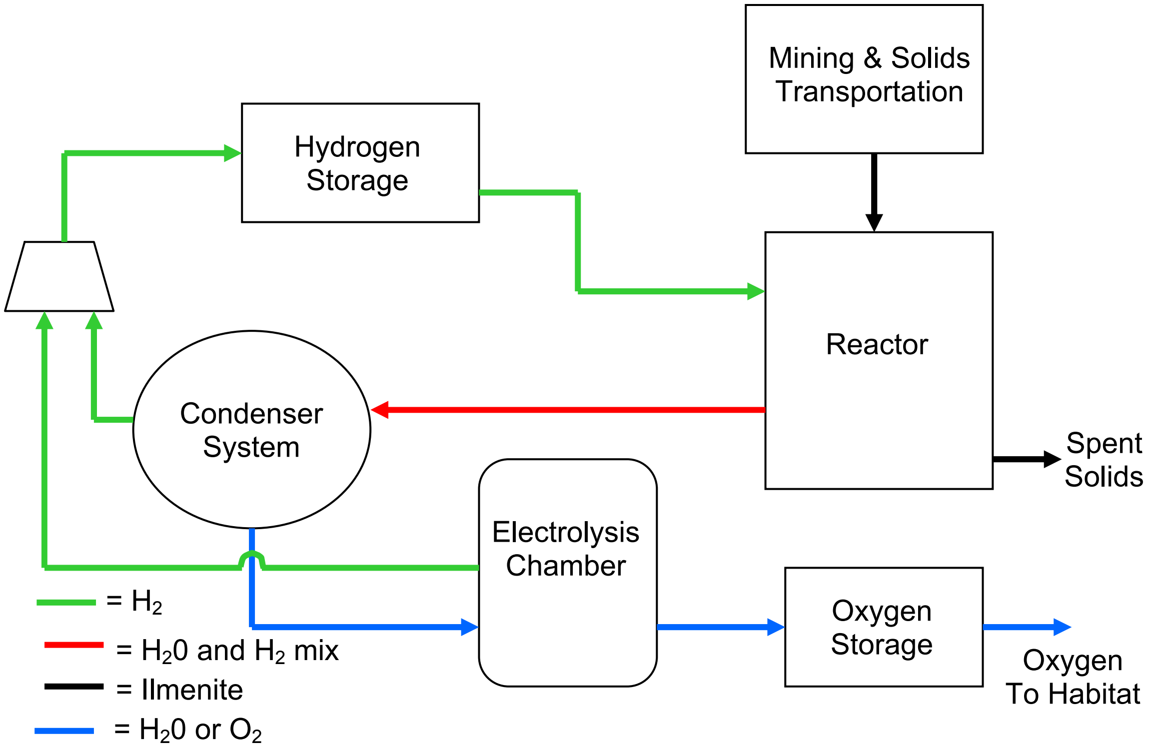


Figure 2: Overall process flow diagram

The PFD above shows the general steps of the process as well as the flow of the streams through the process, the streams are color coded to indicate what components are present in each stream.

Raw Materials

The raw materials, as indicated by the reaction shown previously, are hydrogen gas and lunar soil. The initial charge of hydrogen will be provided to the process by transporting liquid water to the lunar surface from earth. The liquid water will then be split using electrolysis to free hydrogen which will be stored and used to run the reaction and the oxygen used to provide some of the initial oxygen supply. The solid ilmenite will be provided to the process by an automated mining rover. The mining capacity of the rover was determined based on the amount of lunar soil needed to meet oxygen production demands. As stated earlier, 39 moles of oxygen must be produced per hour. Using the oxygen yields as reported by Gibson and Knudsen, 2 wt % of lunar soil, producing this amount of oxygen will require 35 kg of lunar soil per hour. To maintain operation the mining rover must be able to deliver 840 kg of lunar soil per day.

The mining rover will return to lunar soil to a hopper from which it will be fed to the reactor by a series of conveyors. The conveyors move the solid using an internal screw which turns to move the solids contained in the screw down the pipe. The contained screw type conveyor was chosen for two reasons. One reason was because it allows the process to be air locked in the conveyor. The other reason that this style of conveyor was chosen was because it helps address another problem with using lunar soil – containing the lunar dust. Lunar dust is known to be extremely erosive to other solid materials; because of this the levitation of the lunar dust must be minimized where possible and contained if it is not possible to not disturb the dust.

General Reactor Design

As discussed earlier in this report the kinetic reaction model was used to determine the optimum operating conditions for the reactor. While the reactor conditions were set through optimization techniques this does not take into account the physical design of the reactor. This section provides more information about the actual dimensions of the reactor as well as some of the different aspects of reactor design looked at while designing the reactor.

The first major decision that had to be made was deciding between a fixed bed or fluidized bed reactor. Each of the two designs had advantages and disadvantages associated with them but in the end a fixed bed reactor was selected. The main advantage of using a fluidized reactor is the high level of mixing of the reactants this style of reactor provides. The fluidized bed reactor would use the hydrogen gas to levitate or fluidize the ilmenite particles thus giving an excellent contact time and eliminate any concerns of hydrogen diffusion through the bed. The fluidized bed reactor though excellent in terms of diffusion gives rise to a number of concerns including the levitation of the erosive lunar dust, as mentioned earlier, and the high flow rate of hydrogen required to fluidize this bed. To facilitate the decision making between fluidized and fixed bed reactor design a model of the diffusion of hydrogen through the ilmenite bed was developed and studied.

Diffusion model

The diffusion model was created, in this case, to provide an idea of the relative rate of diffusion to the reaction rate. If the rate of diffusion through the ilmenite particle bed is very fast compared to the rate of reaction then the reactor can be designed without great concern for facilitating diffusion, i.e. fixed bed reactor. However if the diffusion rate of the hydrogen through the ilmenite bed is slow relative to the rate of reaction then the reactor will need to be designed to minimize diffusion effects, i.e. fluidized bed.

The diffusion model that was developed in this case was derived from the general continuity equation. For this case the continuity equation was simplified to a one dimensional diffusion equation as shown below.

$$\frac{\partial C_{H_2}}{\partial t} + D_{H_2,H_2O}\frac{\partial^2 C_{H_2}}{\partial x^2} - R_{H_2} = 0$$

In the above diffusion model the R term denotes the reaction rate. This model when solved provided information regarding the rate of diffusion relative to the rate of reaction.

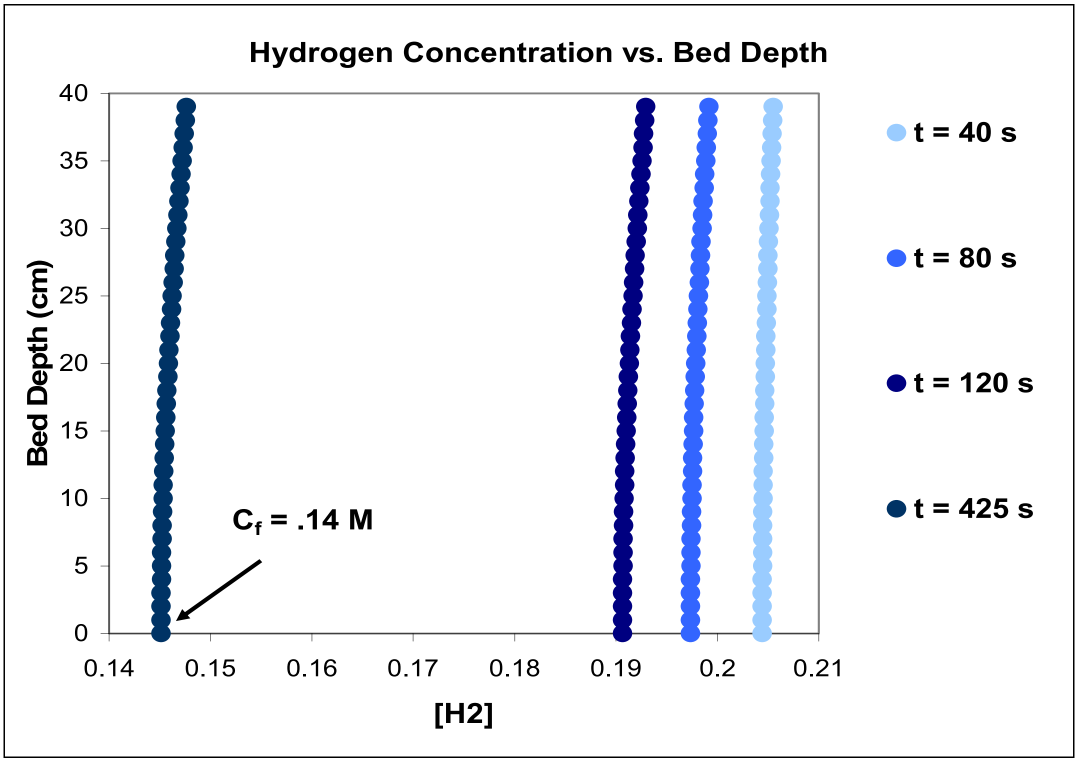


Figure 3: Concentration profile in the ilmenite bed throughout the reaction

The graph above shows the resulting solution to the diffusion model at different times after the reaction began. This provides a snapshot of the hydrogen concentration through the bed depth with zero being the bottom of the bed. From this graph it can be seen that the concentration of hydrogen does not vary greatly through the height of the ilmenite bed. The fact that the hydrogen concentration remains nearly constant throughout the bed indicates that the diffusion of hydrogen through the bed is much faster than the reaction rate, thus indicating that the bed does not need to be fluidized to facilitate diffusion. From these results the design decision was made to use a fixed bed reactor.

Final Reactor Design

With the style of reactor determined through use of the diffusion model and the operating conditions set from kinetic modeling optimization the physical dimensions of the reactor were ready to be set. The reactor that was designed is shown in the figure below.

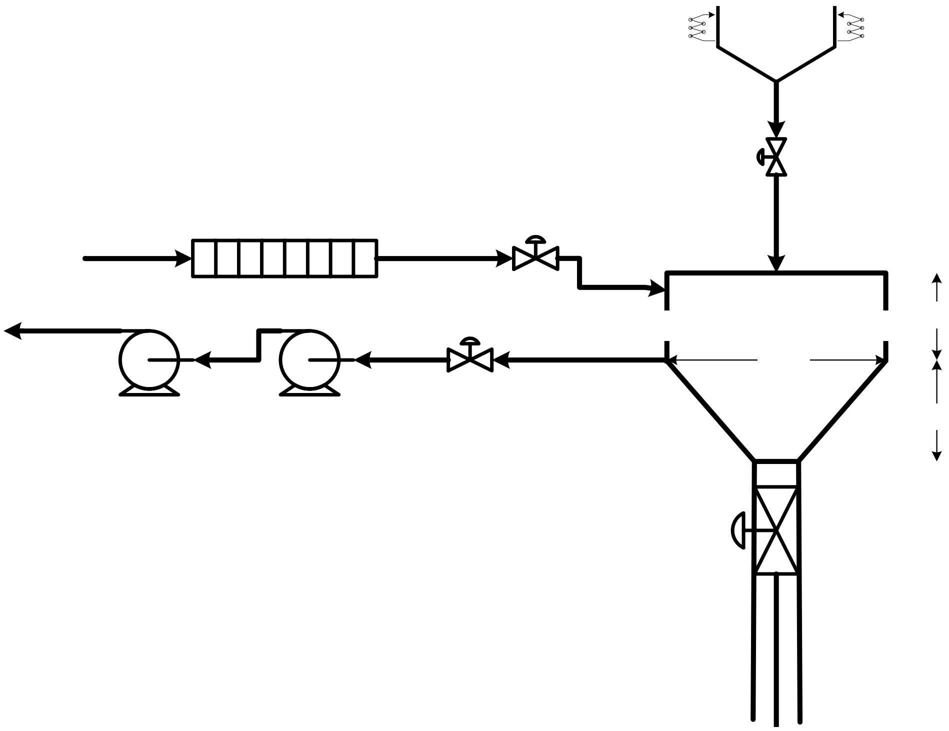


Figure 4: Fixed Bed Batch Reactor

Some interesting features of the final reactor design include the hopper bottom, the vacuum pump on the product exit stream, and the feed hopper each of these items will be discussed briefly. The hopper bottom was added to the reactor to facilitate the removal of the spent solids from the reactor. This design for solids removal was settled on after considering many other options including "trap door" bottom to drop the solids out and a swing arms which was going to be used to force the solids to the sides of the reactor where they would be removed. The vacuum pump of the product exit line is required to air lock the reactor after the reaction has gone to completion and before the spent solids are allowed to leave the reactor. This must be done to minimize the amount of hydrogen that escapes with the solids. The solids feed hopper is a holding tank that is used to store and heat the lunar soil before being gravity feed to the reactor. The reactor dimensions, as shown in figure 4, are a diameter of 1.2 meters and a total height of 1.3 meters. These dimensions were chosen to provide a large contact area between the bulk gas and solid without the diameter becoming so large as to be problematic when considering launch logistics.

Heat Transfer Systems

Reactant Heating

The process as designed involves heating both the solid ilmenite and the hydrogen gas up to slightly over 900°C before the reaction will proceed. There were a couple of options considered to accomplish this heating. The first option considered was to charge the reactor with both the hydrogen and the lunar soil and heat everything inside the reactor by means of heating coils. This idea was determined to be too risky for this process. Having the heating coils contained in the reactor could potentially cause great difficulty in maintenance if one of the coils was to be damaged. Another concept that was studied in detail was the heat integration of the hot reactor effluent and the cold ilmenite feed. This process would use the hot gases leaving the reactor to provide some of the heat required to heat the solid ilmenite. This process was not selected because of the complexity of the solid-gas heat exchanger that would have been required to accomplish this. The heat exchanger would have been a rotary kiln style heat exchanger; the complexity of the moving parts in this exchanger was determined to outweigh the benefits of conserving energy.

The final design selected to heat the reactants consists of two parts. The first part is a line heater to heat the hydrogen as it is fed to the reactor. The line heater will be powered by electrical heating tape. This heater will heat the hydrogen up to slightly above the required 900 degrees to allow for the heat loss associated with the flow through the pipe and heating the reactor walls. The lunar soil will be heated in the feed hopper with an induction heater. An induction heater was chosen because the hopper will be under vacuum while the solids are heated. The vacuum in the hopper makes heating quite difficult because the lack of atmosphere eliminates convective heating. The induction heater will heat the solids to just above 950°C to provide the heat of reaction necessary to drive this reaction to completion.

Condenser System

After the reaction has gone to completion the hot gases created in the process must be cooled. The reactor effluent has to be cooled sufficiently to condense the water vapor so that the hydrogen can be recycled and the water can be sent to the electrolysis chamber to be processed further. Pictured below is a general schematic of the condenser system to be used in this process.

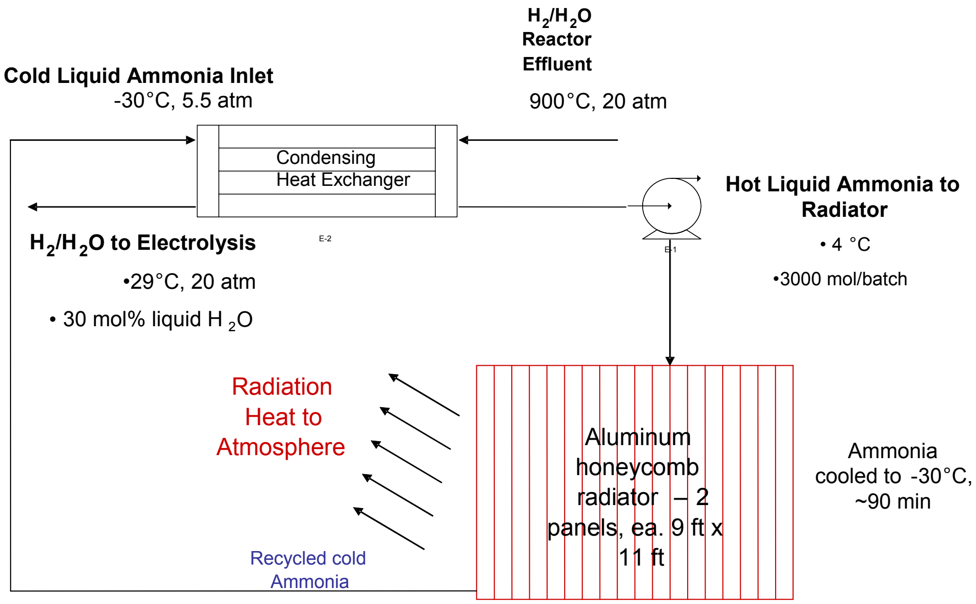


Figure 5: Condensing Heat Exchanger Process Flow Diagram

The condenser system used in this process is an ammonia cooled radiator system. From the above PFD it can be seen that cold ammonia is used to condense the water vapor from the hydrogen gas stream in a condensing heat exchanger. After removing the heat from the water vapor and hydrogen stream sufficiently to condense all the water vapor the ammonia must be cooled before it can be used again. This cooling of the ammonia is a difficult task in the lunar environment because of the lack of convective heat transfer. A couple of different techniques were considered when trying to solve this problem of cooling the ammonia. The first idea considered was using the natural temperature of the lunar surface by burying cooling pipes under the surface. The average temperature of the lunar surface is -30°C. The problem with this option was that the heat transfer properties, namely the conductive heat transfer coefficient, of the lunar surface were not known. If the conductive heat transfer coefficient was not high enough the soil around the cooling pipes would eventually heat up and not provide adequate heat transfer. Since this cooling technique was not guaranteed to work the design turned to the proven vacuum cooling technology used on the international space station. The ISS uses similar radiator cooling technology to maintain the temperature of the space station. These radiator panels reject waste heat to the environment at a rate of 1.5 kW.

Electrolysis Chamber

After condensing the water out of the hydrogen stream it is separated from the hydrogen stream in a phase separation unit and moved to the electrolysis chamber for further processing. The electrolysis chamber is used to split the liquid water in the breathable oxygen and hydrogen gas which can be recycled to the reactor for further use. The electrolysis chamber is a simple design which provides a constant flow of oxygen and hydrogen to their respective storages. The electrolysis chamber is designed to operate continuously by adding level control to the chamber which has its level maintained by adding liquid water from the phase separation tank to the electrolysis chamber as the water level in the chamber drops. The electrolysis chamber using two platinum electrodes and has a total capacity of 20 liters. The power supply to the electrolysis unit must provide 2.4 kW to maintain the oxygen production rate required.

Oxygen Storage

The oxygen that leaves the electrolysis chamber will liquefied and stored for some time before being fed to the habitat for consumption. The system chosen for this process was a modified Claude Cycle. The Claude Cycle is a well understood process which is commonly used to liquefy oxygen. This cycle was modified by removing a heat exchanger from the cycle to conserve the amount of equipment that was required to run the process. The process to be implemented is shown below in figure 6.

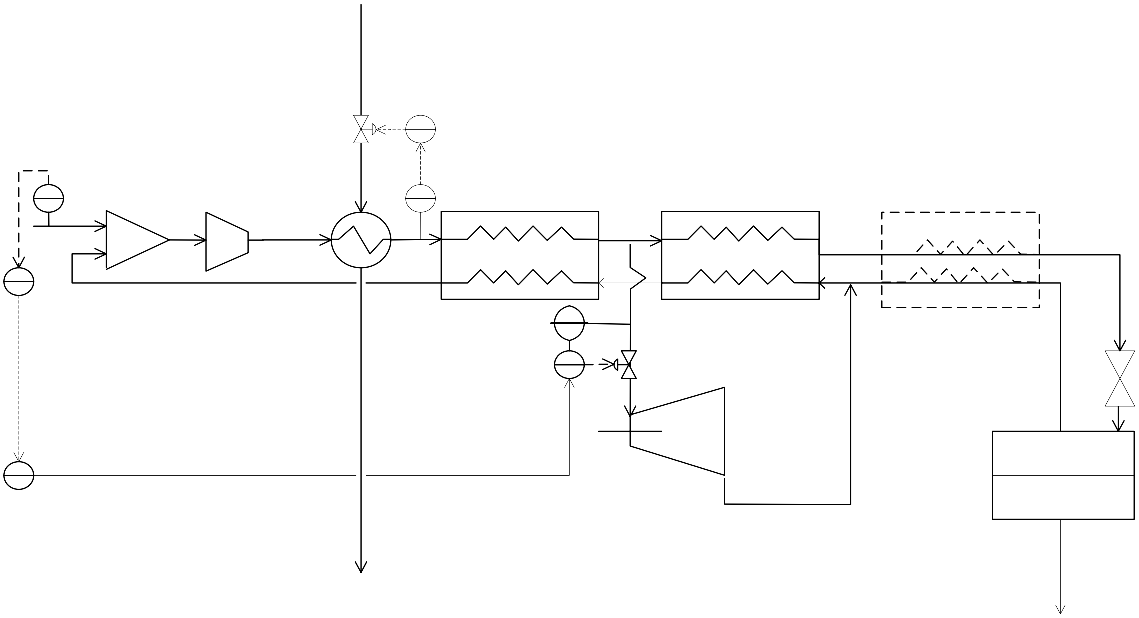


Figure 6: PFD of modified Claude liquefaction process

This liquefaction process also provides a couple of other useful purposes to the lunar outpost. First is it will be able to provide a six month emergency store of oxygen in case of process failure. The liquefaction process is well suited for maintaining this storage because the liquid oxygen has a much higher density so the storage tanks do not require such a large volume to store this quantity of oxygen. The second benefit of using a liquid oxygen storage system is that it is conducive to the new space exploration vision mentioned in the introduction to this paper. If the moon is to be used as a stepping stone to mars then the oxygen required to fuel rockets will likely come from a lunar source. This is very beneficial to any mission to mars because with current technologies this oxygen used as fuel can account for up to 80% of a rocket's launch mass. By providing lunar oxygen for fuel the effective payload capacity of rockets will be increased greatly.

TC
Heat
exchanger
Mixer
Compressor
FT
TT

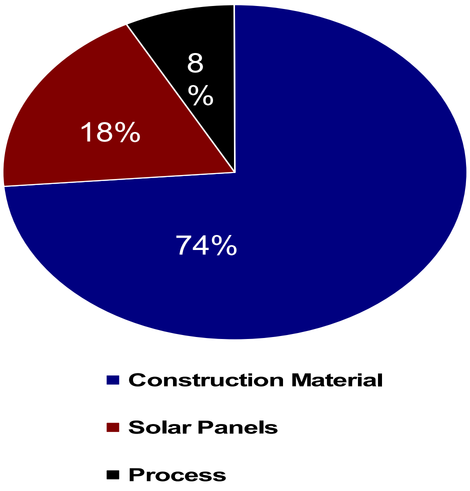
DC

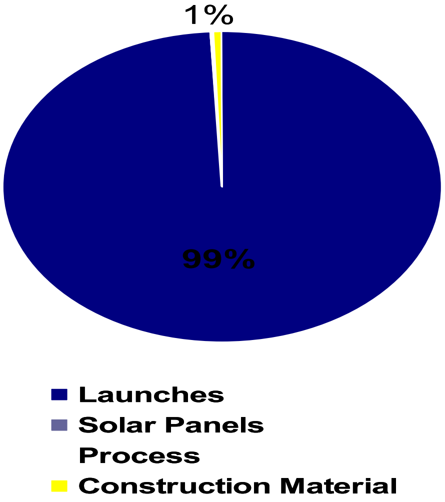
Habitat

The habitat as proposed here for the lunar outpost is a very basic structure. The habitat will be a geodesic dome with a diameter of approximately 15 meters. This structure will be provided with insulation to protect the inhabitants from the cosmic radiation. The oxygen production facility will be located inside the habitat except for the oxygen storage and the radiator panels for the condenser. The detailed planning of the habitat was considered to be outside the scope of this project and will be left as future work. The importance of the habitat to this project is the economic burden of transporting the shelter to the moon.

Economic Analysis

After completing the design of the oxygen production process the cost of the project was estimated to determine the economic feasibility of the design. The goal of this project is not to make money but rather be efficient and operate under a budget. To provide an idea of the relative cost of this process it should be noted that the budget for lunar exploration for fiscal year 2005 for NASA is ~$16 billion with $12 Billion to be set aside for lunar exploration. Below is a chart that shows the relative costs of the different aspects of the project.





From these pie charts it can be seen that the process equipment for this process is very small relative to other costs of the project. For example the process equipment makes up less than 1 % of the total costs when the transportation cost is included. The transportation costs are extremely high because of the set cost per rocket launch. Each rocket launch costs almost $200 Million.

Conclusions

From the detailed study of the production of oxygen on the moon it has been found that this project is feasible both technically and economically. The technical challenges to be overcome before this process can be implemented are minor and should be easily obtainable by the projected start date of 2010. The economics of this process are clearly not a limiting factor in the development of a permanent lunar outpost. From our economic analysis of this project it is clear that during the redesign of the heavy lift rockets, that the cost of launch should be held as a very important factor. The reduction of the cost per launch would make the exploration of space much more affordable. Further information about both the process and project can be found in the full technical report which was submitted with this document.