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HARVESTING THE ATMOSPHERE

An Interactive Qualifying Project Report

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by

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Abstract

The goal of this report was to assess the technical feasibility and social implications of harvesting gases at altitudes in or above the stratosphere for use on a manned lunar base. Through research and calculation, we analyzed the requirements of collection, separation, compression, and delivery of the gases to Low Earth Orbit. This analysis has found harvesting the atmosphere to not be a promising option given current technology.

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Chapter 1: Why Harvest the Atmosphere?

The greatest bottleneck in the exploration of space is the availability of resources. Whether the resources are needed for propellant, life support, or research, the molecules most abundant in Earth's atmosphere such as oxygen, hydrogen, and carbon dioxide are invaluable in the exploration and inhabitation of our solar system. Moving resources through space takes little energy; however, lifting these resources into orbit in the first place is expensive. Providing these simple molecules inexpensively to orbiting spacecraft will be the key to unlocking the door to space exploration.

One of the current projects of NASA is the creation of a manned lunar base. One of the great interests in a moon base is the possibility of mining Helium-3, which is the most efficient and clean fuel for a fusion reaction, and is predicted to be capable of satisfying our growing energy need for the next millennium (Manstov). Helium-3 is rare on Earth, but is prevalent on the Moon's surface. The Moon is inhospitable to human life because of the absence of an atmosphere, water, and breathable oxygen as well as other resources. While oxygen can be mined from the soil layer of the Moon's surface, also known as regolith, the construction of a moon base to mine these materials will require an abundance of initial resources. To sustain human life on the moon, agriculture is needed for a breathable atmosphere and as a source of food. On average, human beings use 0.83 kg of oxygen per day (Living off the Land). Carbon dioxide and water are then needed to start a basic life-supporting ecosystem. There is water on the moon, but it is mostly present at the poles and in small quantities. There is disagreement among scientists about the exact quantity of water on the moon. Estimates range from 11 to 1,300 million tons

(Hall). Since water is rare on the moon, it must either be delivered or its components, oxygen and hydrogen, are needed.

Reducing the cost of making these resources available will open up additional funding for expansion of the space program. A more cost efficient or even profitable space program would not only accelerate the exploration of space, but also the technological advancements that are bound to result. The sooner a moon base is established, the sooner humankind can reap its benefits such as the mining of Helium-3 and as a stepping stone for the colonization of Mars.

One of the main expenses in lifting resources to orbit is the energy expended fighting gravitational pull. Some of the resources that are lifted into orbit from the ground, at great expense, are readily available in the Earth's atmosphere. The most prominent gases in Earth's atmosphere are nitrogen, oxygen, argon, and lastly carbon dioxide. All other components are represented in trace amounts (see Appendix B). With existing technology, most gases can be gathered and purified for commercial use on Earth. Adapting these technologies to work at higher altitudes could lead to a decrease in the energy required to bring these resources into orbit at an altitude of two hundred kilometers or higher (see Appendix A). Since the work required traveling to orbit decreases with altitude, less fuel would be required to launch the resources to orbit. This leads to the question: could resources be gathered at a higher altitude and delivered to orbit with energy costs less than simply delivering resources to orbit from Earth's surface?

Chapter 2: Why Separate the Atmosphere and Separation Methods

As stated in the previous chapter, being able to gather the atmosphere at higher altitudes than the surface of the Earth could provide a less expensive way to accumulate resources for further space ventures. Even so, supposing that a device is able to gather atmospheric resources at this new height, ranging from thirty-five kilometers to Low Earth Orbit (approx. 200km), what materials would it collect and how would we separate the materials necessary for the moon base from the undesirable gases prevalent in the atmosphere?

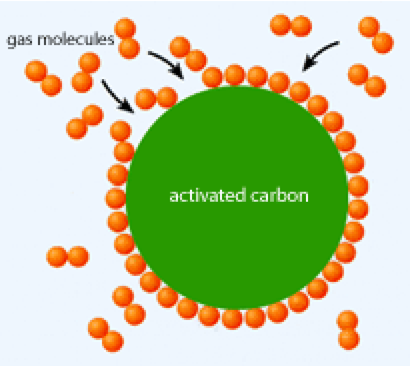
In its raw form, the materials gathered by such a collection device, would be equivalent to a small sample of Earth's atmosphere. The atmosphere is made of several different components, whether it's the largest component of the atmosphere, nitrogen, or the smallest usable component, water vapor, these different resources need to be separated out from the gathered materials and placed in a usable form for various process on the moon base. To do this, one of several separation methods must be used: an adsorption process, membrane separation, or cryogenics. Each method has certain benefits and pitfalls which we will examine before continuing.

2.1 Gas Separation

The moon base, in order to sustain human life, must have several resources. Perhaps the most obvious is a breathable atmosphere. For this, oxygen must be provided for human consumption. Basic agriculture, will aid in maintaining the first requirement and provide basic nutrition. This plant life then requires carbon dioxide and water. Water can then be broken down furthermore into hydrogen and oxygen. As shown, these three resources: atmosphere, agriculture, and water, share a common thread. They are all composed of the same basic elements of hydrogen, oxygen, and carbon. However, as shown in appendix A, hydrogen and carbon dioxide make up less than one percent of the atmosphere and oxygen is approximately twenty-one percent of the atmosphere, thus the main focus of the paper will be on oxygen collection.

2.2 Adsorption

The first method, adsorption, involves the use of an "adsorbent" which influences the concentration, localization, fixation or separation of gases. By using this "adsorbent" the gathered materials may be separated into the desired components. The basic principle in adsorption is that an absorbent, a highly specific chemical compound, attracts the desired material (as shown below).



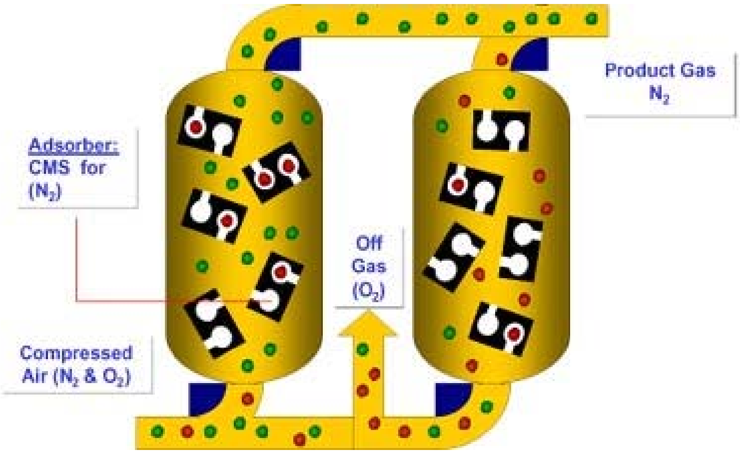
Taken from http://www.eere.energy.gov/hydrogenandfuelcells/storage/basics.html

It can do this several ways, by creating a weak chemical bond between itself, a solid, and the desired gas, often referred to as van der Waals adsorption or a strong chemical bond between itself and the gas, as in chemisorption (Mantell, C.L. 1945 pp.1-3). The adsorbent tends to be made up of porous particulates matter, such as charcoal activated carbon or molecular sieve zeolites, with a large surface area both externally and internally. Gases flow through a bed of absorbent and diffuse into pores where they are preferentially absorbed.

Molecular sieves are a more highly specific type of adsorption. Where as carbon activated charcoal will separate particles, it cannot attain the same purity as molecular sieves. Molecular sieves are another type of adsorption and are a porous material, able to selectively separate molecules on the basis of their shape and size (Naydenov). The molecular sieve crystals themselves are very small particles, as shown below, which are crystalline in structure, and typically one to ten micro meters in size. The holes in them are engineered by choosing different types of molecular sieve or by ion-exchange, so only certain molecules may pass through.

Taken from http://www.gracedavison.com/eusilica/Adsorbents/product/zeolite_molecular_sieve.htm

The molecular sieve crystals are claybinded into particles and then loaded into a tube. The atmospheric gases can then be passed through one side of the tube. The desired gas bonds to the molecular sieve and the remaining air is able to pass through without being hindered. In this way only the oxygen molecules or hydrogen molecules, for example, are allowed to bond to the molecular sieve crystals, see below for example (Ruthven, pg. 19-26). In the example below compressed air is been pushed through a container and the oxygen (red particles) are being removed by the molecular sieves, and the final product, pure nitrogen (green particles) are achieved.

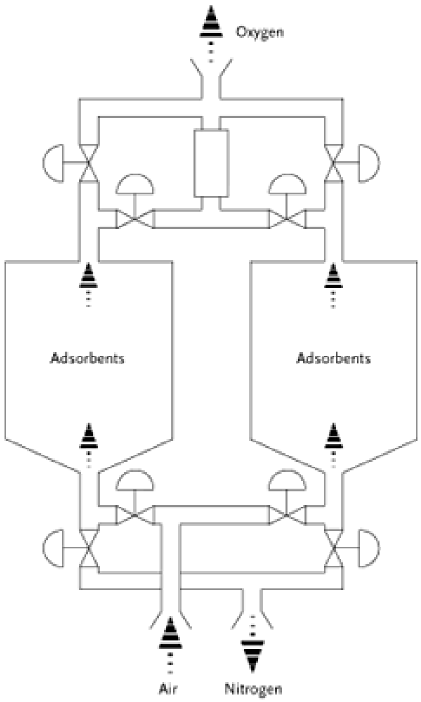


Taken from http://www.igs-global.com/nitroswing/technology.htm

Once the desired gas has bonded to the adsorbent it must be removed via another process to enter into its usable form. Removing the desired product can vary in difficultly. The most common method is thermal swing. Thermal swing, simply put, is a large increase in temperature. When the adsorbent is heated, the adsorbate, or gathered materials become less favorable for adsorption, as in physisorption, and the chemical bonds that formed are released. Thermal swing is often used to help break stronger chemical bonds (Ruthven, pg 342-346).

Another option is the pressure swing process. In this process the adsorbent is regenerated by simply decreasing the overall pressure. Knowing that space is a vacuum, this could be a promising method to use in orbit.

In pressure swing adsorption, there are typically two internal chambers containing the adsorbent. The adsorbate is alternatively moved through both chambers and the chambers alternate in pressurizing and depressurizing.



Taken from http://www.praxair.com/1998annualreport/cryo2.html

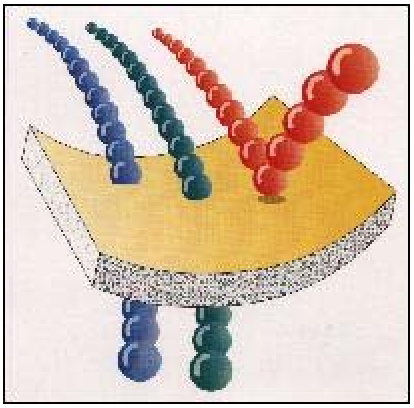
In this way efficiency is maximized since one bed is always adsorbing while the other is desorbing. This also allows for fast cycling and multiple chambers can be used to maximize the amount of desired material (Ruthven, pg 361-363). The last type of removal method is displacement desorption which is usually used when the pressure and thermal swing methods fail. This is due to its overwhelming complexity in comparison to the previous two. In this method a substance is chosen that bonds more strongly to the adsorbent than the adsorbate. In this way, the adsorbate is displaced by the stronger forces of the displacement gas. The displacement gas can then be removed by flash vaporization, and the absorbent may be used again (Dervisoglu).

One of the benefits of the adsorption process is that it allows you to select a specific gas for removal. If the correct adsorbent is found then the desired gas can be removed with about ninety-nine percent purity. For example, supposing that oxygen is wanted for use on the moon base, a zeolite adsorbent, 5A or 13X can be used. Note that, although adsorbents are generally specific, trace amounts of other gases will be present. In the case of collecting oxygen, nitrogen and argon will also be present in trace amounts. The maximum attainable purity for the oxygen is then reduced to about ninety-five to ninety-six percent, which is still very high (Ruthven, Farooq, and Knaebel, pg 227). On the downside, the price to pay for this specific final product is that the apparatus to filter the atmosphere will most likely be large in size. The adsorbent itself will need to be carried up in space as well, adding more weight to the collection device. The desorption process also becomes more difficult in space. If thermal swing is used to superheat the adsorbent than a large heat source or energy source is needed. The pressure swing process may be able to use the vacuum of space to lower the pressure to allow for desorption, yet after this process is completed a pump is still needed to restore the pressure to the adsorption chamber. Displacement desorption also adds excess weight to the collection device. The device will now need to carry the adsorbent, a displacement gas, and a gas to allow for flash vaporization of the displacement gas.

2.3 Gas Separation Membranes

Whereas molecular sieves are crystals in packed beds, gas separation membranes shelled membranes are usually a spiral or multi-tabular shape with a large surface area. The two main types of membranes right now are gas-permeable polymers and ceramic molecular sieve zeolites. These membranes are selective semi-permeable barriers that allow different gases, vapors, or liquids to move through at different rates. In gas separation membranes, a stream of air is pushed across the membrane. The desired molecules or permeating molecules can pass through the membrane, and the non-permeating molecules exit the membrane via another stream of air, the retentate stream

(Freemantle). The diagram below shows this, where the red line represents the retentate stream and the blue and green lines represent the permeating streams.



Taken from http://www.etech.no/pictures/depgassann.jpg

These gas polymer membranes can be measured using two properties: flux and selectivity. The flux is the amount of gas that is able to pass through the membrane for one unit of time and one unit of surface area. The selectivity is a measure of the membranes ability to differentiate between molecules. Ideally, a high selectivity and high flux are necessary for a good membrane (Bleha).

Molecular sieves are crystals claybinded into particles and loaded into a tube, but ceramic molecular sieve zeolites are compressed and arranged into a thin compressed structure. In this way they allow for the same differentiation of molecules as a regular molecular sieve but are more compact. However, they are a relatively new technology and the process of making them is extremely difficult (Tomandl).

While gas separation membranes allow for easy differentiation of molecules, they have several problems when entering the realm of space. For one, a large amount of surface area or membrane area is needed. The equipment will most likely be large and unable to handle multiple streams of air without the further addition of equipment. In addition, since gas permeable membranes are so highly specific, they are often difficult to create. In the case of ceramic molecular sieve zeolites, they are a relatively new technology and no membrane has been made that is large enough to make this process viable. If either system were to break it would be difficult and time consuming process to replace the key components. Lastly, assuming the collection device is moving through the atmosphere, the membrane may be unable to withstand high air pressure and high velocities. The air flow into both systems must be regulated to maintain a constant flux.

2.4 Cryogenics

Cryogenic freezing is another process which will allow for the separation of selected materials from the atmosphere. Cryogenics is derived from the Greek word “Kryos” and the suffix “genics”, which literally means, suitable for production by icy cold conditions. Cryogenics involves the utilization of low temperature processes to produce physical changes in liquids, gases, or solids. Perhaps the coldest substance dealt with in everyday life is dry ice which is -78°C. Cryogenics involves temperatures in the range below -100°C (Sittig, pg. 1-3). Seeing that space is approximately -270.425°C, this method is promising for the separation of components of the atmosphere **(**Straight Dope**)**.

Cryogenic separation of air involves three steps: purification, refrigeration, and separation. In the first step, purification, solids and liquids present in the air are removed. These impurities, usually dust, dirt, hydrocarbons, and water tend to be present in the air from normal human interaction and hinder the second process, refrigeration. However at the gathering altitudes we are collecting the atmosphere is about one percent as dense as on the surface of the Earth, thus there are fewer hydrocarbons and water molecules so the purification process may not need to be as sophisticated. These solids and liquids are usually removed via a variety of mechanical filters and traps so that the remaining air is free of any impurities. After the impurities are removed, the second step, refrigeration, can begin. In this step air is cooled until it liquefies at temperatures lower than -185°C. Perhaps the surrounding air can aid in the process, but otherwise one of the following methods must be used to attain this temperature: a heat exchanger, a Joule-Thomson expansion, or expansion in a turbine. The basic principle of a heat exchanger is to transfer heat from a hot liquid or gas to a colder liquid or gas (Industry Animated).

Joule-Thomson expansion and expansion in a turbine follow the same basic principle. A gas is passed through a small confined space and then allowed to expand rapidly. This expansion causes the gas to cool to a lower temperature. Assuming the temperature is low enough, the gas will liquefy (Sittig, pg. 26-28). After the gas has been placed in liquid form, the last step, separation can occur. The liquid air is fed through a chamber, where it is allowed to trickle down. At the same time a portion of the liquid is heated until it returns to a gaseous state. This gas enters the bottom of the chamber and continues up until the liquid and gas meet. Since the gas passing through the chamber is warmer than the liquid, it causes some of the liquid to boil off. Since the varying components of the liquid have different boiling points, the unwanted gases with a lower boiling point, will vaporize first, and the oxygen, having a higher boiling point, will remain in liquid form and can be bottled for storage (Sittig, pg 98-101). For example, at one atmosphere, oxygen has a boiling point of -182.95°C where as nitrogen has a boiling point of -195.85°C (McClintock, pg 17). The liquid air will be at a temperature lower than either boiling point and the temperature will be slowly raised. Since the boiling point of nitrogen will be reached before that of oxygen, nitrogen will preferentially vaporize. The oxygen, having a higher boiling point, will remain in its current state, while the nitrogen is a vapor on top of it. The oxygen, in its now liquid form, can be stored for later use.

While cryogenics seems a promising method to use in space, due to the extreme cold, there are several problems with it. First and foremost, the apparatus needed to complete the three processes of purification, refrigeration, and separation will be large and take up considerable weight on such a collection device. However, assuming that space itself is used to begin the refrigeration process, such weight might be reduced. If collecting at these higher altitudes proves too difficult, the surrounding air in the upper atmosphere still has a significantly lower temperature than the surface of Earth and this difference in temperature can still be used to aid in the refrigeration process. Second, the boiling points in the vacuum of space will be altered and will be at much lower temperatures, so the apparatus may need several attachments to compensate for this. Thirdly, once the final product is stored in liquid form its liquid state must be retained. The temperatures of surrounding planets, radiation coming from the planets themselves and the operating temperature of such a physical collection device may alter the temperature of the cryogen (Vance, pg. 434-438). If the cryogen is allowed to heat too much, the liquid will revert to its gaseous state and cause the storage container to explode. The cryogen is also usually carried in a high pressure and uniquely designed tank to prevent this. Lastly, the cryogen itself may be highly volatile. Liquid oxygen, for example, is a very chemically active substance. A small amount of heat added, caused by friction or mechanical impact could cause the liquid oxygen to explode (McClintock, pg 19).

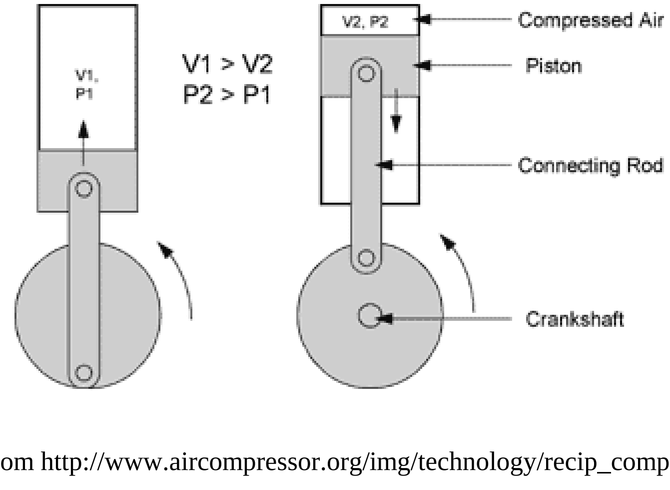
2.4 Conclusions on Separation

Examining the above technologies, the two most prudent for space are pressure swing adsorption and cryogenics. Both these technologies involve using aspects of space to aid in the process. Pressure swing adsorption can use the vacuum of space to help lower the pressure for desorption, but it will still have to carry a large amount of an adsorbent material with it. Cryogenics involves temperature below -100°C. Since space is already approximately -250°C, the device may be adapted to use this temperature, thus freeing up more energy for other necessary processes. Perhaps this energy cost can also help negate the high cost of transporting large amounts of heavy equipment necessary for cryogenics. Pressure swing adsorption is clearly the best choice out of the adsorption types, since thermal swing will require large amounts of energy to sustain its high temperature. Displacement desorption requires a large amount of excess equipment, in comparison to pressure swing adsorption, so it can be ruled out. In the case of gas separation membranes, they are difficult to create and may not be able to withstand the high velocities, if the collection vehicle were moving. They will also need to be large and the resulting equipment will add additional weight. However, if ceramic molecular sieve zeolites were to develop in the next twenty years and grow in strength and size, they would be ideal, since they involve the equipment with the least weight. They also do not require the air to be liquefied or change state in order to be processed. However a compressor might be needed to produce a compact high value load for transport back to LEO.

Chapter 3: Compression

After separating the various components of the air into the necessary final products, they must then be stored to be transferred to the moon base. For efficient use on the moon, large quantities of these materials will most likely be sent at once. To do this the materials can be compressed, allowing for more materials to be stored in the same volume. Neglected the separation methods that leave the resources in a liquid form, the rest of the separation techniques require some type of compressor to aid this process.

The basic principle of a compressor is to compact the entering air usually with mechanical work, such as a piston, so that it occupies a smaller volume then it did initially. There are several various types of air compressors, but perhaps the most common are positive displacement compressors. Positive displacement compressors increase the pressure of the air by reducing the space it occupies. Positive displacement compressors can be further divided into two types: reciprocating compressors and rotary screw compressors (ECompressedair). Reciprocating compressors use a piston moving within a cylinder to compress the air to a higher pressure. This can be seen below.



Taken from http://www.aircompressor.org/img/technology/recip_compressor.gif

They can usually be found as single-acting or double-acting. Single acting or double acting refers to when the actual compression occurs. In a single acting compression system, the air is compressed only when the piston moves in one direction, that is the upwards or downwards stroke. In double acting compression, the air is compressed when the piston moves in both directions, making double acting compression the more efficient of the two processes (Hydraulics & Pneumatics). The specifications are shown for the reciprocating compress below.

	Single-Stage	Two-Stage
Discharge pressure, psig (bar)	25 to 125 (1.7 to 8.6)	100 to 250 (7 to 17.2)
Flow rating, cfm (m3/min)	100 to 750 (2.8 to 21.2)	450 to 4500 (12.7 to 127.4)
Horsepower, hp (kW)	10 to 125 (7.5 to 93)	75 to 1000 (55 to 746)

Taken From http://www.ecompressedair.com/library/aircompressors_p03.shtml#recip

Rotary screw compressors, instead of using a piston typically use two rotors. The rotors will be aligned next to each other and resemble two screws that interlock each other. As the rotors spin, air enters the bottom most part of the screw and is drawn upwards. This motion continues until the gas is pressed against the top of the case the rotors are in and continues into a tank where the gas is stored.

The diagram below shows an example of this, where the blue represents the gas that is being compressed and forced upwards. The specifications for the rotary screw compressor are shown below.

Taken from http://www.purelubricants.com/Compress.jpg

	Single-Stage	Two-Stage
Discharge pressure, psig (bar)	70 to 175 (4.8 to 12)	70 to 150 (4.8 to 10)
Flow rating, cfm (m3/min)	20 to 1500 (0.57 to 42.5)	500 to 2600 (14.2 to 73.6)
Horsepower, hp (kW)	5 to 350 (3.7 to 261)	100 to 500 (75 to 373)

Taken from http://www.ecompressedair.com/library/aircompressors_p04.shtml

For the collection device, the most probable type of compressor would either be a double-acting reciprocating compressor or a rotary screw compressor. A double-acting compressor ensures maximum efficiency since work is being done on both strokes of the piston. Typically double-acting compressors can compress larger amounts of gas at a high rate, but rotary screw compressors require less maintenance. Rotary screw compressors also have the advantage of requiring less power than the double acting compressors. This could be a benefit in space because it would reduce the energy cost of the collection device. Another benefit of using this compression technology in space is space’s low temperature will aid in cooling the components, and the unit will require less internal and external cooling. On the negative side, the flow ratings in both compressors may be much larger than the amount of materials the collection device gathers.

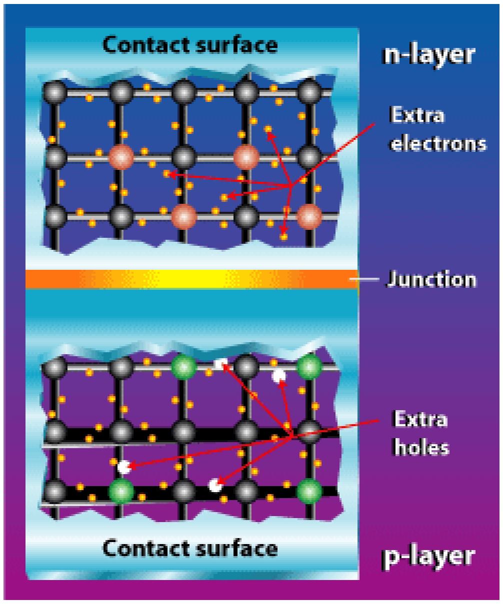
Chapter 4: Energy

An integral part of this project is finding a suitable energy source to power the collection, filtration, compression, and propulsion systems. Selecting the right source for power is important because it needs to be able to provide enough power and still be suitable for use in the upper-atmosphere. Several options are available for consideration: solar power, thermal power, power from magnetic induction, and petroleum-based power generation.

Taking a look at an ideal energy source can provide a good frame of reference when evaluating possible energy sources. An ideal energy source can provide adequate power for our application, is completely renewable, lossless, robust, lightweight, and small. The option that comes closest to the ideal power source is the one that would be the best choice for powering the collection vehicle's air processing equipment.

4.1 Solar Power

The first choice is solar energy. Solar energy can be converted into electricity by photoelectric systems. Solar light is collected by an array of photovoltaic modules. Semi-conductive materials make up the cells and create what is called the photoelectric effect. The cell is constructed with a top layer of "n-type" silicon and a bottom layer of "p-type" silicon. P-type silicon has free electrons that are available for electric conduction. N-type silicon has a deficiency of electrons, called holes. These two layers are in direct contact creating a p-n junction. This is the same type of junction that diodes use to allow current to flow in only one direction (Department of Energy).



Taken from http://www1.eere.energy.gov/solar/images/illust_n_p_layer.gif

The photoelectric effect in solar cells occurs when photons are absorbed. The energy from a photon knocks an electron in the n-type silicon out of its bond allowing it to flow down a wire creating a current. When the electron is freed, a hole is created. Another electron leaves its bond and fills the hole and this process continues until an extra electron enters the p-type silicon to fill the hole. In this manner, light absorbed by the cell can generate direct current electricity, which can then charge a battery or run an electric device **(**Department of Energy).

Taken from http://www1.eere.energy.gov/solar/images/photo_09485.jpg

Photoelectric power generation has many advantages. Solar power is renewable and does not require any refueling or reconditioning. This is a huge advantage because it would be difficult to refuel a collection vehicle in the upper-atmosphere.

There are still some disadvantages to this energy source. The most notable is the efficiency of solar power. With the most advanced current technology, solar panels are only 35.2% efficient. However, research in silicon alloys is showing promise in that various alloys can cover the entire solar spectrum and it is theoretically possible to overlay lattices of these alloys to create a solar panel that is 70% efficient (Preuss).

Because of the low efficiency of current solar panel technology, a large area of solar panels would be needed to meet the power requirements of the collection device. A calculation can be made to determine the surface area of solar paneling required to meet the power needs of the collection vehicle. If we assume that the most significant power draw is a 1,000 horsepower (745,700 watt) compressor, and that 1,367 watts are present in solar energy in every square meter, then if solar cells have a 30% efficiency, 1,820 square meters of solar paneling would be needed to power the device. If efficiency rises to 70%, that number is reduced to 780 square meters (National Renewable Energy Laboratory). Needless to say, this would be an enormous array and would require a similarly large vehicle to hold it.

4.2 Thermal Power

Thermal power was considered initially because infrared radiation from the sun is blocked less by the atmosphere at high altitudes. Further research into this method of power generation has revealed that it is not viable for this application.

Thermoelectric power generation is only meant for low wattage applications. Thermal power systems consist of a thermocouple with a temperature difference between the two ends. The difference in temperature causes a small electric current which can be used to charge a battery for later use. The output wattage is directly proportional to the temperature difference on the thermocouple. This requires a hot side and a cool side to the couple. Due to thermal shielding on the collection device, it will be difficult to keep one side hot and one side cool. Heat flowing to the cool side of the thermocouple needs to be dissipated. This method is not feasible at high altitudes (Global Thermoelectric).

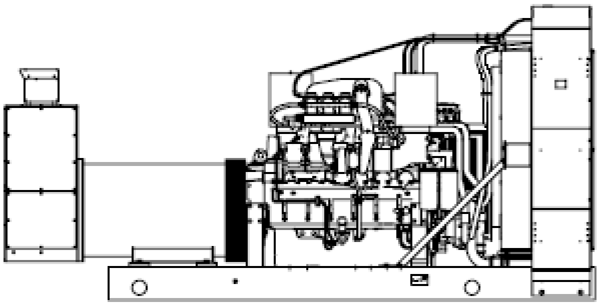
Taken from http://www.globalte.com

Other methods of thermoelectric power generation require a reservoir of boiling water to create steam, which can turn turbines to generate electricity. This apparatus would be large, heavy, and prone to breaking and thus not be suitable on the collection device.

4.3 Electric Generator

Gasoline powered electric generators are capable of meeting and exceeding the power needs of the collection vehicle. This type of power generation system has the ability to be controlled to provide only the amount of power needed at any point in time. An electric generator is essentially a gasoline engine similar to a car’s, but instead of turning wheels, the engine turns a shaft connected to a coil of wire in a magnetic field.

As the coil of wire turns, an electric current is induced in the wire. The flow rate of gas through the engine is directly proportional to the amount of power that the engine delivers.



Taken from http://www.kohlerpowersystems.com/pdfs/g5245.pdf

The major drawback to using this technology for power at high altitudes is that it is not renewable. According to the specifications of a typical 720 kW generator, gasoline is consumed at a peak rate of 51.8 gallons per hour (Kohler Power Systems). In addition to gasoline consumption, since generators are essentially engines, they're prone to wear and tear and would require regular maintenance. Gasoline power generators are additionally only fit to function in Earth's atmosphere because gasoline combustion requires oxygen. This means that generators wouldn't work to power an orbiting vehicle. However, both the necessity of maintenance and the need for gasoline to be delivered to the generator on a regular basis make this solution unsuitable for a collection vehicle of any sort.

4.4 Magnetic Induction

Another idea that was considered was the concept of using the vehicle's movement through the Earth's magnetic field to produce an electric current. The laws of physics explain that a wire moving through a magnetic field produces an electric current. This current is directly proportional to the speed of the wire, the length of the wire and the magnitude of the magnetic field. Upon doing further research, it was concluded that the vehicle would need to travel at an extremely high speed to produce enough electricity to power just low-power electrical systems let alone a high-power electric motor for the compressor system. In addition to the speed requirement, the wire in which the current is induced by the magnetic field would need to be very long. This method of producing electricity is better suited to orbiting spacecrafts which move at higher speeds, due to the low air resistance (Tethers Unlimited).

4.5 Conclusion on Energy

While we cannot generate enough energy using current technology, the method of electricity generation that is most promising for the collection vehicle is solar power. This type of system is renewable, robust and capable of meeting the power needs of the collection device. Although the efficiency is low, there is promising research that has potential for doubling the effectiveness of solar cells. The main disadvantage for this system of electricity production is that it will need a large surface area on the collection device to be effective. Another option is to eliminate the compression stage all together and keep all other processes low-power.

Chapter 5: Collection Vehicles

What everything really comes down to is energy. We are looking to harvest the atmosphere in hopes that it could reduce the great cost created by using enough energy to send resources into orbit from Earth's surface. The positive side of harvesting resources from the atmosphere is that there is less work to be done to get the resources into orbit. The negative side is that due to the steep decline in density of atmosphere, the collection will either take more energy or a greater amount of time, most likely both. Also, the collection vehicle must fight gravity to keep its altitude while collecting. Thus in order to make harvesting the atmosphere more efficient than sending resources from the Earth's surface, renewable energy must take the place of liquid and solid fuels for as much of the collection process as possible. If more non-renewable energy is used to collect a mass of resources in the atmosphere than the amount of energy needed to lift that mass to the collection vehicle altitude, then there is no point in harvesting the atmosphere using such a collection vehicle.

In order to keep energy costs down, a vehicle must be as light as possible, while also being able to carry the equipment necessary for collection of resources. In order to provide as much solar power as possible, surface area is another key ingredient of a collection vehicle, unless of course it draws its power from another renewable source such as the Earth's magnetic field (see Space Tether). One problem with solar energy, however, is that any vehicle relying on solar power must either deliver its collected resources into orbit and land before the sun sets each day or else be able to stay aloft using stored power or other means (see Gas Balloon). Another option would be to circle the globe every 24 hours, but at an altitude of 30 km this would require speeds of approximately 1042 mph (1070 mph at 200 km altitude) relative to Earth's surface, which would take a great deal of energy and require the structural integrity to withstand the forces of supersonic speeds (~760 mph). (This calculation is based on the Earth's radius at the equator being 6378.1 km). We do not believe that solar paneling will ever be efficient or robust enough to make this option practical (see Chapter 4).

5.1 Pathfinder Plus

The first collection vehicle we looked at was a solar powered, propeller-driven craft. We extracted ideas about the abilities of such a craft from the current altitude record holder for both a solar powered vehicle and a propeller-driven vehicle, the Pathfinder Plus. Built by NASA, the Pathfinder Plus is capable of altitudes around 24 kilometers and a velocity of approximately 32 kph (~20 mph). (NASA. Dryden Flight Research Center) The benefit of such a vehicle is its sole dependence on solar power. Unfortunately, it is difficult for propeller-driven vehicles to reach high altitudes because of the decreased density of air. Also the Pathfinder Plus uses eight 1.5 kilowatt motors, but only is capable of collecting energy at a rate of 12.5 kilowatts; thus it is daylight limited and currently is only capable of remaining in flight for about 15 hours before landing. Improvements made by lighter materials and more efficient solar paneling will eventually overcome the limitation in flight time, most probably in the near future of less than 15 years. We do not, however, expect any similar craft to be capable of much greater altitudes due to the decreasing density of air with respect to altitude. The weight of the collection equipment will also require either lower altitudes or increased power efficiency, though this is neglecting the fact that the collection process will either require a great amount of additional power (see Chapter 2 and 3), or in the case that it utilizes the vehicles velocity, it will require additional power to compensate for the drag caused by literally catching air as it flies.

As with all low altitude collection vehicles we considered, delivery of collected resources is complicated. The lowest orbit around Earth possible without constant need for correction due to air resistance is called LEO, or Low Earth Orbit, and is roughly defined as 200-1,200 km (Wikipedia). We do not believe that solar powered, propeller-driven vehicles will ever achieve much greater altitude than the Pathfinder Plus. This is because propellers use the friction of their blades turning in air to push them forward, just like humans use the friction of the feet against the ground to move them**.** Trying to move using propellers in a low-air density environment is like trying to run on extremely slippery ice. So unless a better way of converting the electricity gathered by solar panels into thrust is found, solar powered vehicles in general will not ever reach much greater altitudes than the Pathfinder Plus and certainly will not be capable of reaching orbit. Due to the Pathfinder Plus's low altitude relative to LEO, the materials would have a great distance to be delivered and thus require a large mass of fuel close to what is needed to lift resources from the ground, this fuel would weigh down the craft greatly creating an unrealistically increased need for energy. There are other methods of delivery, however, and they will be discussed in Chapter 6.

5.2 Dipping Vehicle

The second collection vehicle we considered was in some ways the reverse of the Pathfinder Plus. The biggest problem with a propeller-driven, solar powered vehicle is delivery. What if there were a vehicle, which self-delivered the materials? We considered a vehicle, which stayed in orbit at all times except when it dipped into the atmosphere to collect gases. A couple of problems immediately resulted from the idea. First, the vehicle would need to be fuel powered as solar powered devices cannot achieve altitudes close to LEO. As atmospheric density decreases exponentially with altitude (see Appendix B), the collection vehicle would have to either go close to the surface to collect gases or have to spend more time collecting. The collection equipment would also need to be carried on this dip into the atmosphere. The collection vehicle would have to orbit the Earth at a supersonic speed and thus could use this momentum to create lift in the atmosphere, but collecting any gases while moving at a high velocity would change the aerodynamics of the craft and possibly cause it to loose control. Also, since momentum is equal to the product of velocity times mass, the collection vehicle would lose velocity as it collected gas. With its velocity quickly decreasing due to air resistance and taking on masses of gas possibly several times the crafts weight, the collection vehicle will likely need to use a significant amount of fuel to stay aloft and under control. Thus we predict that a dipping vehicle would use more fuel than what is needed to bring resources from the ground. Additionally, the collection vehicle would have to be refueled in orbit, which poses the problem of getting large masses of fuel to a space station reachable by the vehicle. Therefore we believe a dipping vehicle would not be an efficient method of harvesting the atmosphere.

5.3 Space Tether

Another idea for a collection vehicle of sorts came from the concept of the space tether. The space tether is an intersection of two perpendicular wires made from carbon nanotubes, which spins as it orbits the Earth creating electric current in the wires from induction due to Earth’s magnetic field. The Tether would collect oxygen over great periods of time from the minute amounts available in its orbit. There is a problem in using the space tether, however; there is just not enough oxygen in LEO to gather a useable amount. Also, to extend the tether to a length at which it would encounter a useable amount of gas would create friction as the tether spins. This friction could be too much for the tether and might stop it from spinning. Even if oxygen could be collected in a useable quantity, the oxygen available in orbit is atomic oxygen (AO), which causes rapid corrosion due to its high reactivity. (European Space Agency)

5.4 Gas Balloon

A great problem with all of the aforementioned prospective collection vehicles is the energy expended to keep them aloft and fight friction. If there were a vehicle, which required no energy to stay aloft, harvesting the atmosphere would not be much different from collecting gases on the ground. Therefore we considered a gas balloon. Gas balloons are capable of altitudes of almost 35km (Gas Ballooning Information) and do not need to utilize solar power to ascend to an altitude and keep it. Gas balloons are able to achieve great altitude based solely on the fact that they are less dense than air and therefore naturally rise until the atmosphere's density equals the balloon's average density. Also a gas balloon can be any size and therefore could provide as much space as it would need for solar paneling. The problem with using a gas balloon is that the weight required to lift any equipment would require an extremely large balloon as the average density of the gas, balloon, and all onboard equipment must be equal to the density of air at the target altitude. If it is possible for a gas balloon to carry the necessary 1,820 square meters of solar paneling and equipment, then we see this as the best option. However, the delivery becomes a problem as will be discussed next.

Chapter 6: Delivery

The shuttles currently used to deliver resources into orbit are extremely heavy. The fuel and oxidizer on NASA's shuttle weigh 1,589,000 pounds alone (NASA. External Tank).

The collection vehicle options discussed previously provide ideas for how to harvest gases from the atmosphere, but the more viable options are incapable of altitudes even a quarter of the way to orbit. Thus they require a delivery system. The most basic option for a delivery system is to carry a rocket capable of launching from a vertical free-fall. While this is similar to the methods currently used to bring resources up from the ground, the starting altitude will mean that the rockets require less fuel and thus would cost less to use. A company, t/Space (Transformational Space Corporation), is developing and currently testing such a vertical fall launch device called the CXV under contract with NASA (t/Space). The problem with such a delivery system, however, is that the CXV, while much lighter than other spacecraft, still weighs 8,100 lbs and currently needs to be dropped from a large aircraft (Physorg.com). The key to harvesting the atmosphere is enabling a collection device to gain and retain altitude with as little energy use as possible. Hence a four ton delivery device may not be feasible.

Another option we considered for delivery of collected resources was a type of rendezvous. This option would involve a second vehicle already in orbit, we'll call this the pick-up vehicle, which would decrease its speed in a calculated way causing it to fall to Earth. The vehicle would need to be fuel powered as it would have to correct its trajectory in order to meet the collection vehicle. After rendezvous with the collection vehicle, the pick-up vehicle would carry the resources back to orbit, probably to a space station as it would need to refuel. This option would eliminate the need for the collection vehicle to carry a heavy delivery device such as the CXV. The problem with this type of pick-up vehicle is that it might use too much fuel. The proposed collection vehicles that need a delivery system are less than a quarter of the distance (at most) to LEO (Low Earth Orbit). Also, Newton's Law of Gravity dictates that Earth's gravity only decreases by about 6% between sea level and LEO. Thus the pick-up vehicle would have to carry enough fuel get back to LEO from the collection vehicle, plus fuel to correct its trajectory as mentioned before.

A better option for delivery might be a device which launches materials into space using powerful magnetic fields such as a railgun. Railguns are currently used to simulate high velocity collisions in space, but could potentially be used to deliver resources into space. The problem with using a device like a railgun is that due to the unpredictability of wind and air resistance, the projectile fired from the railgun would need a way to decrease or increase its speed when it reaches space in order to correct any changes made to its trajectory by air resistance if it is to enter orbit. This could be done in several ways discussed later. It is also possible for a railgun to be very light as it is simply made from two parallel conductors carrying a current (see Chapter 8). The law of equal and opposite forces, however, would demand the collection vehicle to be capable of canceling out this force by remaining stationary. This opposing force could possibly be achieved by simultaneously firing an equal mass of unneeded gas in the opposite direction, assuming the ground is cleared below for safety.

In order to ensure the launched resources entry into orbit, the container fired from the railgun would either have to have its own trajectory correction system or else would have to be picked up by an already orbiting vehicle. A trajectory correction system could be many different things. It could be a fuel-based propulsion system, or another option would be to use induction in a way similar to how the space tether works, or it could be something completely different such as a solar sail, which would use the force of the suns photons reflecting off mirrors to push it in a desired direction. It is possible however that induction and solar sailing would not be strong enough to correct the trajectory in time for the resources to enter a reasonable orbit.

Chapter 7: Social Implications

Assuming that harvesting the atmosphere could be a successful venture and substantially decrease the cost of bringing oxygen and carbon dioxide to orbit, this would have a great impact on both the space program and the world. The most direct implications would be decreasing the cost of life support and agriculture for both the space station and the moon base. This would also allow for increased personnel to be sustained in space and for a more comfortable environment, as agriculture, similar to what is on Earth, and greater living space, will be possible. Visionary institutions such as NIAC (NASA Institute for Advanced Concepts) would gain credibility as well as funding for further research into advanced concepts.

The less direct implications are far-reaching and involve all aspects of society: commercial, public, and political. The success of lunar Helium-3 mining will create a great deal of commercial interest due to the immense potential of providing a new nuclear energy source for the next millennium. This would also encourage commercial interest in further space exploration and possibly even commercial interest in space as a vacation destination. After a brief period of helium mining, the government might create a private company to handle mining operations. This “capitalist” company would most likely be subsidized by the government to keep energy prices low enough to compete with energy companies run by socialist governments such as China. Oil producing countries will most likely suffer heavy revenue losses and this could possibly lead to political turmoil.

If helium-3 replaces fossil fuels as the primary source of electrical energy, the public of the United States will most likely view space exploration as a justified investment. This will encourage our nation's leaders to support advanced concepts in space applications such as more advanced space stations and bases on other planets. However, the public could also view the mining of the moon to be destructive and worry about consequences to future generations such as decreasing the Moon's mass enough to alter its orbit or its gravitational effects on the Earth. The public may also worry about polluting the Moon's surface and removing large quantities of gas from the atmosphere of the Earth. The issue of removing gases from the atmosphere will possibly be of great public concern. Many environmental activists may view this as disturbing the natural balance of the Earth's biosphere.

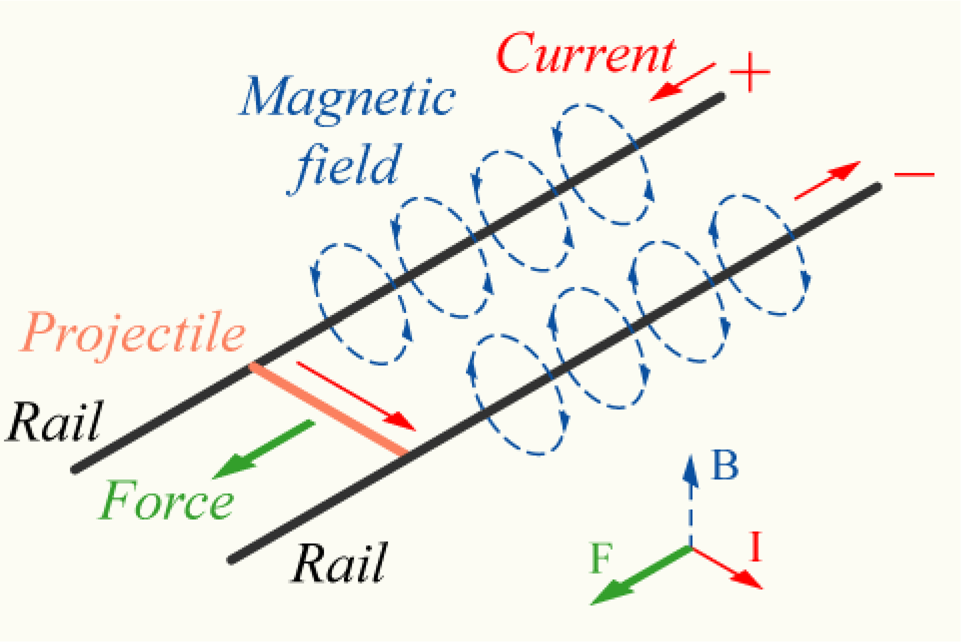
There will also be implications for the international community. First off, the United State's independence from foreign oil and the great energy potential of the moon will force other nations to consider improving their space program or even create one if they have not already done so. As so few countries have a space program, this will encourage international cooperation or a commercial space race. This will also encourage the international community to establish a trade system between the Moon and Earth. The Moon will send helium-3 to Earth and in return the Earth will send back resources such as hydrogen and oxygen. An international treaty may also need to be created to allow for collection of gases over given countries and protect against the spacecraft and aircraft of other nations entering their legal airspace. Assuming that eventually there are multiple moon bases owned and operated by various countries or commercial companies, the surface of the moon will need to be divided in some agreeable fashion. If the United Nations is designated as the agency to divide the moon amongst various parties, then its power will grow considerably. However, if the United

Nations is not chosen as this party, then whatever party is chosen to designate these areas will instead gain this significant political power.

Chapter 8: Other Possible Technologies

If harvesting the atmosphere proves not to be feasible, NASA must develop other options of delivering resources at reduced cost. Here are some other possible technologies that should be researched as alternatives for cheaply transporting resources into orbit.

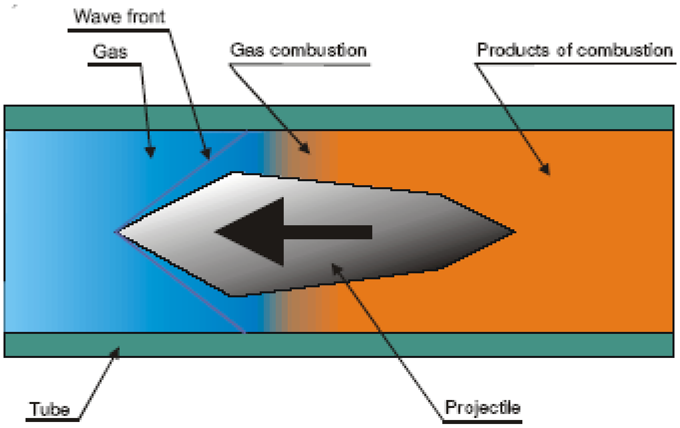
- Railgun – this is a simple projectile gun that utilizes two parallel rails with opposing currents generating a voltage potential between them. The basic construction is as follows:



Taken from http://en.wikipedia.org/wiki/Railgun

By passing current through the rails a magnetic field is induced. The projectile spans both rails and has the same current flowing through it. According to Lorentz's law, the magnetic field applies a force on the projectile propelling it out of the gun. This same principle may be applied to launch a projectile into space. The projectile will need to rendezvous with a second vehicle in space, or be capable of entering orbit on its own (see Chapter 6: Delivery).

- Ram accelerator – this is another type of projectile gun which uses ramjet technology to accelerate an object to high speeds.



The projectile starts in a tube and is surrounded by a gaseous propellant. The propellant is ignited behind the stream-lined projectile and causes an increase in pressure pushing the projectile forward. This has the potential to launch an object, perhaps filled with the necessary resources for the moon, into space (Kobiera).

- Gas balloon delivery – The basic premise of this concept is to fill a balloon with a gaseous mixture that is less dense than the surrounding atmosphere and attach a payload of resources to be delivered into orbit. Once the balloon reaches its maximum height, it will rendezvous with a space craft that enters into the atmosphere, picks up the payload and exits again into orbit. This idea is similar to the gas balloon collection vehicle but may be more efficient because it delivers the gases collected at ground level instead of carrying heavy collection equipment.

All of the technologies listed above show promising insight as other possible methods of delivering resources valuable to space habitation. We believe that further research into these technologies could offer alternative solutions to cheaply deliver resources into orbit.

Chapter 9: Conclusions

In order to further continue the exploration of space, NASA needs to develop cheaper ways of carrying resources to orbit than their current methods. However, due to the heavy weight of equipment needed to collect resources from the atmosphere as well as the rapidly decreasing atmospheric density with respect to altitude it is our conclusion that harvesting the atmosphere is not a viable option given current technology. There are several inherent tradeoff problems with the collection device that make it challenging in the extreme to meet all the constraints. As discussed in previous chapters, we have failed to find a cheap (energy efficient) method for collecting and delivering gases into orbit, which would not require breathtaking technological advances, some of which would make harvesting the atmosphere unnecessary, such as the space elevator or the mass accelerator.

The two greatest challenges to this concept are weight and energy. All of the collection vehicles discussed in chapter 5, with the exception of the dipping vehicle, have a common problem; they cannot sustain a heavy payload and they have to go slowly at low altitudes. The dipping vehicle has other equally challenging problems that raise questions about the possibility of doing more than breaking even on energy consumption. Current technology for filtration and compression of the atmosphere is massive. The combined weight of equipment and collected gases may be too great for the vehicle to sustain its altitude. If breakthroughs are made in solar power technology, this problem might be solved. Currently, however, a high power lightweight renewable energy source does not exist. While solar paneling might provide such an energy source in the future, the issue of delivering the materials that we have gathered into orbit will need to utilize other technology than solar paneling. The reasoning behind this is that a solar powered device can only reach altitudes of approximately twenty-four kilometers because they utilize propellers which require higher densities of air than is available above the stratosphere. If solar paneling, or another renewable energy source, overcomes this altitude limitation by finding a way of converting electricity to propulsion other than via propellers, then harvesting the atmosphere will be unnecessary as resources could be brought up with no non-renewable energy cost. There are other options for delivery that do not utilize solar paneling or fuel (see Chapter 6). Technologies such as the railgun and ram accelerator would obviate the need for harvesting the atmosphere as they could be fired from the ground (as opposed to from stratospheric levels) without a great increase in the cost of delivery to LEO.

In conclusion, we have not found harvesting the atmosphere to be a feasible solution to the current high cost of launching resources into orbit. While future advancements in technology may provide solutions to the challenges of harvesting the atmosphere, we believe that there are other more promising technologies being developed, such as those discussed in Chapter 8. We also believe that the implications of an inexpensive method for transporting resources to Low Earth Orbit are too great to be neglected.

Appendix A

Ratio of Air Density at Altitudes to Sea Level

Altitude (km)	Percentage Density Compared to Sea Level Density
0	100.0000000000%
10	33.8000000000%
20	7.3000000000%
30	1.4000000000%
40	0.3166000000%
50	0.0827900000%
60	0.0246900000%
70	0.0081980000%
80	0.0029790000%
90	0.0011690000%
100	0.0004897000%
110	0.0002172000%
120	0.0001013000%
130	0.0000493800%
140	0.0000250400%
150	0.0000131500%
160	0.0000071320%
170	0.0000039810%
180	0.0000022810%
190	0.0000013380%
200	0.0000008029%

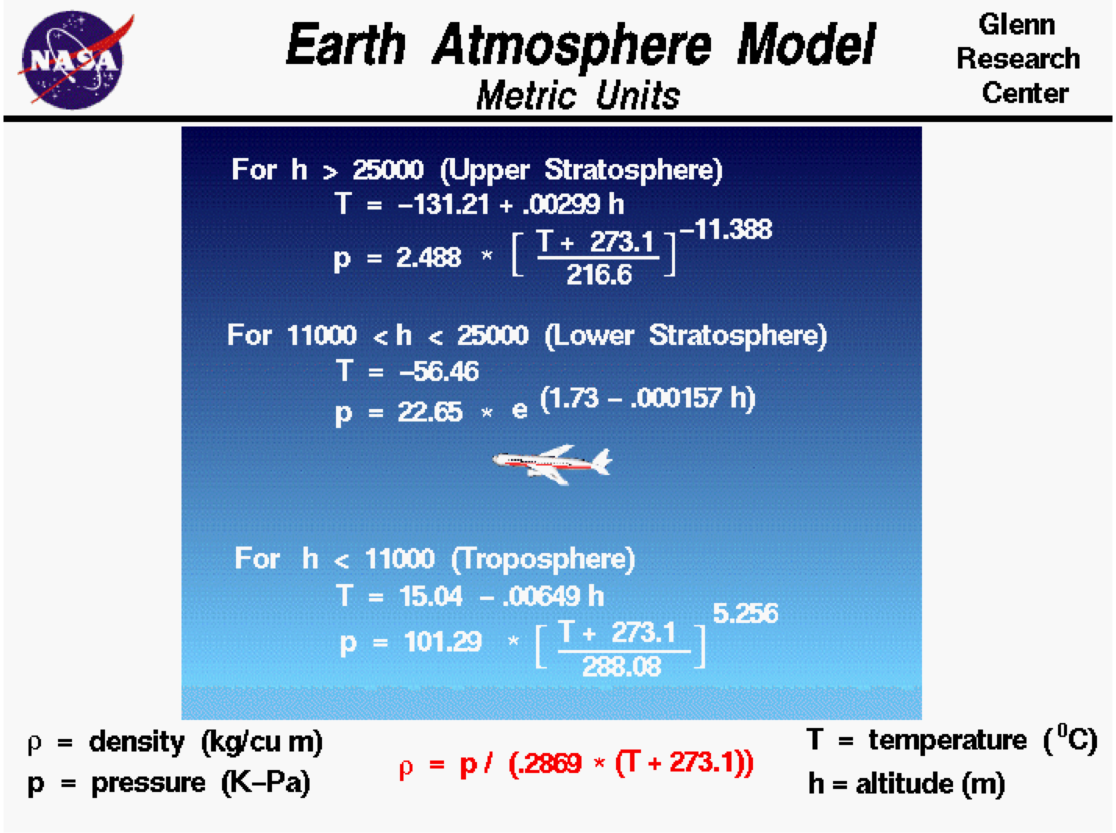
Appendix B

Composition of the Atmosphere

Constituent	Chemical Formula	Molecular weight	Percentage of this constituent in the atmosphere, by volume	Total mass of this constituent in the whole atmosphere (grams)
Nitrogen	N_2	28.0134	78.084 %	$3.866 * 10^{21}$
Oxygen	O_2	31.9988	20.948 %	$1.185 * 10^{21}$
Argon	Ar	39.948	0.934 %	$6.59 * 10^{19}$
Carbon dioxide	CO_2	44.00995	0.0315 %	$2.45 * 10^{18}$
Neon	Ne	20.183	0.001818 %	$6.48 * 10^{16}$
Helium	He	4.0026	0.000524 %	$3.71 * 10^{15}$
Methane	CH_4	16.04303	0.00015 %	4.3×10^{15}
Hydrogen	H_2	2.01594	0.00005 %	$1.8 * 10^{14}$
Nitrous oxide	N_2O	44.0128	0.00003 %	$2.3 * 10^{15}$
Carbon monoxide	CO	28.0106	0.000012 %	$5.9 * 10^{14}$
Ammonia	NH_3	17.0306	0.000001 %	3×10^{13}
Nitrogen dioxide	NO_2	46.0055	0.0000001 %	$8.1 * 10^{12}$
Sulfur dioxide	SO_2	64.063	0.00000002 %	$2.3 * 10^{12}$
Hydrogen sulfide	H_2S	34.080	0.00000002 %	$1.2 * 10^{12}$
Ozone	O_3	47.9982	~ 0.00004 % (variable)	$\sim 3.3 * 10^{15}$
Water vapor	H_2O	18.01534	~ 0.5 % (variable)	$\sim 0.017 * 10^{21}$
Total atmosphere	-	28.9644 (average)	-	5.136×10^{21}

Note: Percentages do not add to 100% due to the variability of water vapor and ozone in the atmosphere. (Taken from http://othello.mech.northwestern.edu/~peshkin/scifair/Atmosphere.html)

Appendix C



Earth Atmosphere Model

Metric Units

Glenn
Research
Center

For h > 25000 (Upper Stratosphere)

$$T = -131.21 + .00299\,h$$

$$p = 2.488 * \left[\frac{T + 273.1}{216.6}\right]^{-11.388}$$

For 11000 < h < 25000 (Lower Stratosphere)

$$T = -56.46$$

$$p = 22.65 * e^{(1.73 - .000157\,h)}$$

For h < 11000 (Troposphere)

$$T = 15.04 - .00649\,h$$

$$p = 101.29 * \left[\frac{T + 273.1}{288.08}\right]^{5.256}$$

ρ = density (kg/cu m)

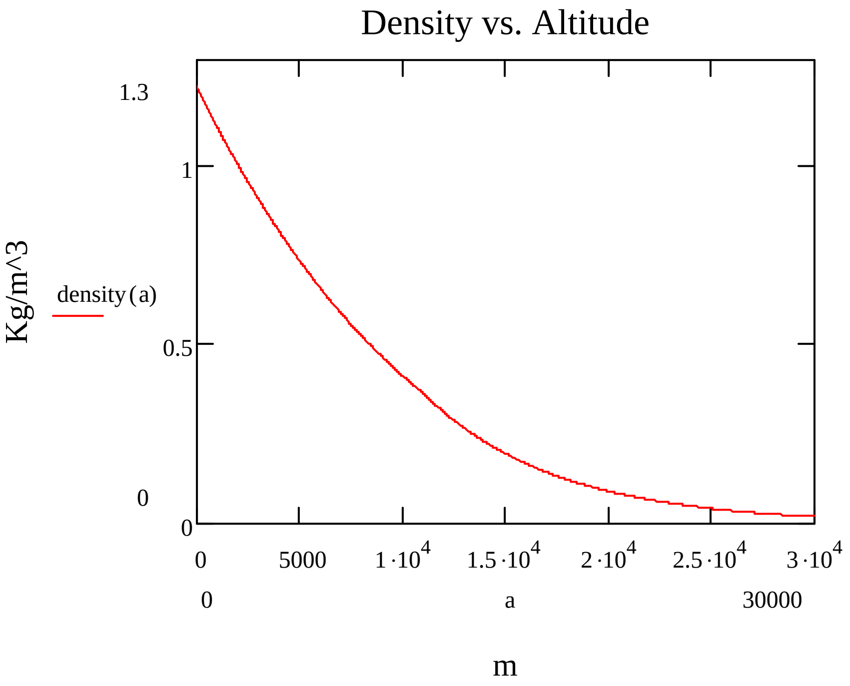
p = pressure (K-Pa)

$$\rho = p \,/\, (.2869 * (T + 273.1))$$

T = temperature (^{0}C)

h = altitude (m)

This model was taken from
http://www.grc.nasa.gov/WWW/K-12/airplane/atmosmet.html



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