Project Number: JMW-HAHF

THE LOW EARTH ORBIT ATMOSPHERIC GAS HARVESTER

An Interactive Qualifying Project Report

Submitted to the Faculty

of the

WORCESTER POLYTECHNIC INSTITUTE

in partial fulfillment of the requirements for the

Degree of Bachelor of Science

by

Brendan Malloy

Thomas Huynh

Brian Kolk

Date: March 3, 2007

Professor John Wilkes, Advisor

Abstract

This is a technology assessment investigating the feasibility of a space craft capable of extracting oxygen (and other gases) from the lower exosphere. Key components that would be required to operate such a spacecraft were researched to determine if the concept was technically feasible and economically viable as a profit making venture. The resulting study of existing and emerging technologies led us to conclude that an unmanned gas harvester in low earth orbit is indeed feasible. It is also potentially profitable and would have profound socio-technical implications.

Table of Contents

Chapter 1: Overview

The purpose of this research is to investigate the technical feasibility and relative cost of gathering valuable gases (needed by the space program for propulsion and life support) from the upper atmosphere or lower exosphere at altitudes in Low Earth Orbit. The alternative of lifting them from the Earth's surface is very expensive. Current spacecraft need to consume 80-90% of their initial fuel supply in order to reach Earth orbit. The ability to cheaply replenish fuel and oxidizer in orbit would increase the range of current and future spacecraft and provide the basis for a new space industry. It might even lead to a new space based trade system and service economy.

This project report will focus on methods of gathering, filtering and distributing the various gases as they separate and escape into the higher layers of the atmosphere. We will proceed from the assumption that the gathering and separation equipment would be in Low Earth Orbit (LEO), but could move higher or lower in the atmosphere as needed. We will first attempt to determine if it is possible, and then if it might actually be cost effective to harvest valuable gases from the upper atmosphere to support space activity in Earth orbit, on the Moon and beyond. In particular, such an undertaking should not only be less costly over time than the current means of transporting these materials to orbit, but it should also create the infrastructure for a profitable space trade market.

The market that the harvester will initially appeal to is in Low Earth Orbit. Refueling research satellites, telecommunications satellites, GPS, weather satellites and spy satellites could prove to be a very lucrative initial market. Currently, most satellites carry sufficient fuel to make enough reboost burns to live out their intended five to ten year lifespans before they slowly succumb to atmospheric drag and burn up on re-entry into Earth's atmosphere. If these satellites could instead be refueled (as well as upgraded, refitted and repaired) periodically so that they could maintain orbit and functionality, the companies and governments that utilize them could become major buyers of our product, liquid oxygen, and other related services that could accompany a refueling mission. If our refurbishing and resupply methods prove to be cheaper than building and launching a new satellite, the financial success of this entrepreneurial venture is likely. The International Space Station and the NASA space shuttle, as well as the space craft from countries like India and China that are looking to enter the space race to the moon in the near future, could also effectively utilize our product. The ISS needs to periodically reboost just like the satellites do, but since it is such a major investment it is designed for a much longer life span than a simple telecommunications satellite. Currently, fuel is launched from Earth in order for it to maintain orbit. The ISS could be a very visible customer and perhaps even a testing platform for key components of our harvester.

Current and future manned spacecraft will likely form a very different and equally important market for liquid oxygen. Since most of their fuel is used just to reach low earth orbit, their range and maneuverability in space is severely limited. If the space shuttle or, even better, a new Single-Stage-To-Orbit space craft could be completely or partially refueled while in orbit, their range of operation and time spent in space could be greatly increased.

Another promising market of the future will be the lunar habitat. Nitrogen is a key ingredient necessary to make fertile soil and a self-sufficient moon colony will need at least a large initial supply in order to sustain plant life on the moon. Oxygen will also be a key component to a successful lunar colony. It is necessary not only for life support but also for making water and running air breathing machines with internal combustion engines. Oxide rocks are common on the moon but it requires an immense amount of energy to harvest oxygen from them. If our methods are more cost effective, a relationship with organizations operating on the moon could prove to be quite profitable.

1.1 Branching Off from the Past

This is not the first time that the idea of an atmospheric harvester has been explored. This project is the continuation of a previous IQP study that looked into this very problem, albeit from a different angle. The study Harvesting the Atmosphere by Andrew Port, John Scimone and Geoffrey Verbeke was a general technological investigation into the idea of harvesting gases from the atmosphere. They concluded that harvesting the atmosphere could not be done, or could not be done in a manner that was efficient enough to be worth doing.

There were some self-imposed restrictions that affected their feasibility study. They stressed looking into technology that already existed and their interpretation of the atmosphere was not completely accurate. While they were aware of how the atmosphere's density changed with altitude, they assumed that there was an "edge of space" around 100km and ignored the atmosphere's qualities at higher altitudes.

The fact that the previous study was largely restricted to modest extensions of present day technology is key to understanding their conclusion. This kind of assumption immediately closes the door on a whole world of useful breakthroughs that are already in the works and forces the potential implementation of technology that will be out-of-date by 2020. This was especially apparent when examining the actual gathering vehicles that were considered for the job. An undertaking such as this cannot be done effectively by conventional means. If it could we'd already be doing it, and no breakthrough would be required.

Two of the vehicles for a gas separation system considered by last years team were the Pathfinder Plus, a solar powered, propeller driven airplane, and a gas filled balloon, the latter of which was ultimately concluded to be the better option. The main flaws with both of these are that they can only reach about 30km, an altitude nowhere near Low Earth Orbit, and it is unlikely that either could hold aloft a significant amount of weight. Since their maximum attainable altitude is so low, delivery of product to orbit becomes a major problem. Their only solutions to getting the payload to orbit were either launching a container on a rocket that was mounted on one of these vehicles, or using a railgun.

The idea of the rocket is simply counter productive even if you ignore the additional weight it would put on each aircraft. The mission is to gather fuel and repeatedly launching a rocket would mean burning some of their own fuel. The use of a railgun would essentially be an admission of defeat to a competing launch technology. The purpose of designing a high-altitude gathering vehicle is to avoid the need for such a delivery system.

The railgun would have to be mounted on Earth, which would allow for all the gas gathering and production to be done on the ground and then launched to orbit. The purpose of a harvesting system is to make it possible to refuel in orbit *without* having to launch oxidizer from Earth. In order for harvesting to be done effectively, the entire infrastructure must be in Low Earth Orbit.

The previous study did examine one method for harvest from orbit but decided it had too many flaws to be worth implementing. This system involved a spacecraft being launched from a space station and dipping into the atmosphere as low as it could, and coming to a near stop. Here it would either hover or move very slowly as it gathered and processed the air. After filling its oxygen tanks and ejecting waste gases such as nitrogen, the craft would use boosters to reach orbit and dock with its space platform and deposit what had been gathered for further processing into liquid oxygen. This method requires a craft that is both aerodynamic and strong enough to withstand all the stresses of re-entry and repeated boosting back in to orbit. This system is also counter-productive since it requires the vehicle to burn fuel, and would therefore be refueling on the same gases it was harvesting. Since the vehicle would be taking in a large amount of air during the dive, they found that it wouldn’t actually be aerodynamic at all and require constant course adjustments, which would burn even more fuel. In the end they decided they would use all or most of the fuel gathered and could not hope to do more than break even.

1.2 Emergence of the New Question and Introduction to Paul Klinkman

All of the previously considered systems for gathering atmospheric gases were based on one key assumption. It was believed that the composition of the atmosphere did not significantly differentiate with altitude. That is, whether you took a measurement at sea-level or at one hundred kilometers, you would find roughly the same ratios of nitrogen, oxygen, hydrogen and the other gases. The only difference in the measurement at the different altitudes would be the densities of the gases. Our team took on this project with the same basic assumption about the atmosphere and we initially assumed the need to harvest at as dense an altitude as possible. That changed when we were introduced to Paul Klinkman.

Paul was brought on as a sponsor and technical advisor to the project. He graduated from Worcester Polytechnic Institute in 1976 with a BS in computer science and later received an MA in political science and a MS in computer science from the University of Rhode Island. Paul is an inventor whose research and technical design interests focus on solar power and space exploration. He had already been working on the idea of an atmospheric scoop several months before he was brought on as a technical advisor and sponsor to this project. His previous and continued research proved to be invaluable during the development of this Low Earth Orbit atmosphere harvesting system.

The most significant piece of data that Paul brought to our attention was about the make up of the atmosphere. We had assumed that because we wanted to be able to harvest from orbit, the only way to effectively gather any gas would be to dip into some of the denser areas of the atmosphere. Paul's research showed that, while we were correct about the atmosphere's exponential decrease in density with increasing altitude, we were mistaken in believing that was where the important details ended. What in fact occurs in the higher altitudes above one hundred kilometers is that the various gases that make up the atmosphere begin to differentiate into layers based on their densities. While nitrogen is the most prevalent gas at sea-level, other gases (such as oxygen) predominate at altitudes most people don't even acknowledge as still within the Earth's atmosphere.

This new information completely changed the nature of the problem. It allowed for an entirely different approach to the harvesting the atmosphere. Rather than being forced to dive into a lower altitude where the air is more substantial, we could instead target a higher altitude that contained a layer rich with the particular gases we wanted to harvest. Since these layers exist at orbital altitudes the questions of how fast the harvester needs to be going during a dive in order to be able to reach orbit again and how much could be gathered during a single dive became irrelevant. The new vision of harvesting the atmosphere became steady, constant gathering at a fixed orbit of 400km, where the oxygen concentration is highest (see Appendix A), for years at a time. The gas gathering idea had changed from the aerodynamically impossible to technologically viable and economically promising in a single meeting.

The project was no longer a general overview and feasibility study of the idea of harvesting the atmosphere. It had become something much more concrete and specific; we had an invention concept to assess. Using Paul's prior research and guidance we were able to focus on what such a system would have to do and what it might look like. Our job was to conceive of a paper prototype system for gathering gases while in Low Earth Orbit suitable to support a patent application. Our investigation turned to researching some of the key components of the harvester that would be vital to its success, both technically and economically.

1.3 The Team's Role and Baltimore

When Paul was brought on as technical advisor and sponsor to the project, he brought with him a general idea for harvesting the atmosphere. Feasibility assessment and fine tuning were needed in order to create the much more elegant and convincing gathering system we were left with at the conclusion of the research necessary to support a patent claim. During the weekly meetings, we worked closely with Paul as we tried to decide what the key components of this space craft would be. The team's job was to question Paul's ideas during brainstorming sessions in an effort to gain a better understanding of the mission as a whole as well as trying to flesh out ideas that were not previously considered.

Due to the largely positive outlook that we had as to the potential success of this mission, undoubtedly caused by the information Paul presented regarding the atmosphere, we were no longer trying to prove that harvesting was technically possible but rather whether it could more than pay for itself and be profitable, as profit potential would justify a new company. The team's responsibility still included trying to find the major problems that could prove the atmospheric harvester to be a technical impossibility but the focus was now on elegance and economics. We had to be cost effective.

After most of the major research and brainstorming was completed, we accepted an offer to present part of our project at the International Association of Science, Technology and Society convention in Baltimore, Maryland. The IASTS is an organization that focuses largely on understanding the social impact of scientific and technological change of the past, present and future. We were asked to create an informative presentation regarding a proposed Low Earth Orbit gas harvester that explained some of the technical details of our work as well as laid out some of the ways we believed society would change and benefit from this breakthrough invention. We also learned that our work had unexpected implications for the fields of "Technology Assessment" and "Forecasting Technological Change" (Flaherty, Luca, Monfreda, 2007).

Still, the main focus of the presentation was to support the idea that the age of the space entrepreneur had arrived. We realized that if this harvester were ever implemented its goal would be make money and turning a profit with a space-based production infrastructure is not something that has ever been done before. Ventures such as landing on the moon and the construction of International Space Station, while excellent examples of the development of space technology, have not produced any real economic return. The Apollo missions cost an enormous amount of money to fund and even though reaching the moon was an amazing accomplishment, people have questioned whether what we gained in return was really worth the price? The ISS was expensive to build and continues to be expensive to maintain. It does provide a place to perform experiments that some may consider invaluable to science but is that knowledge worth the nearly 30 billion dollars that have been spent? The proposed harvesting system has the capability to, at the very least, pay for itself and quite possibly create a profitable industry if implemented successfully. So far, only information gathering and relay satellites (communications, weather and Earth sensing) have made money. We want to generate goods and services for a new emerging market.

While the notion of forming a new space faring company leading to a lucrative space industry might have been interesting to certain audiences, we realized that the members of the IASTS were going to be more interested in the ways society would benefit from the technology we were claiming was possible. We cited examples of things the harvester could work with in tandem as a refueling vehicle for satellites, the ISS and especially the space shuttle and the up and coming Single-Stage-To-Orbit space vehicle. Significant uses also arise during the development of the lunar habitat. The need for resources on the moon might just lead to the formation of the first trade system in space if the harvester was able to satisfy some of the needs of a lunar colony that exports something to Earth.

The experience in Baltimore was definitely a positive one. The presentation was well received by all those in attendance and seemed to stir quite an interest in the idea of harvesting gas from the exosphere. The stir was due to the fact that even the few space enthusiasts present had never heard of this idea before that morning. The reaction we received in Baltimore further acknowledged the potential we knew this invention had and got Paul recognition for his innovative idea. The project's academic schedule had served as a deadline to push him to get the idea to the point of having the patent application submitted and pending so that we could speak openly about his idea in this report and in Baltimore. For that, he thanked us.

Chapter 2: The Low Earth Orbit Atmospheric Harvester

For several months we held weekly meetings to discuss both Paul's ideas for how a Low Earth Orbit atmospheric harvester would work and to consider the social implications such a device would undoubtedly have for the future of space industry. We decided that our time would be best spent researching and discussing the components of the harvester that were vital to its success. Our job was to prove that all the critical components were within the state-of-the-art or a short extrapolation of it. These key pieces of technology needed to be simple, efficient and reliable in order for the harvester to remain operational for the intended ten year life span. The duration of operation will have a significant impact on the harvesting system's ability to generate profit, and paying for itself is a goal that too often eludes space ventures.

2.1 The Maw

The maw is the device in the front of the harvester that acts as a scoop that will collect all the gas particles. The maw is tentatively planned to be 100 feet in diameter and 200 feet long. The 100 foot diameter is determined by the density of the gas at the altitude we are operating at (400km) and the amount of gas we want to collect in a given amount of time, about 100 tons per year.

The maw and the gas particles, which are highly energetic at 600C, will not behave like a scoop traveling through a fluid. Instead, the particles will act as individual atoms and thus make things a little more difficult in the capture process. When a particle in this situation bounces off a loose atom or the wall of the maw, it will travel off in a random direction at high velocity. The long length of the maw will help keep the encountered particles from escaping the harvester. There will be an existing cloud of particles placed inside the maw that will help control the activity of the incoming particles. The cloud of particles will be nano-particles that consist of 100 silicon atoms which vastly out mass any oxygen atom that are incoming. Thus, this cloud of nano-particles won't be lost into space and can stay inside the maw to help slow and capture the oxygen atoms. Incoming particles will bounce off the walls and the cloud of particles in the maw until they loose enough energy to be susceptible to travel with the flow of the particles into the harvester. Some incoming particles will hit the cloud of particles in the front end of the maw, bounce out and not be captured, though a 90% capture rate of incoming particles is expected. Given that 80% of the captured particles will be oxygen, that should suffice as a rate of capture.

To help with the capture of oxygen atoms, a Langmuir pump will be placed at the end of the maw. This pump is capable of working at very low pressure of atmosphere and will draw a steady flow of atoms into the harvester. The particles being used as the cloud in the maw to slow incoming oxygen particles will be filtered out and cycled back to the other end of the maw, so they can continue to slow incoming oxygen particles indefinitely. Figure 2.3 shows the heavy particles along the side of the maw being used to create a flow into the Langmuir pump.

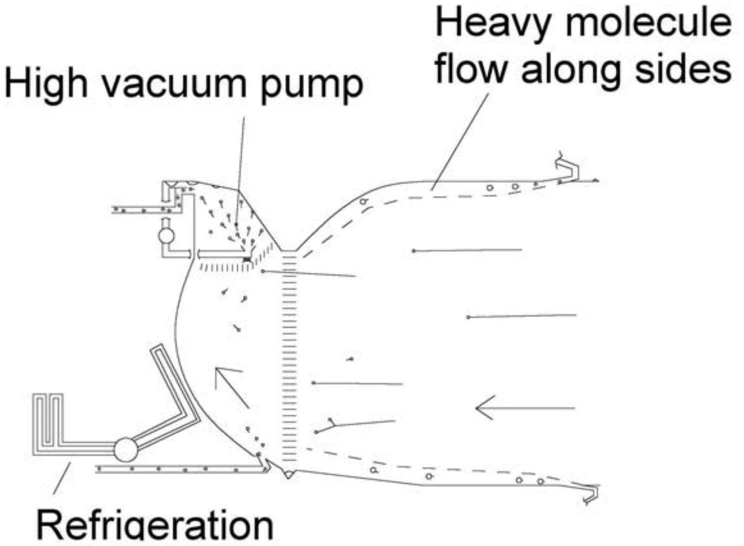


Figure 2.1

The walls of the maw will encounter heavy friction due to the loss of energy from the very hot incoming particles and therefore the walls will heat up quite a bit and need to be cooled. The cooling for this part of the system will be encompassed in the design of the cooling radiator onboard for the system as a whole. It must be capable of bringing the 873K particles down to 90K. The total load will be about what was anticipated because after coming down the maw the particles will be at a lower temperature because of the loss of kinetic energy. Cooling the maw and particles together will be the equivalent of cooling just the particles by 90%.

The outside of the maw will be constructed of a material resistant to space junk collisions and Kevlar should suffice. The inner side of the maw will need to be made of a material able to efficiently transfer heat and also able to resist space junk impacts that may enter the maw as well. A tough copper alloy would be able to do both these jobs sufficiently.

While the harvester is in low earth orbit, operating continuously year round, it will encounter, periodically, solar storms where harmful radiation will be thrown at the spacecraft. To cope with this phenomenon, the maw should be able to close down for a while by having the one side close against the opposite side, protecting itself from the harmful effects of a powerful, but short lived, solar storm.

2.2 Propulsion

The propulsion system is by far the most technically delicate component onboard the Low Earth Orbit Gas Harvester but without it, the device is not an elegant solution. As the gas particles we are collecting impact the maw, our gatherer will begin to experience aerodynamic drag forces. These forces will slowly cause the harvester's orbit to deteriorate until it eventually deorbits and burns up in the atmosphere. Because our goal is to harvest gases to be used as fuel, the propulsion system not only needs to restore all the momentum lost to drag forces, but also consume as few resources as possible in order to maximize the amount of product that can be sold. Ideally, one does not want to burn any fuel to stay in orbit. Upon considering these essential facts, we soon concluded that an electrodynamic tether (EDT) was the ideal method of propulsion, and just because it had not been done before did not mean that it wouldn't work. The concept was well established in the literature.

An electrodynamic tether is a long wire extending from a satellite or other space craft that is capable of turning electrical energy into kinetic energy. The benefits of using the tether are immediately apparent. Its greatest advantage is that it is an entirely propellant-free form of propulsion. This keeps the harvester from burning off some of the fuel it is harvesting in order to maintain orbit, maximizing production. The lack of a conventional engine also avoids producing pollution in the area of space being harvested, which could degrade, corrode or clog the gatherer over time. This approach also reduces the stresses the harvester would need to withstand if undergoing repeated reboost burns. Since the main goal of the mission is to gather oxygen, a potentially volatile chemical, the risk of catastrophic failure caused by a problem during a burn is also eliminated. In short, it is an elegant solution to a key problem.

The design of an electrodynamic tether is very simple. A long, 7km-10km wire is extended from the body of the harvester with the counterweight attached at the opposite end. A current of appropriate magnitude, provided by solar paneling, is directed down the length of the tether. According to a NASA report investigating the proposed use of a tether on the ISS:

> The EDT can work as a thruster because a magnetic field exerts a force on a current-carrying wire ($\mathbf{F} = l\,\mathbf{IxB}$). This force is perpendicular to the wire and to the field vector. If the current flows downward through the tether connected to the [space craft], the force exerted by the geomagnetic field on the system has a component that accelerates the [space craft] along the direction in which it is already moving.
>
> **- Johnson and Hermann, 1998**

The same report suggests a 10km tether running a current of 5kW to 10kW could produce thrusts up to 0.5N to 0.8N respectively. The ideal material for the tether is carbon nanotubes, which cannot be manufactured to the necessary dimensions with current technology but a major improvements are likely be made so the capability may exist in time for this mission’s launch. A substitute material called Dyneema, a strong, crystalline plastic, could be used for a prototype as it has already been proposed in some tether designs.

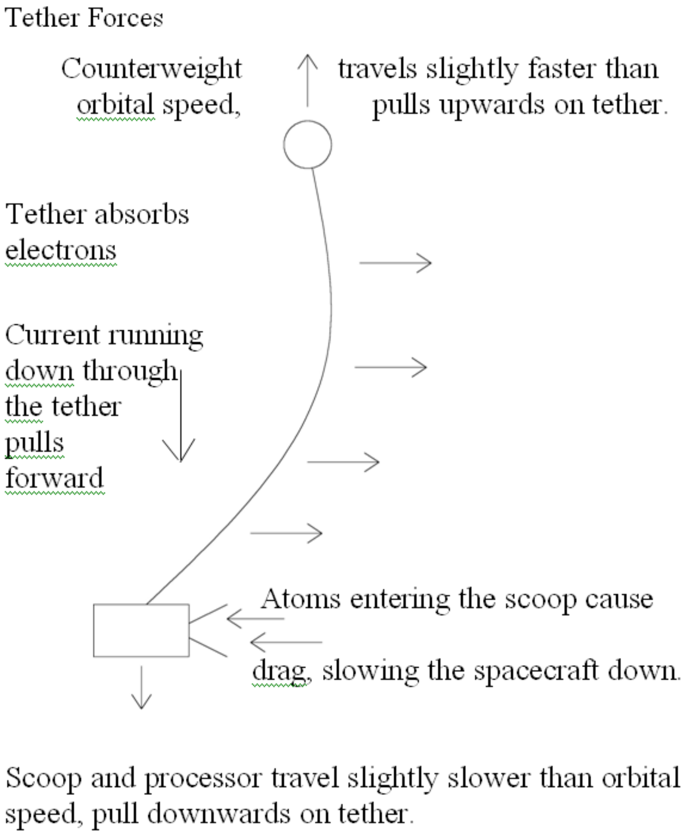


Figure 2.2

The problem with using an EDT for propulsion is that a tether has never been tested for this function. The mission's success rests on the shoulders of this promising, but not yet flight tested, and hence unproven technology. It is also a bit uncertain as to whether a single EDT will be able to output sufficient thrust to overcome the momentum lost due to particles colliding with the harvester's maw. A possible solution could be to attach multiple tethers to the harvester but the dynamics of a multi-tether space craft need to be investigated. The tether also faces the possibility of being severed by space debris and micrometeoroids. In order to prevent tether failure from the single collision, the tether should be a spaced, multi-strand wire. If a complete break were to occur, the tether would likely recoil, possibly causing physical damage to the harvester or altering its course. A system, similar to one recommended for use on the proposed tether for the ISS, for detaching the tether after a break could be installed to prevent the repercussions of such a break. It is evident that adopting this elegant technology carries an element of risk. Thus, provisions for replacement, backup or redundancy with an alternative booster system have to be considered.

2.3 Processing

Though outer space is commonly thought of as being extremely cold, the few gas particles that are present are actually very energetic. Figure 2.3 shows the temperature of particles in Celsius as a change in altitude occurs. Since the spacecraft is operating around 400km the particles collected will be around 600C or 873K. The gas collected at this high temperature will have to be cooled to separate the different kinds of gas particles and make it more manageable to store and use, as current rocket designs use liquid oxygen and not gaseous oxygen as the oxidizer.

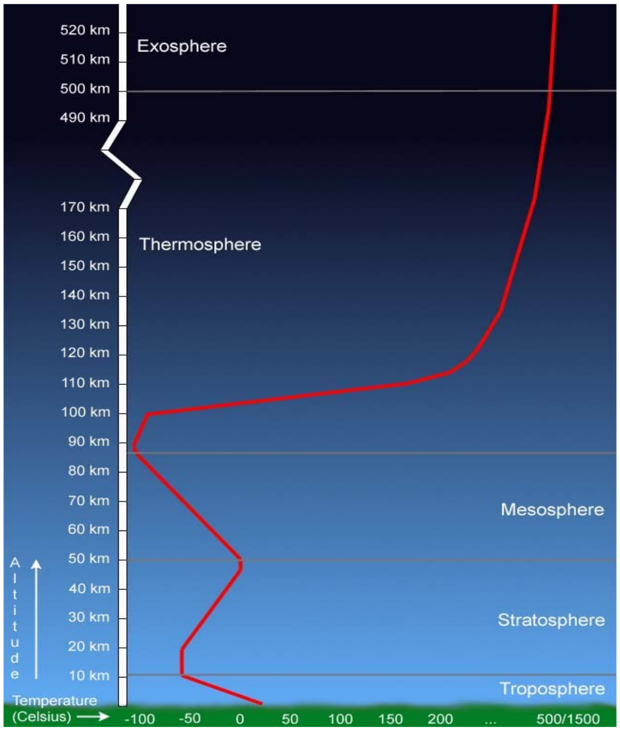


Figure 2.3

The gas will be cooled from 873 K (the temperature it is at when it is collected at 400 km) to 90K while compressing it to 22psig to match that of the storage on the space shuttle external tank. This process will have two benefits; it will separate each gas into its own tank and also transform each gas into a more usable form (liquid).

The process of cooling and compressing the collected gas will also separate all the gases we collected because of the different boiling points each possesses. As the temperature drops, the nitrogen and oxygen and other gases will turn to liquid at their own distinct temperatures, when each of these occurs the specified gas can be drained and stored in a tank.

To achieve this cooling and separation process we will need large radiators to get rid of the heat in the energetic particles. Unfortunately radiators in space do not work exactly like they do on Earth. On Earth they take advantage of convection heat transfer (forced cooling) to a large reservoir of liquid or air that allows for much faster cooling of the specified object compared to the conditions one has to deal with in low earth orbit. In low earth-orbit there is no excess reservoir of air or liquid surrounding the harvester that could be used as a coolant in the heat exchanger cycles. The only means to get rid of the excess heat is simply radiate it out to space. The cooling process with only radiation and no convection cooling takes a much longer time to achieve the same result. Figure 2.4 below demonstrates this with plotting the cooling of a resistor vs. time using the different cooling methods of convection and pure radiation.

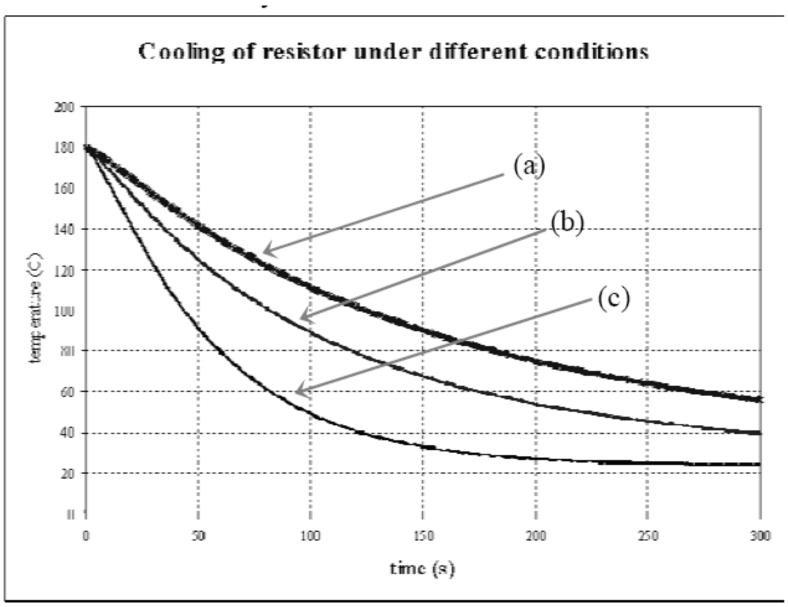


Figure 2: Cooling curves for (a) cooling in vacuum, (b) natural cooling and (c) forced cooling

Figure 2.4

Although this is an experiment in keeping a resistor cool, the principle is the same for the cooling of anything using these methods. The time required to cool an object using just radiation in a vacuum scenario is much longer than compared to a scenario on earth using convection (forced cooling) method. The scenario of the vacuum is what we have to deal with on the harvester in low earth-orbit.

While in some stages of the cooling process, on the harvester, a liquid medium in a heat-exchanger stage can be accommodated, eventually all the heat we started with will have to be radiated out to space before that liquid can be reused in the radiator again for cooling. It will require a large surface area radiator to accomplish this. In addition, the gas will have to be cycled through many heat exchangers multiple times, as one pass through a heat exchanger will not produce the desired result.

As reference, there is a HRS (heat rejection system) being looked into as the cooling system on a nuclear electric propulsion technology that could be used on the proposed harvester. This is a good technology to look into because it is being planned for a nuclear drive which produces a lot of heat that needs to be removed and the HRS is being designed to operate between 600-875K which encompasses our beginning temperature of 873K. The HRS being designed on the nuclear electric propulsion technology is set to be 170m^2 surface area, which dominates the size of the total spacecraft. A large surface area is needed with as many small fins as possible to maximize radiation cooling. As mentioned before, a liquid present in a heat-exchanger can speed up the process, though it creates a backlog of coolant to re-cool. The HRS uses NaK as a coolant, which has a high specific heat, optimal for heat transfer.

The problem of processing the gas will not be the bottleneck for the unmanned harvester spacecraft being able to function. Through current and emerging technology of radiation cooling in space, the gas collected can be separated by cooling it. The only question is how large (and expensive) the radiation system will have to be to process gas at the required rates.

2.4 Distribution

The first part of the process of distribution for the gases is when each gas is drained into its own storage tank in the filtering process on the harvester. One possibility is that these tanks will be completely detachable to be moved and attached onto some other spacecraft for use. A separate transport vehicle would probably be used for moving the tanks. Depending on how much gas we are able to collect and how quickly, a separate space platform may be set up as a place to hold the storage tanks while they wait to be purchased and picked up by visiting spacecraft. Again, a transport vehicle could be used to move the tank from the harvester to the platform. This platform would not be manned permanently, but perhaps man-tended every few months.

These are a few possible methods for distribution of the gas collected. None of them have been picked as the best method since more research is needed to decide on one. The point is that this is a problem solvable within the current state of the art of space technology. No breakthroughs are needed, just an assessment of the tradeoffs involved.

2.5 Feasibility

Based on current technology and the assumption that specific improvements and breakthroughs will be made, we believe that the Low Earth Orbit Atmospheric Harvester is an entirely feasible production system. It is capable of having a significant impact on the space industry, not only with the service it provides, but also with the individual technologies it displays. The EDT and cooling radiator will definitely have broader implications. Ironically, the success of our tether propulsion system could cut into own future market for reboost fuel needed by other satellites and space platforms. Thus, the gas harvesting industry we envision will have to keep innovating and adjust to developing opportunities and technologies as they arise. Still, there is a good initial market to develop the cash flow required to support that kind of research and development.

We realize that technical problems still need to be addressed in future, more in depth studies, but we are confident that solutions will be found during the testing phases of the major components. For example, we know that the materials necessary to create the harvester’s maw exist, but the interaction between the air particles and the maw need to be studied in great detail. The electrodynamic tether, while not the only possible form of propulsion, greatly increases the mission's effectiveness but it is an unproven technology. Significant testing is needed in order to justify basing the mission's success on such an underdeveloped propulsion system. Finally, we know that radiating heat into space during the processing stage is difficult with present technology; but with nuclear drives in development, we believe that the problem must and will be solved. When it is, similar radiators can be adapted to fit the needs of gas harvesters.

Chapter 3 Discussion

3.1 Social Implications

3.1.1 Profitable Venture

Launching anything into space is very expensive. However, this is expected to change with breakthroughs in science and technology. The atmospheric harvester is one of these new technologies that can drastically decrease the costs of maintaining spacecrafts in earth orbit and may decrease the costs of moving objects from low earth orbit to geosynchronous orbit. This is an infrastructure technology that can support itself. We envision a commercial setup utilizing the atmospheric harvester that will collect oxygen gases and compress it in to liquid oxygen, which is needed for a variety of functions in space.

The current cost of shipping a payload into space varies depending on the mode of transportation. There are several options including manned and unmanned system launches, however, the most important factors are the space transporting vehicle and the destination of the payload. The main current choices are either the space shuttle or different classes of unmanned rockets that can deliver the payload. The space shuttle is tremendously more expensive than the expendable launch vehicles normally used to put satellites into orbit. It is only used when the mission needs to be manned. Manned missions are generally required for space laboratory experimentation and the assembly or repair of space structures. The delivery of payload is usually accomplished by unmanned missions. With the conventional unmanned rockets, the cost of lifting payload to LEO is approximately $10,000 per pound of material. The destination of the payload, whether to low earth orbit or geosynchronous orbit also greatly influences the cost of the mission.

For most missions into space 95% of the fuel is spent getting into space, leaving a meager 5% for the mission, maneuvering, and returning to earth.

With the implementation of the atmospheric gas harvester, we will (in principle) be able to replace all the LOX used by these vehicles and other spacecrafts. This is important because LOX is 80% of the mass of the fuel by weight in most current systems of both solid and liquid rocket fuel. A fresh supply of LOX will increase their range and the duration of missions in space. Most importantly the introduction of the atmospheric harvester may be the first profitable space production venture in the history of the space program.

For example, Russia's Proton rocket can carry a maximum of 45320 pounds of payload to LEO. In order for the Proton rocket to reach GEO, it would have to take a smaller payload and replace that weight with fuel so that it will be able to reach GEO. In fact, most rockets can only take half to one quarter of the weight from LEO to GEO. The atmospheric harvester will provide a means to refuel the rocket so that it will be able to lift close to its original maximum payload capacity into GEO by refueling its oxygen tanks (it will still need to carry more of the other liquid fuel components). This will help alleviate some of the problems of accessing GEO, which is problematic for rockets lifting off for GEO directly from earth. The result is a tremendous cost reduction to GEO as the Proton now has one of the most cost efficient payloads to LEO ratios.

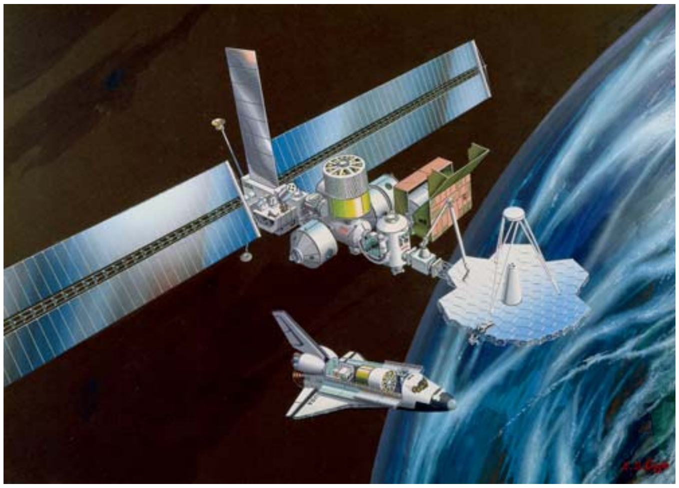
The only space structures that are currently being refueled in space are space stations. The US uses the space shuttle to deliver supplies, including oxygen and the Russians used the unmanned Progress rocket as a freighter. However, since there is currently no other refueling station in space, the atmospheric harvester will generate a new market because there are no competitors. We think it will also be the first space venture to make money.

Country or Agency	Name	Cost ($ millons)	Payload to LEO (lbs)	Payload to GEO (lbs)	Success Rate	Manned Capability?
Russia	Proton	50	45320		89.66%	Yes
China	Long March	59	20240		90%	Yes
USA/Orbital	Pegasus	25	1000		94%	Yes
USA/Orbital	Taurus	20	3000	1500	90%	Yes
USA/Lockheed	Atlas III	105		10000	100%	Yes
USA/Lockheed	Atlas V	138		11023	100%	Yes
USA/Boeing	Titan III	45		7500	75%	Yes
USA/Boeing	Titan IV	400		12700	96%	Yes
USA/Lockheed	Delta IV	90		9285	98%+	Yes
Japan	H-2	190		8818	70%	Yes
Japan	H-2A	90		11023	85%	Yes
ESA	Ariane 5	120		26400	80%	No

Table 1 Statistical Data from "Proton 8K82K" of five major agencies and their current state.

Another branch of market possibilities includes transporting the LOX to a range of orbiting space vehicles. With multiple tethers surrounding the harvester, the likelihood of a large spacecraft, when coming to refuel, colliding with one of the tethers are high enough to be a risk factor. Thus, the dock for refueling will probably be separated from the production plant. As noted earlier we envision storing small tanks of fuel to be exchanged for empty tanks with other spacecrafts on a platform near the harvester. The docking mechanism will use high precision targeting system to prevent human errors of damaging the platform such as the Progress Rocket collision wit MIR that ultimately led it the abandonment of the space station. The spacecrafts would drop-off their empty tanks and pick up full tanks. The empty tanks will then be “tugged” to the atmospheric harvester to be refilled. This would require a universal docking mechanism for all the tanks so that they will be interoperable with existing US and foreign technologies. It is likely that this routine transfer process will be automated and unmanned, but a man-tended platform with a manned control booth from which the automatic system can be altered or overridden and shutdown is envisioned.

As technology is advancing, it is likely that by 2020 such man-tended platforms will be common. We see them supplanting at least half of the existing satellites over time. The space industry is moving away from stand-alone satellites to carry instruments toward larger, multi-purpose platforms. We think these will soon be large enough to be man-tended (visited several times a year, but not constantly occupied). These will be large platforms holding the instruments previously scattered over 20 satellites. Space junk production will be outlawed, so old instruments will have to be retrieved or boosted into deep space or de-orbited to burn up on reentry. The market for refueling, servicing and maintaining these platforms that will emerge is of great interest to us, given the need to refuel and the LOX that the atmospheric harvester provides will meet most of this requirement. If bulk hydrogen can also be harvested in LEO, and we think that is can, though it is harder to do, one has both components for rocket fuel and water. The fuel will be used to not only keep the satellites and platforms in space but also it will propel the technicians needed to routinely service or replace failing or obsolete satellites and platform instruments. This is a new market niche (platform service) that the product of the atmospheric harvester is likely to require us to deliver. This market will result in both robotic and man-tended service contracts since the fuel delivery system will be asked to carry other things as well and probably install them. The telecommunications, global positioning, and military satellites are often in geosynchronous orbit. Military satellites regularly “pass” over territories on a regular and predictable schedule. Their owners and our clients may want to make them more capable and less predictable. This is achievable if they are willing to burn fuel to change orbit and re-orient them, processes that now shorten their lifespan. Currently, when they run out of fuel, their service life has ended and they not only have to be replaced but also they become space junk. The ability to refuel them will be highly valued as it will extend the asset’s service life and improve its capability. Thus, refueling contracts will generate a steady revenue for this emerging gas harvesting industry. The primary product will be LOX, but sales of all hydrogen one acquires as a byproduct will also be brisk. After resupplying LOX is mastered, it will not be long before harvesters are designed to gather hydrogen and positioned so as to maximize the hydrogen yielded.



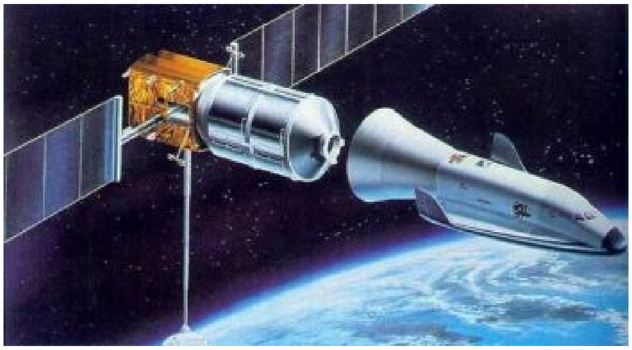
A space shuttle docking with the atmospheric harvester.

3.1.2 Space Tourism

Vacationing is an important part of modern secular cultures. Pilgrimages to shrines are an equally important part of non-secular cultures and attract secular tourists as well. The main focus of tourism in secular cultures is to relieve stress and introduce the client to situations and conditions that are different enough from their everyday lives to be educational or thought provoking experiences. Exotic locations have always been an interest to those who like to travel. Everyone has seen space during the night skies but few have had the opportunity to experience the vastness of space. Space tourism has already been proposed as the next great development for the thrill seeking wealthy tourist.

The first high visibility space tourist, Mark Shuttleworth, pioneered the idea of traveling into space as a unique once in a lifetime out-of-earth experience. He spent a week on MIR. It has long been part of the NASA, manned space mindset, and mystique that seeing Earth from space is a surreal experience similar to enlightenment. Astronauts talk about a new perspective and never being quite the same again. So space can be a mind and life altering experience. However, unlike Mark Shuttleworth most people do not have the $20 million that he paid to become a cosmonaut for an 8-day space trip.

With technologies such as the atmospheric harvester supplying a steady source of oxidizer for fuel, the possibility of a space hotel resort or cruise ship does not seem too far-fetched. Consider the possibility of a space resort orbiting just below GEO. This would allow the resort to follow earth’s rotation slowly enough so that the passengers are able to view different angles of the earth throughout their 1-2 week stay. Every week there would be a space shuttle to transport new people to the resort, people back to earth and bring fresh food and supplies. Bulk, non-perishable supplies such as LOX could travel separately in cheaper, slow freight carriers that were unmanned. A shuttle would fly between a space station in LEO and the space resort near GEO and never face the stresses of reentry. This would also mean that the space shuttle would be completely reliant on refueling in space with LOX and some hydrogen supplied by the atmospheric harvester (or delivered from Earth at far greater cost). Until a space elevator is built the rocket industry will be needed to deliver people from Earth. We do not think that the tourist industry will wait for the construction of a space elevator but it may help justify building one by the end of this century. In this scenario, the atmospheric harvester would play a crucial role delivering fuel and breathing air to the clientele of the space resort. The result is likely to be a very lucrative market for LOX. Spacecrafts returning to Earth do not need to replace their oxygen often, unless it was vented for some reason. They can reprocess the carbon dioxide produced by breathing animals and machines for a considerable period, by a chemical filtration process or by feeding the carbon dioxide to plants to convert it back to oxygen. However, a permanent space facility will need to import oxygen unless it also supported as the necessary amount of plant life for equilibrium. The space hotel resort will be optimized for human habitation. Space harvesting and human tourism need one another. The hotels will also want hydrogen for when it is combined with oxygen, water will be created, which they will need a lot of as well.



A ship carrying people from the LEO space station to the GEO resort.

Artist’s rendition of the nautilus space resort.

3.1.3 Lunar Trading

With the atmospheric harvester supplying oxidizer and other fuel components to spaceships, reaching GEO will become trivial. The next logical step would be to continue to the moon. Construction of a lunar base could be started within the next ten years and space tourism will be pushing for new exotic locations. A hotel in the lunar orbit will follow soon after a near GEO hotel, and a cruise liner vehicle for the 3 day trip between them will approximate an Atlantic Ocean crossing in the early 20th century. The inhabitants of a lunar base (scientists, tourists, miners and support staff) would need certain essential supplies. Such supplies would be food, water, and again air for breathing.

Oxygen is present in the moon rocks, but getting at it will be costly, probably more costly than importation from the upper atmosphere of the Earth. Shipments of oxygen, nitrogen, hydrogen, carbon dioxide and food could be made so that the crewmembers would have a sufficient supply, growing their own plants and importing meat and fruit. Carbon dioxide could be imported to the agriculture facilities on the moon from the space hotels. If the lunar base colony were able to gather the hydrogen molecules hitting the lunar surface from the solar wind, it could potentially be reacted with oxygen on the moon to supply the quintessential need of water. If not, they will import hydrogen gathered in LEO to make water. The supply of nitrogen and carbon dioxide would be used for plant growth (see Moody, Songer, Groezinger, 2007).

As the lunar base gets started, there will be a large overhead of necessities that it needs from Earth. Thus, it will provide at least a temporary market for the atmospheric gas harvester both for oxygen and fuel delivery. If the scientists on Earth are able to build a sustained nuclear fusion reactor by 2020, then they will look for better yield energy sources. Helium-3 would be invaluable to a moon base with a trade deficit to Earth since the moon regolith is relatively rich in Helium-3, as it is deposited there by the solar winds. There is no Helium-3 on Earth due to the atmosphere deflecting the solar winds. This situation could lead to a gas trade system between Earth and the moon. This would most likely take the form of hydrogen for Helium-3 exchange given that there is oxygen in the moon rocks and with a fusion reactor to meet the energy demands of mining it, the moon will cease importing oxygen and start to sell it to spacecraft stopping there to refuel en route to Mars and beyond. A space shuttle riding the solar wind with a sail would probably transport the gases needed on the moon from an atmospheric harvester in the hydrogen layer of the exosphere and in return the moon will provide Earth with Helium-3 in the same tanker freighters. However, Paul Klinkman doubts that this will be necessary as he is working up an idea to gather hydrogen molecules from the solar wind as it passes over the surface of the moon. This would eliminate the need to transport hydrogen to the moon. This seems like a long shot to us, as the hydrogen layer around the Earth is coming off of the oceans of a water drenched planet, not the sparse solar wind. However, this is still a future market for our proposed gas harvesting company, whether it is gathered near the Earth or on the moon.

3.2 Contributions That Have Been Made

3.2.1 Contributions Made to WPI

WPI has long fostered a continuing partnership with its alumni such as inventor, entrepreneur Dean Kamen. Paul Klinkman is a similar case. He is no stranger to the WPI community as he was a part of the class of 1976. As an alumnus entrepreneur, he approached his alma mater some space enterprise ideas related to harvesting gases from the atmosphere. He went through Gina Betti, in WPI's Entrepreneurial program in the management department and eventually met Professor John Wilkes. Wilkes had similar interests and was teaching a course on team dynamics in research and development departments using aerospace corporations and laboratories as an illustration. Paul spoke to the class about the gas harvesting idea but these students were unable to grasp its significance. Instead they judged him to be a "crackpot" due to his lack of credentials and job based legitimacy in this field. Since the breakthrough idea was too undeveloped to be appreciated, Wilkes invited Klinkman to co-advise (really he was the sponsor) an IQP to develop, clarify and assess it. We were that IQP team. From there we went on to discuss some of the social implications of such a breakthrough project, since it was an IQP, not an MQP.

Through this IQP at WPI, WPI has collaborated with an entrepreneur inventor who had an idea and was able to help him turn it into a patent and present it at a national meeting. The next step for this patent-pending idea is to be prototyped and tested. In order for prototyping to occur, WPI would have to allocate some more resources such as student and faculty time, office and lab space and financially back this program with administration and legal support. Due to the afore-mentioned patent pending, the atmospheric harvester has a chance to prove the basis for a highly profitable business, if it is developed within the next 7-10 years. So the clock is ticking, but so far WPI has not been willing to invest. WPI did not supply any patent lawyer or pay for the patent application. Klinkman covered these expenses himself.

Had WPI helped Paul with the patent process it would have secured property rights. However, it has foregone them and left Pay to take the next step on his own. Paul still prefers to work with WPI and share the profits and risks to a certain point. In order for WPI to fully support this endeavor a faculty member of WPI who is specialized in the field of aerospace and has the right credentials would have to certify the potential of this idea. One way to stimulate WPI’s interest of Klinkman’s (and Wilkes’) ideas is to continue to develop the idea with IQP and MQP teams. However, Wilkes cannot advise an Aerospace MQP.

Following this project, WPI now has the opportunity to setup more projects. One of them, a management MQP, should explore the case for creating a company and other projects should look into some of the deeper technical aspects of the gas harvester space system. Several IQPs involving research and development could be setup with social science and chemical engineering or physics advisors to study the organizational environment required for creative success. This would be something to do in cooperation with NIAC, NASA or hopefully an aerospace firm that we hope will buy into Paul's startup company once the technology is proven with a NASA grant. WPI's management department could organize a full-scale project management MQP overseeing the three technical development teams, which will be presented to the world as IQPs.

This project has laid the groundwork for future activities that are in accordance with WPI's projects program, but it cannot lead directly to three Aerospace MQPs. For that to happen, an in house champion would have to be found in that department to advise the projects. This person would have to be impressed enough with what we have done and want to look into it further. So, one of the projects next year will have to be a Delphi study in which the gas harvester idea is listed and gets assessed for "promise" by experts at WPI and elsewhere. We have produced an item suitable for such a study (see Appendix C). Depending on how it fares the next round of projects at WPI will be IQPs or MQPs, which are probably two years away.

3.2.2 Contributions Made to Ourselves

We as students have been given the opportunity to work on the feasibility study of a novel idea and it has been most gratifying. Not many students are able to take part in real world projects that will most likely influence space policy and the future interplanetary economy. We are among the fortunate few. The knowledge gained from this experience is second to none as we were able to work with other students of science, engineers, an inventor, and even space enthusiasts and entrepreneurs while trying to explain and refine this idea. This project also involved a MBTI personality assessment that gave us more insight about our main collaborator, Klinkman, (INTJ), our group members (ISTJ, ISTJ and ISTP) and our advisor, Professor Wilkes (ENTP). The simple fact that our group members are very similar yet a bit different from our sponsor and very different from our advisor, allowed this project to be propelled by the interplay between cognitively diverse people who all contributed in different ways, despite the fact that none of us really had the "right" credentials to do what we were doing

3.2.3 Contributions Made to Paul Klinkman

Paul Klinkman was the external sponsor to this project. He originally set out with the goal of proving whether or not it was feasible to gather gaseous molecules from the upper atmosphere. However, with our aid, the IQP project sped up his process of developing this idea. We concluded that not only would a device along the lines suggested be possible but also potentially profitable at low earth orbit altitudes. Our backgrounds as engineers gave Paul Klinkman's ideas positive reinforcement to continue his design of the maw structure and the rest of the platform through 3 or 4 iterations. The evolved and got specific as he dealt with us and a patent lawyer. We were able to assist him and encourage the development of his ideas. Our mechanical engineering backgrounds allowed us to crucially scrutinize his designs for flaws to help correct and optimize some of the functions of the atmospheric harvester.

Working with Paul Klinkman, we were able to gather new ideas and develop a concept for the potential market for the product of such a device. Our expertise in technology and a bit of research into current space markets helped us design the framework for an atmospheric gas harvester that could be the basis for a profitable enterprise.

3.3 The Project Future

It is possible that our project is only the beginning of a series of several Interdisciplinary Qualifying Projects (IQPs) and Major Qualifying Projects (MQPs). Below are some of the possible projects and a short description about each project.

- Lunar Trade Program (LTP) – This could be an IQP that will explore further the nature of a lunar trade system. It will involve an economic analysis of the supply and demand for the gases under various scenarios on the moon. The key variables will include population size, daily functions, and energy consumption. It will also analyze how the resources of the moon might be sold on Earth and how self-sufficient a moon base can be, if agriculture is established there.
- Prototyping the Atmospheric Harvester (PAH) – This could be an IQP/MQP that would explore the challenges of building all the necessary structures, parts and devices for the atmospheric harvester platform. It would involve a multidisciplinary team of engineering majors who would be willing to participate in an experiment and incidentally be assigned to design a component for the atmospheric gas harvester prototype. This

three team project would result in a proposal to be submitted to NASA Institute for Advance Concepts for funding. If funded, we can build it the next year in MQP teams advised by aerospace faculty members. Technologies such as tethers, gas processing, and heat radiation will have to be addressed by different teams. Schemes for product sale and marketing are other issues that need to be explored in a management MQP. Also, there should be an IQP team like ours, which focuses on new product development – in this case the possibility of hydrogen harvesting in LEO, GEO or on the moon.

- Role of WPI Alumni (RWA) – This could be an IQP that would study potential benefit to WPI, its students and alumni, if they started bring their ideas to the college for development, as Paul Klinkman did. Their goal would be to determine how ideas from external entrepreneurs compare to those coming from area businesses as a focus for a project experience. Along the way we can study the cognitive mixes found in the more successful of these joint initiatives.

3.4 The Role of an External Technical Advisor

Paul Klinkman was not just an integral component of this year's How High and How Fast IQP. He was the sparkplug and stayed involved to participate as a full team member. This is unusual for a sponsor. He pushed but also assisted the group with many ideas. Our original project goal was to redo last year's project and determine if gathering gases was feasible. However, with Paul came along his knowledge of the stratification of molecular gases at various altitudes in space. This was the first major twist in our project.

It propelled us from determining the feasibility of atmospheric harvesting and confirming that it was possible to thinking in terms of economic return and potential markets and social implications.

Once the first hurdle of determining the feasibility of atmospheric harvesting had been completed, we looked towards Paul for his guidance as to the next step to be taken. As an entrepreneur, he had many ideas about possible designs for such a platform. Working with his concept and a few suggestions on how it should work and how it would be used, we pushed him to select a feasible design with the fewest possible risky elements. That allowed us to develop the different scenarios for the markets that might utilize the technology of the atmospheric harvester. In the end, one product for an existing market became the basis for a design. He felt that the concept was capable of being adapted to do much more but other gases and locations raised new problems. He can consider some other gas markets in detail next year, with another team.

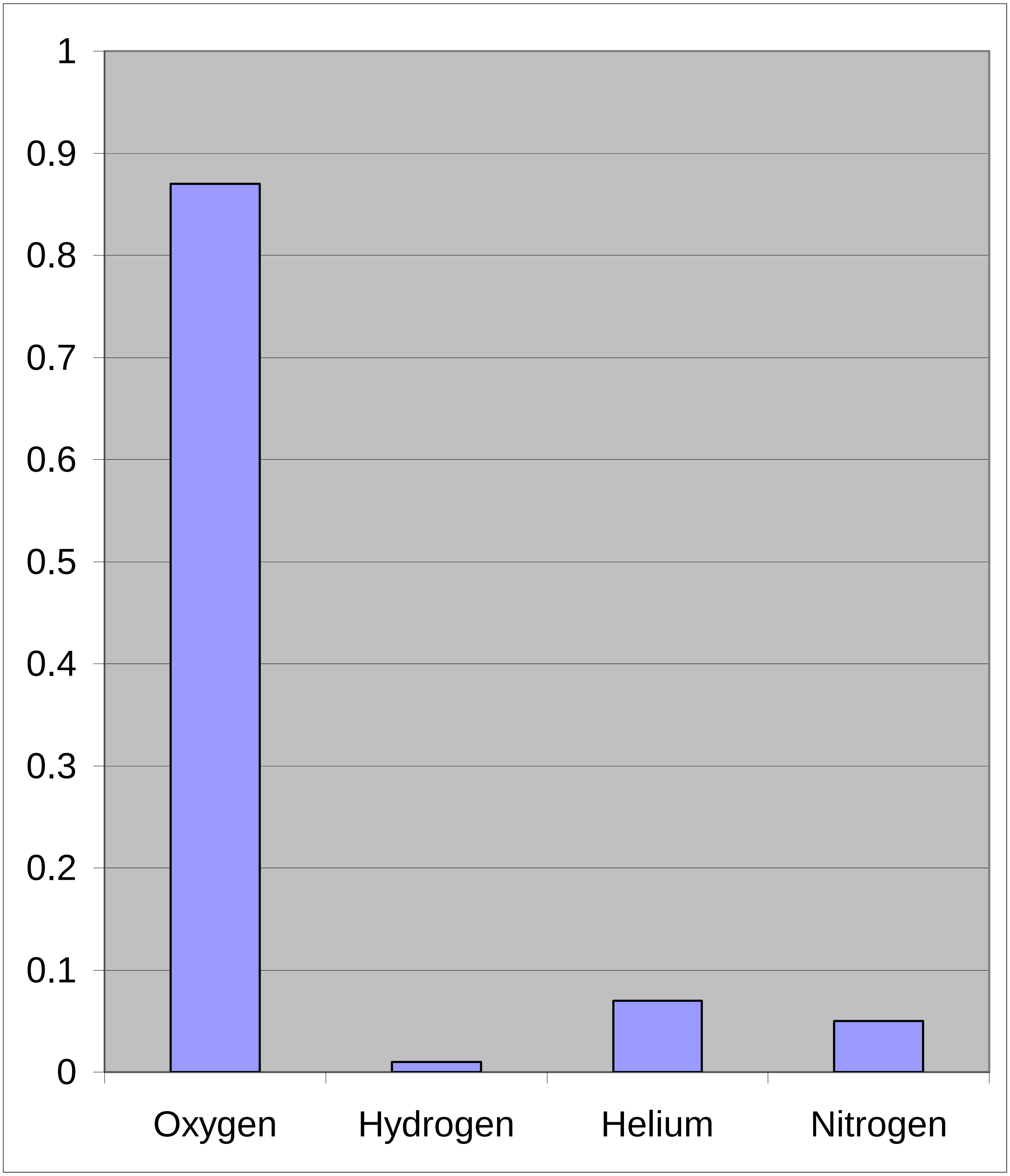
3.5 Conclusion

Based on the assumption that breakthroughs are going to be made in electrodynamic tether and radiator technology, we believe that an atmospheric gas harvester operating in Low Earth Orbit is feasible. We also believe that, after researching several initial and future markets, the harvester will be economically viable and capable of generating a profit. While confident in our results, we understand further research into various components of the harvester (most notably propulsion, heat dissipation and distribution) is still needed in order to justify the creation of a working prototype.

The effects of a company implementing the system, or a similar system, proposed in this report should also be examined in greater detail. Interactions between spacecraft and platforms in Low Earth Orbit and geosynchronous orbit as well as the trade system between Earth and the moon should be studied as the formation of a space economy will undoubtedly have a significant impact on the space industry and humanity.

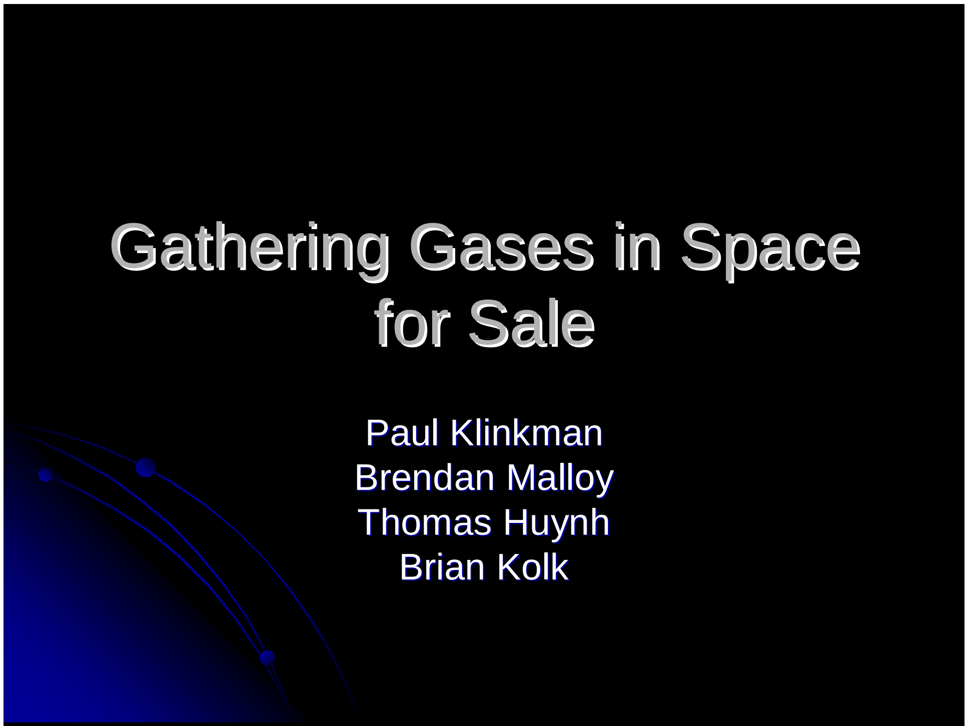
Appendix A

Typical atmospheric composition at 400 km



Appendix B

Slides from Baltimore conference presentation



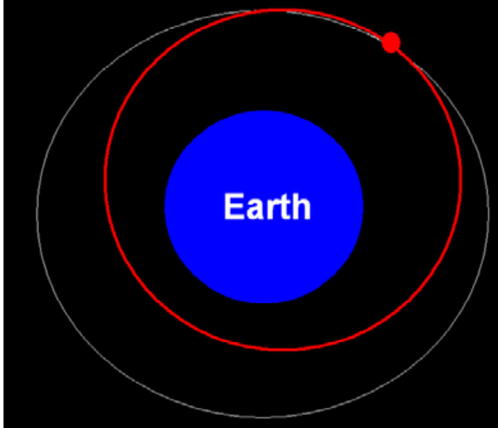
Gathering Gases in Space for Sale

Paul Klinkman
Brendan Malloy
Thomas Huynh
Brian Kolk

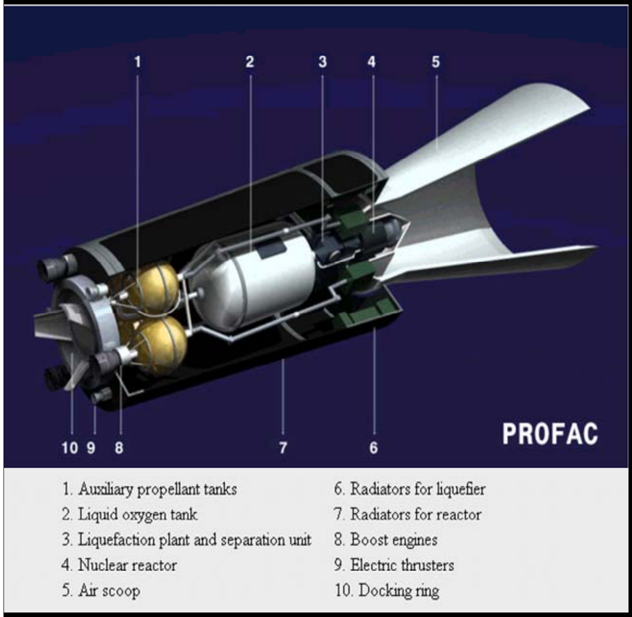
The Market

- Oxygen
  - Oxidizer for reboost rockets on satellites
  - Refueling the space shuttle
  - Refueling the upcoming single-staged rocket
    - Vastly increasing the range of our current spacecraft
  - Life Support
- Nitrogen
  - Lunar Agriculture – Needed to make soil fertile

Previous Study



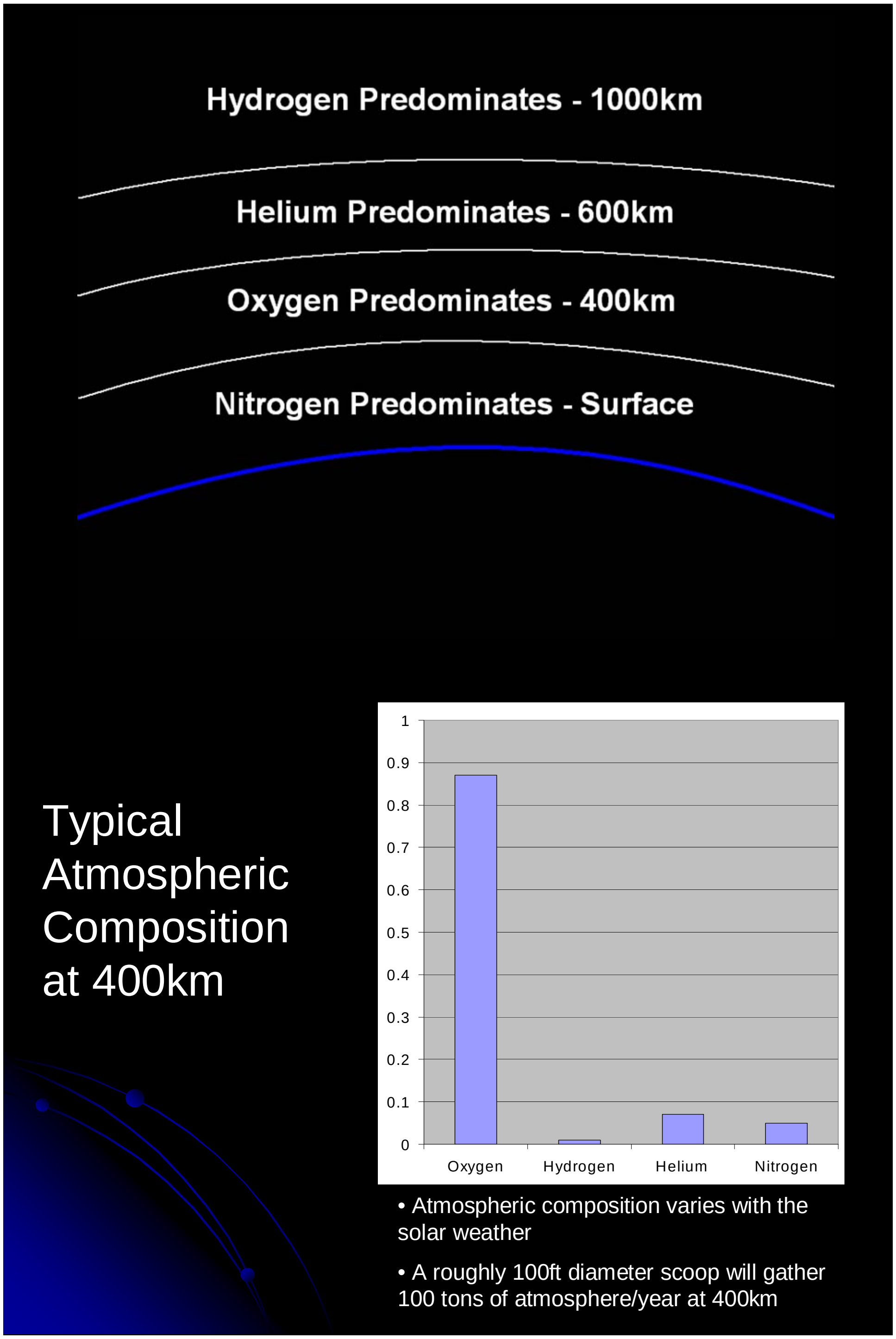
- Assumed that the harvester had to be able to reach altitudes where the air was more dense.
- Assumed that atmospheric composition did not vary with altitude
  - 78% Nitrogen, 21% Oxygen, .93% Argon, and .04% Carbon Dioxide at Sea Level or 100km+ up.



1. Auxiliary propellant tanks
2. Liquid oxygen tank
3. Liquefaction plant and separation unit
4. Nuclear reactor
5. Air scoop
6. Radiators for liquefier
7. Radiators for reactor
8. Boost engines
9. Electric thrusters
10. Docking ring

A Vintage 1959 Atmospheric Gatherer

www.bisbos.com/rocketscience/spacecraft/**profac**/**profac**.html



Hydrogen Predominates - 1000km

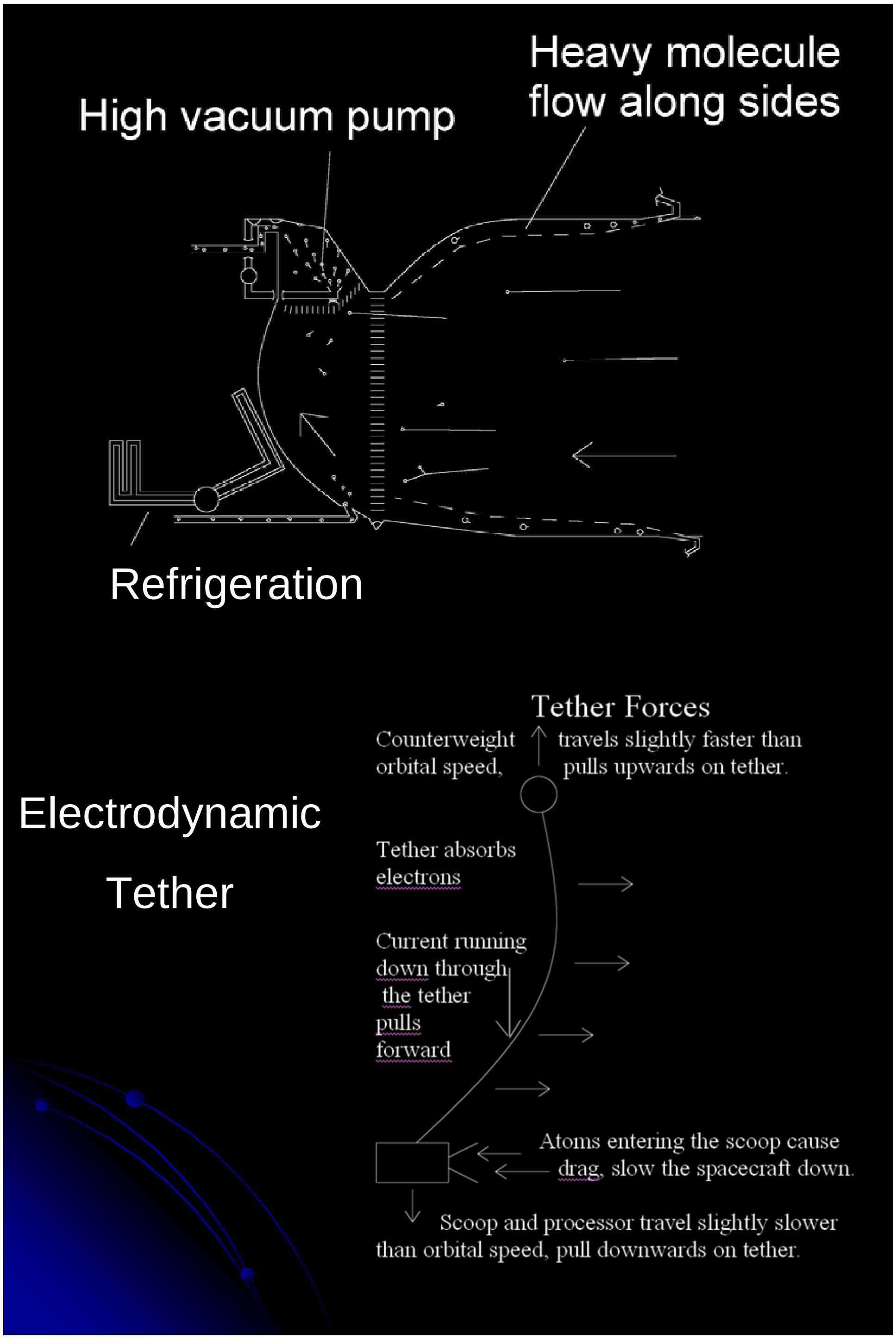
Helium Predominates - 600km

Oxygen Predominates - 400km

Nitrogen Predominates - Surface

Typical Atmospheric Composition at 400km

- Atmospheric composition varies with the solar weather
- A roughly 100ft diameter scoop will gather 100 tons of atmosphere/year at 400km



High vacuum pump

Heavy molecule
flow along sides

Refrigeration

Electrodynamic

Tether

Tether Forces

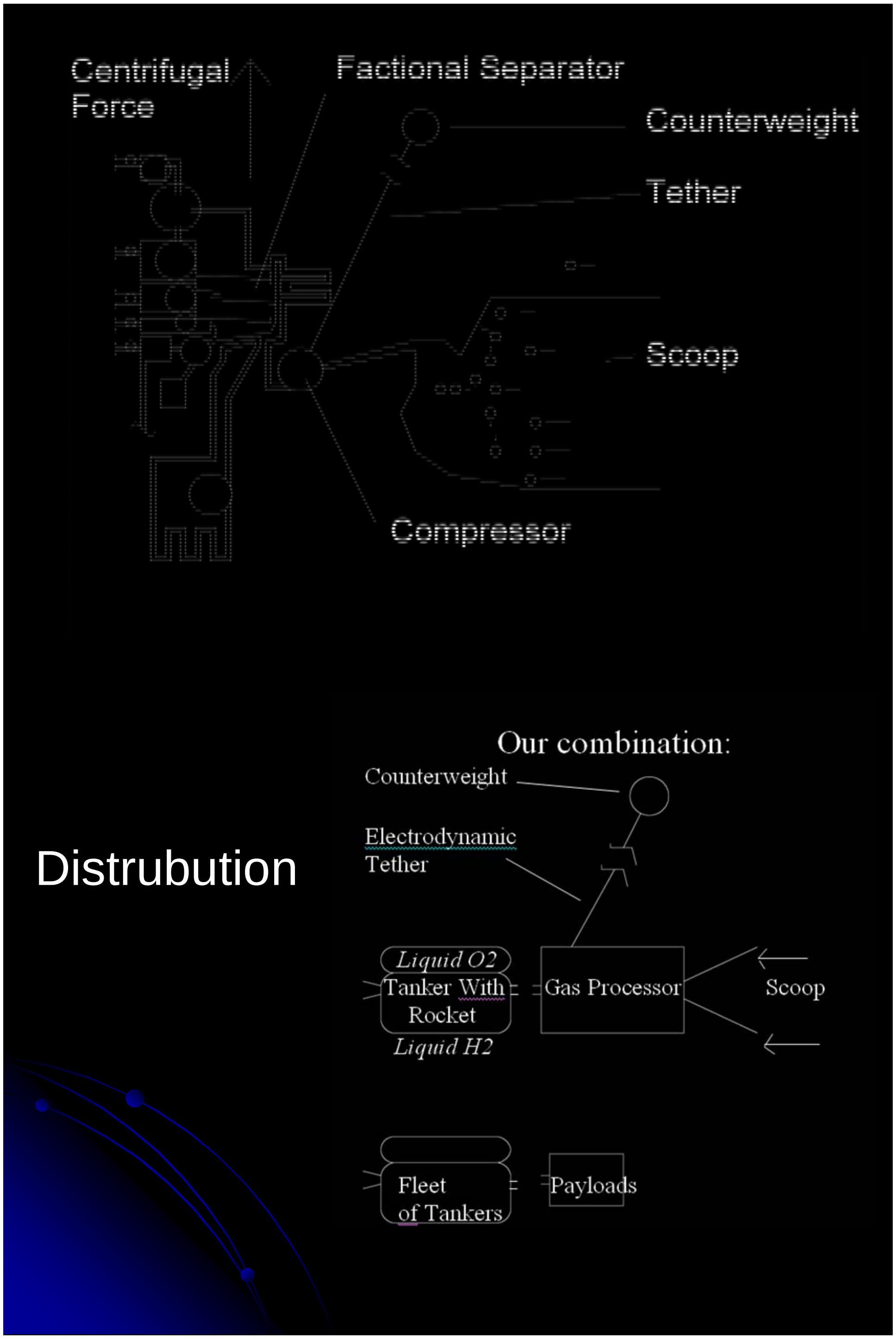
Counterweight travels slightly faster than
orbital speed, pulls upwards on tether.

Tether absorbs
electrons

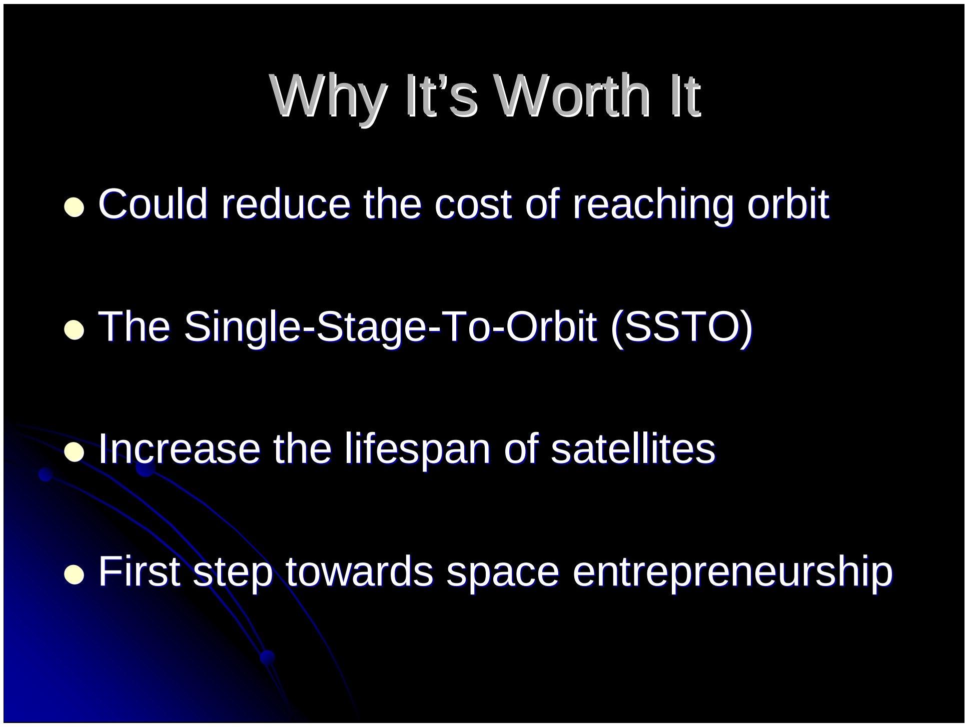
Current running
down through
the tether
pulls
forward

Atoms entering the scoop cause
drag, slow the spacecraft down.

Scoop and processor travel slightly slower
than orbital speed, pull downwards on tether.



Distrubution



Why It’s Worth It

- Could reduce the cost of reaching orbit
- The Single-Stage-To-Orbit (SSTO)
- Increase the lifespan of satellites
- First step towards space entrepreneurship

Appendix C

New Breakthrough Survey Scenario

As humanity branches out into space, the need for readily available resources will shape the economy of the future. The ability to harvest the upper layers of the Earth's atmosphere for gases such as oxygen, which is used for life support and oxidizer in rocket fuel, could create one of the first seller's markets in space.

A harvester orbiting at 400km, an altitude that, while very low in density, contains roughly 89% oxygen could harvest several tons of liquid oxygen per year. Using a large maw and vacuum pump, the harvester would operate continuously for about 10 years. In order to maintain momentum, the gatherer would use an electrodynamic tether, a form of propellantless propulsion, which utilizes a long wire infused with large current that pushes off of the Earth's magnetic field.

If the Low Earth Orbit Atmospheric Harvester is developed with the proposed technology it has the potential to revolutionize the space industry. Technologies such as the electrodynamic tether allow the harvester to maximize the amount of fuel it can gather by not consuming any resources during operation. The only weakness the harvester possesses at this time is the fact that some of its key components are unproven technologies such as the radiator to dissipate all the heat gained while harvesting and the electrodynamic tether.

Bibliography

“Air Separation Technology Overview” November 2006. <http://www.uigi.com/compair.html>

Barry, Patrick L. “Building a Better Rocket Engine” 10/14/2005. November 2006. <http://science.nasa.gov/headlines/y2005/14oct_betterrocket.htm>

Bergeron, Aaron. Fritz, Douglas. Mosig, Timothy. "Earthly Implications of a Return to the Moon; Fusion, Health, and the Space Industry." Worcester Polytechnic Institute. Worcester, MA. May 2005.

Brayshaw, Peter. Farnham, Brooks. Leslie, Jon. “The Future of Unmanned Space: A Speculative Analysis of The Commercial Market.” Worcester Polytechnic Institute. Worcester, MA. December 2004.

“Breakthrough in Propellant-free Space Propulsion” Science A GoGo 7 February 2002. September – October 2006 <http://www.scienceagogo.com/news/20020106223110data_trunc_sys.shtml>

Cohen, Leonard. Comee, Shaun. Ronge, Mark. "Assessing Cases For Space Stations." Worcester Polytechnic Institute. Worcester, MA. October 2006.

Colm O’Sullivan. “A simple experiment to study cooling by convection and radiation” February 2007. <http://www.physics.ucc.ie/staff/Didfyz%20paper.pdf>

“Cryogenic Air Separation and Liquefier Systems” November 2006. <http://www.process-cooling.com/CDA/Archives/ebde76fc3c5b7010VgnVCM100000f932a8c0____>

Dooling, Dave “Electrical Tethers” Science @ NASA 22 January 1999 <http://science.nasa.gov/newhome/headlines/ast22jan99_1.htm>

“Electrodynamic Tether” Wikipedia. 23 October 2006. September – December 2006 <http://en.wikipedia.org/wiki/Electrodynamic_tether>

“Electrodynamic Tether Propulsion” Advanced Space Transportation Technology Summary October – December 2006 <http://data.engin.umich.edu/Icarus/documents/ProSEDS/tether.pdf#search=%22Tether%20propulsion%22>

“External Tank” September 2006. <http://science.ksc.nasa.gov/shuttle/technology/sts-newsref/et.html#et>

Flaherty, Bill. Luca, Oana. Monfreda, Mike. “The Effect of Cognitive Preference on Forecasting Space Technologies” Worcester Polytechnic Institute. Worcester, MA. March 2007

“Heat Rejection Radiators” November 2006. <http://www.lockheedmartin.com/wms/findPage.do?dsp=fec&ci=11295&sc=400>

“Icarus Satellite Project” University of Michigan. October – December 2006 <http://data.engin.umich.edu/Icarus/proseds_ed.html>

Johnson, L and Herrmann, M. United States. NASA. *International Space Station Electrodynamic* Tether Reboost Study Alabama. Marshall Space Flight Center. July 1998

Klinkman, Paul. Personal Interviews. September 2006 – 24 February 2007

Mark Shuttleworth >> Biography. Mark Shuttleworth. 13 February 2007. <http://www.markshuttleworth.com/biography/>

Mason, Lee S. “A Power Conversion Concept for the Jupiter Icy Moon Orbiter” February 2007. <http://gltrs.grc.nasa.gov/reports/2003/TM-2003-212596.pdf>

“Micropet: Propellantless Propulsion for MicroSats” Tethers Unlimited, Inc September – December 2006 <http://www.tethers.com/microPET.html>

“Non-Cryogenic Air Separation Processes” November 2006. <http://www.uigi.com/noncryo.html>

“Outer Space” Wikipedia. October 2006 <http://en.wikipedia.org/wiki/Outer_space>

Port, Andrew. Scimone, John. Verbeke, Geoffrey. “Harvesting the Atmosphere” Worcester Polytechnic Institute. Worcester, MA. March 2006

“Space Shuttle external tank” Wikipedia. September 2006. <http://en.wikipedia.org/wiki/Space_Shuttle_external_tank>

“Space Shuttle Solid Rocket Booster” Wikipedia. September 2006. <http://en.wikipedia.org/wiki/Space_Shuttle_Solid_Rocket_Booster>

“The Space Shuttle The Ascent Stage” October 2006. <http://www.cdli.ca/CITE/sts_ascent.htm>

“Tether Propulsion” Wikipedia. 25 February 2007. September – December 2006 <http://en.wikipedia.org/wiki/Tether_propulsion>

Wade, Mark. “Lox/LH2” November 2006. <http://www.astronautix.com/props/loxlh2.htm>

“Windows to the Universe” November 2006. <http://www.windows.ucar.edu/tour/link=/earth/images/profile_jpg_image.html&edu=elem>

WPI Collabrative for Entrepreneurship and Innovation. Worcester Polytechnic Institute. 30 February 2007. <http://www.wpi.edu/Academics/Depts/MGT/CEI/>