Project Number: JMW-OXGR

INNOVATION & CREDIBILITY: THE LOXLEO STARTUP

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

Ryan Fossett

Geoffrey Karasic

Lucas Lincoln

Peter Moore

Thomas Max Roberts

Date: May 5, 2008

Professor John Wilkes, Advisor

Abstract
This team was formed to carry out research and development on a low-earth orbit oxygen gatherer, consider outsourcing various components and to examine our own team dynamics (from an MBTI perspective). The project's technical emphasis shifted to social research in response the comments of a NASA reviewer who stressed the need for technically credible partners. Visibility and credibility were sought by doing a Delphi study. Brief descriptions of Klinkman's LOXLEO and Demetriades's PROFAC devices were the stimuli in this study.

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Introduction

Though the excitement of the space race is long behind us, and current NASA crafts utilize technology over a decade old, the promise of space travel has not been lost on the individual. The trend toward privatization of the space industry, evidenced by the success of the X prize competition and the Boeing company's increasing success in producing space hardware, suggests now may be the time for the private sector to reinvent space travel. Paul Klinkman, a WPI alumnus and prolific inventor, has devised a craft can do just that: the low earth orbit gas harvester.

The objective of the IQP is to aid in the realization of Klinkman's invention while investigating the experience of working on a research and development team. The team acted as both technical critics and creative consultants for Mr. Klinkman throughout the designs development process; which started with technical development, then transferred to skeptical analysis, and finally settled on the hunt for credibility.

The hunt for credibility manifested in a Delphi-style mailing and a number of interviews, including an open communication with Sterge Demetriades, an aerospace industry professional who invented the Propulsive Fluid Accumulator in the late 1950's. The Propulsive Fluid Accumulator is an idea that shares much, conceptually, with the device envisioned by Paul Klinkman. The discovery of Demetriades, in parallel with the experience with Klinkman, provided an insight into the politics of revolution in science, and how it's changed (and remained the same) since the Cold War.

Working with Dr. John Wilkes allowed the team to gain insight into the social implications of a successful shift in the space paradigm and to determine the attributes of a successful R&D team based on Myers-Briggs Type Indicators; and the social dynamics of research as examined though R&D case studies. A deep understanding of the roles of each personality type in a research and development team provides the ability to synthesize an ideal research and development team.

The LOXLEO Oxygen Harvester

This project revolves around an invention by Paul Klinkman, a WPI computer science graduate. The device, which the team officially named LOXLEO (for gathering Liquid OXygen in Low Earth Orbit), was the focus of the teams R&D efforts and social and political forecasting effort.

The LOXLEO device gathers oxygen ions, as well as ions of other species, in the uppermost region of the atmosphere. In its current configuration the device orbits the Earth at an altitude of 350 kilometers. At that height orbital velocity is 7884 meters per second. The orbital period is a little over 90 minutes.

At the altitude of 350 kilometers the number density of particles is approximately 10^5 per cubic centimeters. Contrast that with the approximate sea-level number density of 2.6×10^{19} molecules per cubic centimeter. This goes against a common misconception that space is entirely empty. In fact, there are vast resources to be tapped. Over a relatively short period of time enough gas can be gathered to approximate sea-level density gas which can be converted to liquid oxygen.

While a final design for the gatherer is probably five years away a few basic specifications have been agreed upon. No component on the spacecraft will extend beyond the cross-sectional area of the inlet. This will ensure that the full extent of the drag force experienced by the spacecraft is due to the gas particles being gathered, thus preventing any unnecessary drag.

The propulsion to overcome the drag experienced at that altitude will probably not draw on the gathered gas to serve as a reaction mass. Mr. Klinkman wants the gathering operation to be one hundred percent efficient. Thus an alternative form of propulsion is needed.

Further criteria, as well as technical details are discussed in the Outsourcing portion of the text.

Components of the Oxygen Harvester:

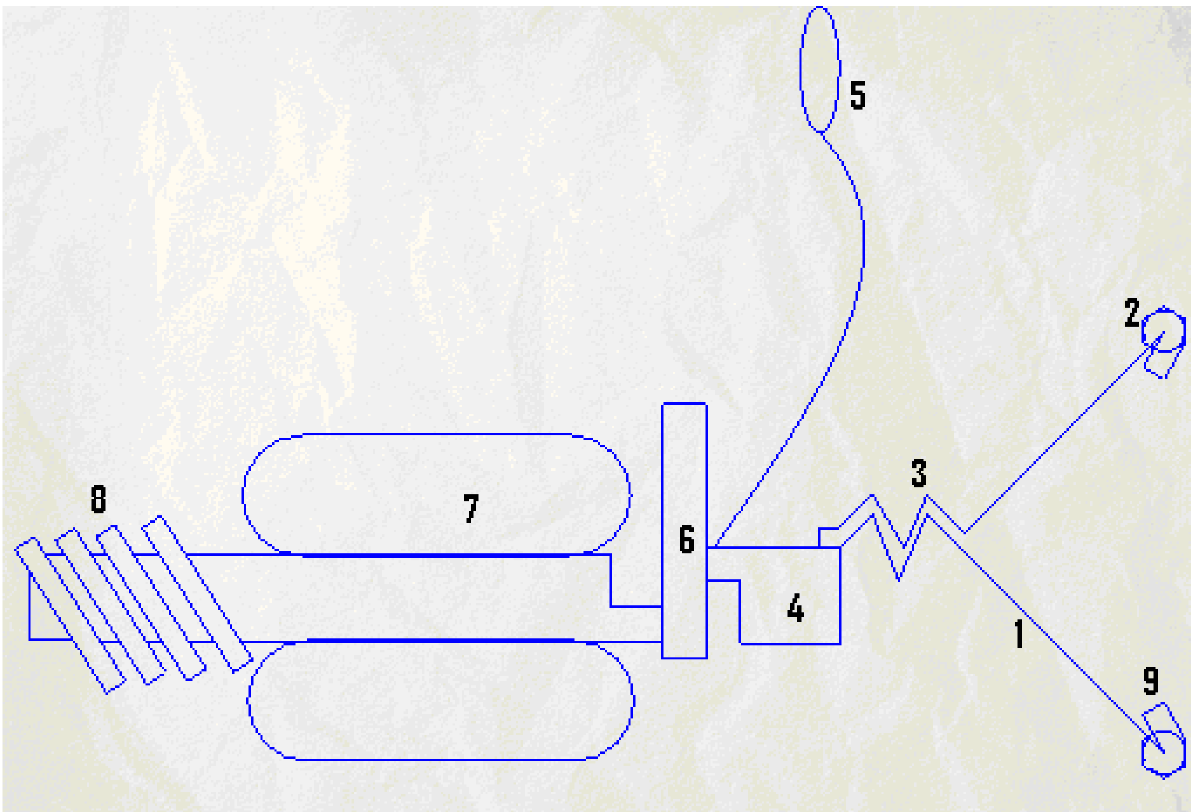

Figure 1 - LOXLEO Components

This drawing is not to scale. The purpose of this drawing is only to give the reader an idea of the main features of Paul Klinkman's idealized device; one which consumes none of the gathered gas. The backup plan would use no more than half of what is gathered.

1.) The dissipative inlet, referred to as the maw/scoop at the front of the gatherer that collects the oxygen atoms. This part of the device spins causing mercuric oxide that has built up on the walls to be forced outward.

2.) The cooker/heaters will be placed at the extremes of the maw to catch the mercuric oxide and separate the mercury from the oxygen, which is then pumped to the condenser.

3.) This variable pitch decreasing radius tube rotates causing atoms that have been forced to the base of the maw by the mercury spray to be pushed into the condenser.

4.) The condenser to liquefy the oxygen.

5.) The electrodynamic tether provides the propulsion for the device by sweeping through Earth's magnetic field.

6.) The radiators to remove heat from the process of liquefying oxygen.

7.) Large storage tanks to store the liquefied oxygen, which later can off loaded to vehicles that need to be refueled.

8.) Solar panels will provide the power for the condenser, heaters, and electrodynamic tether.

9.) Mercury spray nozzles that will spray a constant flow of atomized mercury to ensure that oxygen atoms that have entered the maw will not bounce back out.

A Historical Background

The work of the team, and inventor Paul Klinkman, came to the attention of Sterge Demetriades, whose PROFAC invention subsequently became a major part of the project due to an AIAA presentation by Professor Wilkes and Mr. Paul Klinkman. Mr. Demetriades's experience provided an ideal case study on the interface of society and technology. Demetriades invented his fluid accumulator in a much different time than Paul Klinkman, and with a much different set of skills and credentials. Nonetheless, the similarities between the struggles faced between Klinkman and Demetriades are striking; as both faced the towering wall of a paradigm-based opinion that what they wanted to do was impossible or simply not worth the effort. Both stood by personal moral codes despite the difficulties they created, and both observed as outsiders of the operation of politics and institutions beyond their control, which were skeptical of (or threatened by) their claims.

Sterge Demetriades

Sterge T. Demetriades was born and raised in Greece. He went to a small, technical high school in Athens where he would later return, once at Northrop, to recruit new people into his field. He attended Bowdoin College where he received his BS in Physics, Math and Chemistry then got his MS in Chemical Engineering from Massachusetts Institute of Technology. He finally ended up in the Jet Propulsion Laboratory of Caltech as a graduate student. It was here he developed the concept of PROFAC as part of his graduate work.

Back home there were disputes between the Turks and the Greeks over borders, and this tension resulted in a fellow student, a Turk, assaulting Sterge from behind, bloodying his ear in December 1956. The incident was minimized by Sterge's supervisors for the magnitude of the offense, but he persisted in insisting that the Dean find out why he was attacked-and whether he was safe from future attack. His grandfather was killed by a Turk, his father by a Bulgarian, so to Sterge, Greek Orthodox-Islamic tensions were to be taken seriously. By March the Dean had had enough and told him to drop the matter or he would be expelled. Sterge eventually ended up leaving Caltech due to this lack of action. By contrast the Turk graduated and became an academic at a school in California.

Leaving Caltech, Demetriades took his work on PROFAC to Northrop where he continued to develop it, and rose in ranks to the head of Space Propulsion and Power Laboratories. Once sufficiently advanced, he presented the concept to NASA, which assigned someone in Huntsville working with Werner Von Braun to review it. NASA unexpectedly declined to develop the technology. Demetriades' idea was probably not accepted because it wasn't seen as essential to NASA's immediate space goal – reaching the moon and getting back safely.

As an aside there is evidence that there is actually more to the story. The concept was reviewed and dismissed by people in the space establishment. Demetriades claims that Von Braun himself later apologized to him for that decision.

The concept of cost efficient space missions, especially paying extra to build a space infrastructure, wasn't a pressing issue during the Apollo Program, as space travel was still relatively new. At this point in time, refueling and a low average expense per trip were not priorities, simply learning to live and operate in space was. On top of this, there was the next step in the space race between the United States and the Soviet Union, which was the race to the moon. No one cared how we got to the moon, as long as we got there first. Setting up an infrastructure for inexpensive and regular space travel, such as PROFAC would do, was not an R&D priority.

In addition to the cold war concerns, PROFAC used a nuclear reactor as a power source. Shippingport, the world first commercial nuclear power plant, had gone critical for the first time only three years earlier. The application of nuclear power was still an experimental and immature technology under development by the US Navy. Technologists were more focused on the question of whether a nuclear rocket was possible, than they were on how they could use one to power a chemical rocket. The manner in which Demetriades intended to use it, which was in a ramjet configuration, was quite unconventional thinking. The design was a hybrid of nuclear and chemical power, and Ernst Stuhlinger, a key ally of Von Braun described this as having no real economic advantage over the direct use of a nuclear drive in space. Demetriades does not seem to have seen the Stuhlinger review until we recently brought it to his attention. He commented that what was not said was as important as what was said. Stuhlinger did not say would not work. Demetriades went on to state that the application of a nuclear drive outside of the biosphere would be much safer than the idea of launching a nuclear rocket from the ground. He even considered it safer than the nuclear powered aircraft carriers floating in harbors around the world due to its much lower power level. Still, doubts and debates about whether and how to use nuclear reactors in the space program further reduced enthusiasm for the immediate development of the concept in the 1960s.

The end for the PROFAC device came quickly and decisively. Sterge, disappointed with the response from NASA, began publishing his work in Britain. He also began a series of presentations at ARS (forerunner of the AIAA) on the PROFAC device. As he had been working on this project while at Northrop, a company with government funding, this searching for another application didn't go over well with the U.S. intelligence agencies. At the time of the presentations, USA-USSR Cold War was underway and the race to the moon was the focus of the space race. During the Korean War, a dispute between the Unites States and Britain over the exportation of advanced Rolls Royce jet engines to the Russians caused the US lose faith in the ability of its ally of WWII to keep a military secret. To avoid another technological boost to the Soviet Union, a Congressman threatened Demetriades with deportation if he did not stop giving public presentations about the PROFAC concept. It was considered an especially serious matter to do so in countries with left wing socialist sympathizers in positions of power. While the United States wasn't interested in the immediate application of the device, its cold warriors definitely didn't want the Russians developing it first. Therefore the reports prepared at Northrop were classified by the US government, presumably at the request of the Air Force, and the four existing reports of about 1000 pages concerning four – six key inventions were stored away safely. He was then without a clear role at Northrop. Rather than move on to a series of different projects at the company, Sterge left the aerospace field looking for a place an immigrant could operate without security restrictions. Since then he has been the founder, president and chief financial officer of three very profitable small corporations, and made considerable money on software innovations. He later got into renewable energy sources to deal with the inevitable energy crisis, working heavily with people interested in using seaweed as a source of biomass for alternative fuels after the oil era ends.

PROFAC

One of Sterge Demetriades first inventions (or really series of at least four inventions) was a system he called the Propulsive Fluid Accumulator system, or PROFAC for short. A paper he published in 1959, titled “A Novel System for Space Flight Using a Propulsive Fluid Accumulator,” describes this system for atmosphere harvesting in a partially developed state. PROFAC is an orbital device that remains at an altitude of roughly 100km, gathers atmosphere, and stores oxygen-enriched air. The idea would be to have a device that would gather the fuel for rockets in the most convenient place for them to refuel, thereby lowering launch weight and implicitly expenses. This would act as a gas station for both nuclear spacecraft drives (where the air is used as a propulsive fluid) and chemical (hydrogen) rockets (where the air is used as an oxidizer). A moon-bound vehicle that is refueled in Earth’s orbit requires roughly 5% of the fuel mass required of one launched directly from the Earth to the moon. In this regard, not only would the PROFAC concept drastically reduce launch costs beyond LEO especially to GTO, but would also make Earth-to-Moon shuttling a affordable, and then justify a lunar base and lunar development program.

There were three basic types of the PROFAC design. PROFAC-A was a concept for an aerospace plane that would use the fluid accumulator design to not only power the craft as it flew, but to also store gases for later missions to places where gas could not be collected. The design of this aerospace plane involved considerable attention to wing shape and structure that suggests it was a kind of shuttlecraft. The advantage seemed to be that it reached LEO with mission equipment, but little to no fuel and then refueled itself and other spacecraft that would depart from the plane while low orbiting. It could then go to higher orbit and deploy the spacecraft bound for deep space missions. On its way back it could carry out other LEO missions as well such as service space stations.

Clearly the needs of both chemical and nuclear drive were being kept in mind and covered. What was not clear is whether the balance of fuel consumption vs. collection rate in very LEO would work out. Stuhlinger first raised the economic issue, saying that using a nuclear reactor to refuel chemical rockets seemed more complicated than just using nuclear drive overall. Klinkman was more to the point. He focused on the narrow problem of station-keeping, as Demetriades wanted to operate in the densest part of the upper atmosphere where substantial thrust would be needed to overcome drag and stay in orbit. Further, nearly 80% of what was gathered would be nitrogen – not oxygen. Would enough oxidizer he gathered to come out ahead to fuel and serve the other needs of chemical rockets? Only if one could stay aloft using up primarily nitrogen, and keep most of the oxygen. Thus, the nuclear reactor superheating oxygen depleted air and ejecting it – not burning chemical fuel. The second device was known as PROFAC-S, which was an orbital stationary structure, but of little interest to the topic at hand. PROFAC-C was the design for the orbital refueling platform. All three of these devices had potential, but the core concept was the truly revolutionary idea that could have changed the way the space industry operates today.

The structure basically consists of two orbiting components, the Orbital Vehicle and the Accumulator. The Orbital Vehicle, containing the actual PROFAC apparatus, functions as a ramjet powered by nuclear or solar energy and provides the thrust required to overcome it's, and the Accumulator's, drag. The Accumulator, which is located concentric or parallel to the Orbital Vehicle, gathers atmosphere and stores it as liquid in

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The Accumulator in this design is by far the most revolutionary and complex component. At the altitude the Accumulator needs to orbit, around 100-120 km, there will be a substantial amount of drag on the craft in the range of 0.92 lb_f/ft^2. In order to overcome this deceleration, a magnetogasdynamics ramjet is used to propel the craft. This device uses the ionized gas molecules being forced into the inlet of the device as a means of expulsion to provide momentum for the craft. In layman's terms: the charged gases enter the ramjet, are compressed and then propelled out the back by a strong magnetic field. The gases that are not used for propulsion are fed into the PROFAC part of the Accumulator. The collection of atmosphere is done by funneling the incoming molecules, with estimated temperatures around 1100^o K, through a series of heat exchangers in which liquid helium will cool the gases directly to a liquid state at near 30^o K. In order to remove all this heat, a significant radiation mechanism would need to be adjacent. The dimensions of this radiator would be a direct function of the altitude the craft was flying at. A diagram of the PROFAC and MGD driver is shown in Figure 2[1].

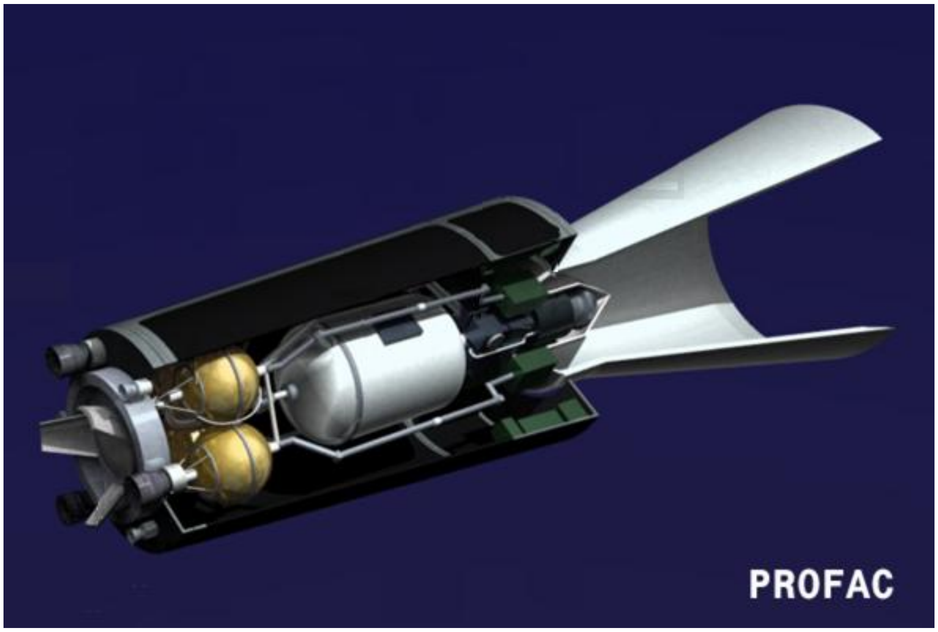

Figure 2: PROFAC Cross-Section

There exist two main variants in Accumulator operation. As the atmosphere intercepting the inlet of the craft is considered to be stopped with respect to the vehicle, two different forms of operation can take place. The first is called uninterrupted flow, where the atmosphere come into the device and is only slowed down before it is expelled by the MGD driver. This method most likely would not be implemented in the orbital PROFAC, but more likely in the PROFAC-A aerospace plane. The second method is known as interrupted flow and this would by how the PROFAC device in question would operate. As gases come into the inlet, they run straight into the PROFAC device and are put into storage tanks. As the MGD driver needs gas, it will extract an amount from a reservoir tank.

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[1] This is Rocket Science. <http://www.bisbos.com/rocketscience/spacecraft/profac/profac.html>

One of the biggest problems with the PROFAC design is its means of energy production. A nuclear reactor is used to power the MGD driver as well as the compressive components of PROFAC. Nuclear power is the only means of propelling a craft that needs to be in the upper atmosphere as continuously, or at least as long as the PROFAC apparatus would be. At the time there was not an active environmental movement to raise objections, but nuclear power plants were the focus of demonstrations by the 1970's and the Three Mile Island accident of 1979 shutdown the industry in the United States, while Chernobyl in1987 created international resistance. A nuclear device reaching supercritical mass on the ground is a rare but potentially catastrophic environmental and safety hazard. However, in the upper atmosphere the consequences would be more like atmosphere bomb testing which was occurring in the 1950's but later banned and thus nearly unthinkable today, but reasonable at the time. Most alternatives to this energy source are either too short-lived or too weak to even consider, but one involves increased complexity and cost, though it should work. Demetriades has followed the interest in space based solar energy with interest. Though beaming down energy to Earth from space is of questionable value, he considers the case for beaming it between spacecrafts fairly sound. Collecting solar energy in a higher orbit with little drag and beaming it to a spacecraft operating at low altitude with considerable drag seems feasible, but it is complicated compared to using a nuclear reactor and keeping it safe via redundancy and the technology used to keep nuclear weapons safe enough to transport around the world.

When comparing energy consumption of the PROFAC device to others being considered or already implemented, the potential for increase in fuel-to-lifted payload is orders of magnitude in difference. A chemical rocket requires 16 grams of fuel to lift and orbit one gram of payload, while the theoretical open-ended reactor rocket (or nuclear rocket) can lift 100 grams of payload per gram of nuclear fuel. The 16 to 100 grams delivered is already an increase of 6.25 in lifted mass per fuel mass, but with the implementation of the PROFAC device, an increase of an additional ten times the value could be put into orbit, assuming certain advances in conversion of thermal energy of the engine to direct energy of the exhaust is improved. This dramatic reduction in consumed fuel makes the environmental impact of PROFAC significantly less than that of today's conventional rockets. Due to this conservation of fuels, an order of magnitude cost reduction per space mission would be possible. The implications were, and are, revolutionary.

Our Interactions

In Sept 20, 2007, at a presentation at the AIAA meeting in Long Beach, California, Professor Wilkes co-presented with Paul Klinkman "Gathering LOX in LEO: Toward A Hunter – Gatherer Economy in Space." It included a description of the Klinkman design. Klinkman mentioned PROFAC in his talk, as he had the PROFAC name and a date from an internet source. During this presentation, a member of the audience stood and remarked that Klinkman's device was similar to that of a Sterge T. Demetriades PROFAC device. This was Wilkes' first exposure to the inventor of PROFAC, which had come to Klinkman's attention in what seemed to be an industry concept drawing with no inventors name or published source. The audience member left before he could be asked for more details. After this presentation, word got back to Sterge and he ended up contacting Professor Wilkes by phone. Sterge was surprised that out of all his achievements over his life, someone was getting interested is his early flashin-the-pan concept of PROFAC. He understood that it was an independent development by Klinkman that had led him to look for precedents, but still welcomed the rediscovery.

At this point we had only read a brief overview of the design and had an abstract from a larger paper. However, it was now clear that one could produce an addendum to the prior "breakthrough" Delphi panel study. One only needed a few paragraphs on each concept and now a source and abstract in the words of the original author was at hand. In addition to having Klinkman commit to a brief description of his concept, it could be coupled with one on Demetriades' PROFAC and they could be sent out jointly for expert assessment to see if one seemed more promising than another. How they both fared relative to other controversial technologies was also of interest.

It was a struggle to word the PROFAC description despite trying to quote Demetriades as much as possible. Sterge was disappointed in our representation of the device, stressing it's fueling itself rather than serving as a refueling depot or "gas station" in space. From where he stood we knew absolutely nothing about PROFAC and he wanted us to make a full study of it. He assigned us the task of finding the best public (but unpublished) document that described the design. Demetriades explained what he legally could, given that it was classified. This was an AIAA paper. We were struggling to get the published works, and were fortunate that a Harvard librarian decided to make a "cause" of finding this paper, and took us "above and beyond the call of duty" attitude toward our request. It was not in the Harvard collection but he found it elsewhere.

Sterge explained what he thought was the reason that the device was not a priority for the space program. What was clear was that during the Cold War era, the one thing the US government didn't want was the Soviet Union to get their hands on this potentially revolutionary design and develop it first. Actually, Sterge was under the impression that they already were aware of the possibility and had done some preliminary research on it. Suppressing PROFAC was not going to slow them down substantially but it would end progress in the USA. Once it was classified, he had hoped it would be developed in secret and really just wanted to be sure he got credit in the open literature. Actually, the idea was lost, never developed and dropped out of sight.

Sterge considered the four AIAA papers he'd scheduled (based on the four major Northrop reports) the best public treatment the idea would get. Only one was presented before the material was classified, though he thought a second was in the ARS-AIAA archives, as it was accepted for the presentations. Hence, he found us the reference and number for that, sending us the abstract. So from where we stood, it looked like Sterge thought of us as inexperienced undergraduates and most likely unqualified to work on his creation. He knew that we hadn't seen the entire document, but we were under pressure to write a paragraph length description, and found his article and two abstracts to be sufficient for that purpose.

In editing the PROFAC description, Sterge got a chance to read Klinkman's description of LOX-LEO. He decided to comment on that too. Demetriades was offended by the apparently crude and incomplete nature of Klinkman's design, and the fact that Klinkman was an outsider and didn't use the right words or seem to know the relevant literature. Sterge was also critical of the practicality of the tether design and the high altitude at which the LOX LEO device flies. Although he was somewhat apathetic towards us over the phone, and at one point even mentioned the desire to be paid a consulting rate, for all the time required to bring us up to speed. We thought that maybe a face-to-face meeting would bring about a more cooperative interaction. From this idea grew an effort to somehow meet with Sterge Demetriades.

We first invited him to come to WPI to present on his PROFAC idea to an aerospace audience, as professor Wilkes surmised that many WPI students, staff and alumni would be interested. The New England section of AIAA was interested in co-sponsorship but only if the WPI chapter of AIAA proposed the idea to them. There was no consensus in the chapter about whether to do this or invite a currently active NASA administration. In the end they did neither. On top of this, Sterge was also reluctant to travel. Next, we proposed going to California to interview Sterge, but the budget for the trip was far more than WPI normally spends in support of data gathering. Finally we tried to arrange a videoconference at Caltech, but even that somehow went awry when Caltech was reluctant to help set up a videoconference for less than $1000 for their end alone.

Toward the end of the project we conducted a phone interview with Demetriades to discuss some physics but also whether or not he'd received any new interest in the PROFAC device since we sent out our Delphi study descriptions. He said he hadn't but went on to tell us more about the device's operation and mentioned that the Russians had already used a PROFAC like concept. His tone this time was much more understanding as he knew we were undergraduates and could not get all his classified papers and fast track his interrupted research program. His main concern was the proper representation of his idea. He felt its day would come and just wanted to receive credit for coming up with it first.

Future with Sterge Demetriades

In the path of the LOX LEO/PROFAC (Paul Klinkman/Sterge Demetriades) relationship, there lie several landmines. Sterge is an intimidating, brutally outspoken character, but has experience and contacts we need. He was a successful technologist and succeeded in this field after being trained in it. His first success was in solving the problems leading to the explosion of the Titan 1. Paul, a definite introvert, has creativity and purity of originality but no relevant credentials and is not considered a commercially successful inventor. Hence, Paul would stand a significantly better chance with the support of a man like Sterge, but is ambivalent about a partnership with such a stronger personality who is critical of the way he expresses his ideas as an outsider to the field of aerospace. He also derives strength from a generation of aerospace dreamers who want to see space travel actualized before their time is up. Both men want the respect of the other, while at the same time they differ about fundamentals of the strategy and technique and tend to dismantle the other's ideas in arguing for their own. It also seems that both men want the limelight to themselves as each, did in fact, independently create this concept and are going to have difficulty sharing the limelight. Somehow this innovative refueling project needs to get the ball rolling quickly as the next generation of spacecraft is being designed now, as the present space fleet will be decommissioned in 2010. The concept needed to be proven by 2012 to justify refueling capability in the new spacecraft to start flying in 2015.

Klinkman vs. Demetriades

While these two men don't seem to agree on the spacecraft's specific proposed design, they have similar concepts and are both marginals to the aerospace industry today. Sterge left academia due to ethnic conflict and chose the hard road to getting his concept accepted by the industry his gamble did not pay off despite a promising staff at Northrop. He could continue working on the idea quietly, or wait ten years till new decisions were being made about staying on the moon. When he left Caltech without setting up another university laboratory and entered into industry, he put the likelihood of the revolutionary design's acceptance in jeopardy. He did this because of who he was as a person, a vulnerable immigrant who could not openly flaunt the government, not because it was advantageous to him economically. Klinkman, a Quaker pacifist, is trying to advance a field in which the military is a major funder of R&D. He refuses to cooperate with the Air Force (which was classified documents he could use) or use their resources as a moral choice, and in doing so, endangers his creation's chance at success.

Both these men, although from very different backgrounds have made choices reflect their values, rather than enhancing their odds of success. Maybe this means that in order to get where you want to be, you have to make personal sacrifices like Von Braun did building the V2 rocket for the Nazi's to get experience to reach for the moon. An old expression is "nice guys finish last," it might be very relevant to the aerospace field, which is supported by government more for its military implications than its capacity to advance the human race into space.

In a manner out of both of these men's control, they are once again in a similar plight. Both have related ideas that challenge the existing paradigm of what can be done in space and how to operate there. In the early sixties, when Sterge was trying to get PROFAC accepted, the prevailing concept was to build a big rocket with a lot of fuel and get to the moon. The infrastructure one would build to support many trips to the Moon, or even a potential shuttling system to space stations rather than a half dozen, was far from anyone's mind except the dreamers like Von Braun, Werner was trying to preserve what was built in the in the late 1960's and had no time or energy to come up with a new infrastructure in 1968. Von Braun's legacy would become the concept of a cheap shuttle sufficient to build a space station. He fully expected a more elegant shuttle to follow and then departure from the space station to the moon. However, this concept would be lost when geopolitical concerns resulted in a space station in the wrong location and of the wrong design to be a transshipment facility and staging area. Sterge, with a little economical insight into the future, saw the potential to design an affordable and substantial means of reaching the Moon by collecting the bulk of the fuel in the upper atmosphere. Von Braun's people thought it could be done, but didn't see the point so NASA missed the opening and the Air Force closed the door.

Klinkman faces a different kind of paradigm induced blindness. He is an outsider looking in at everyone in the aerospace industry and academia. As a computer science major from the seventies, who is he to propose revolutionary space ideas? What these people are missing is that Klinkman has the gift of a creative mind combined with an unobscured view of what aerospace could be. Without conventional wisdom and past compromises to hold him back, he is able to give serious consideration to what is really needed. An expert in the field of aerospace would have stopped him or herself from considering this possibility. Only the young and outsiders are likely to get past the inherent problems. While some outlandish ideas may be futile, there is always a chance that a good idea was lost or overlooked. Nowadays in science when a great discovery is made it is generally not by several people in one field, but a conglomeration of people from different fields. This is because people outside a field are marginals who have never explored the concepts of another and hence do not know what is considered impossible. Hopefully the common fruit of these two minds will not be wasted, and the rediscovery of PROFAC will help LOX-LEO get a fair hearing.

The Struggle for Credibility

A Shift in Focus

Initially the IQP team members were going to be participant observers in an R&D team process. The plan was to study the effects of the cognitive style mix of members on the team in terms of a group dynamic. A previous IQP team suggested that Klinkman's ideas were feasible overall, but more work was required in a few key areas for the design to work. As a functional R&D team, four of us would assist Mr. Klinkman in furthering the development of his ideas.

Not long into the project however, there was a shift in focus. The team received a letter from a NASA reviewer in the STTR program that read:

> *This proposal is very intriguing and if the concept were successfully developed the benefits to NASA would be tremendous. It is advised that the proposers team with credible engineers and scientists to truly explore the feasibility of their idea to gather oxygen in space.*
>
> *–NASA Spokesperson*

It seemed clear that the source of the resistance Klinkman was meeting in the Aerospace community was his lack of credibility due to a lack of experience with the technology. How could he hope to run a cutting edge research project or startup company that could support NASA effectively? As an industry outsider, a computer scientist, his ideas were not going to be taken seriously even if correct. The teams design efforts ceased. Further development of the technical design seemed futile at this juncture. What the project needed was the endorsement of someone with some credibility who could critique the device and then progress could be made.

The teams focus shifted from design work to finding out how controversial the idea was. The next step would be to obtain credibility if at least 25% of the panelists considered the project feasible. It was decided that a forecasting method known as a Delphi study would be the most effective way of gathering feedback from the community. By asking experts in the field for their reactions to the project the level of controversy could be estimated and maybe some potential supporters would reveal themselves.

The Delphi Instrument

The forecasting technique utilized for this project was a Delphi study. Similar in principle to a focus group, a panel of specialists is assembled in an attempt to assess ideas and estimate levels of consensus about what approaches are most promising. A Delphi study, unlike other forecasting techniques, does not require that the respondents meet or directly interact. In fact this is to be avoided until their independent assessments are recorded. Instead, a central party, such as the IQP team, is able to send descriptions and key questions (as well as some related background information in this case) to a selection of individuals in an effort to gauge their reactions as a distribution of experts. A Delphi study has one distinct advantage over other forecasting methods considered, its inherent lack of obligation on the part of the panelists. A typical Delphi study consists of less than 5 pages of background information and questions that can quickly be answered; a total time commitment of no more than an hour. The survey is conducted for the most part through the mail, so the panel can consist of experts from anywhere in the country. The team felt that a much larger base for respondents would allow for the aid of more qualified individuals and increase the chances of a response.

The study consisted of fifty-eight aerospace professors along with twelve active scientists in NASA from cities around the country who were heading up a unit and could debate the ideas. They were mailed a packet containing the Delphi study with no prior contact. A copy of the Delphi study can be found in the appendix of this report. The cover letter informed them that a group of students was conducting research on potential scientific breakthroughs, and their social implications. They were instructed to read a brief description of six technologies that show potential for a breakthrough. Included was a response form along with post marked envelopes to return the study to WPI. The panelists were instructed to rate each item on three criterion. First, the significance on a 5 point scale from trivial to revolutionary. Next, Likelihood also on a 5 point scale from impossible to expected. Finally, they were asked when they thought the technology might be implemented.

The goal was to asses the credibility in the community for Mr. Klinkman's idea and determines if Demetriades's idea carried more weight solely due to the credibility he had in the community having published formally and first. The first two technologies included on the study were Demetriades's PROFAC and Klinkman's Lox in Leo followed by three other technologies that previous IQP groups had completed Delphi studies on. The team expected that the three technologies previously studied would have approximately the same positive feedback rate as before. Responses to these technologies will allow the team to gauge the responses for Klinkman's device; i.e. calibrate the results with regards to the optimism of respondents. Also, directly comparing the responses to PROFAC to those of LOX in LEO should shed some light on the credibility issue. An added bonus to this 'study' is that it is free publicity and increases the visibility of the idea, a pre-condition to credibility. By getting the responses of experts, the team may be able to locate a LOX in LEO enthusiast who would be willing to champion the idea and partner with Klinkman as the NASA reviewer proposed; opening the door to a $100,000 first stage STTR grant.

The goal for the study was a panel of twenty respondents with a one in five positive response rate. This would suggest that there is at least enough interest in the community to consider it an area worthy of legitimate investigation. While not everyone will support it enough to look into it personally, if just a few find it interesting enough to bring up, to discuss the implications with their colleagues, the idea will be back on the table for the first time in 50 years.

Results

A scatter of responses began to appear in just a week after they went out. When the study was closed, 4 weeks later, a total of 12 responses had been collected. Studies conducted by other IQPs doing Delphi panels typically had a sample size of at least twenty, but several of these were done in two waves of testing, so this could be considered a successful first wave. And by one means it was successful: a positive feedback rate of 25% was observed. Several interesting phenomenon were observed from the responses.

First, as expected, the three 'control' technologies received almost exactly the positive response rate they did in previous studies. The following table shows an overview of the previous study compared to ours.

Average Likelihood Response (scaled from 0-4)		
	Previous IQP	2008 Study
Single Stage to Orbit	3.4	3.33
Ram Accelerator	1.7	1.66
Space Elevator	1.4	1.58

This suggests that panel produced by this study has a good distribution of responders. The second observation was the stratification of the responses. Initially, the responses were extremely polarized. The first half of the responses received were either extremely skeptical or very supportive of the ideas in the study. After that, weeks into the study, middle of the road responses began to come in. None of the later six respondents seemed strongly partisan either for or against the idea and coincidentally this was the group that provided the most useful feedback. This stratification can be observed in the following chart.

	Profac			Tether			LEOLOX			SSTO			Ram Acc.			Space Elevator		
Respondent	**S**	**L**	**T**	**S**	**L**	**T**	**S**	**L**	**T**	**S**	**L**	**T**	**S**	**L**	**T**	**S**	**L**	**T**
1	0	1	0	2	3	1	0	1	0	2	2	0	0	1	0	0	0	0
2	2	1	0	2	3	2	1	2	0	1	2	0	1	1	0	2	1	0
3	1	2	0	3	3	3	3	3	2	3	3	3	3	0	0	3	2	1
4	4	3	1	3	4	2	4	3	1	3	3	2	3	3	2	4	3	2
5	4	3	2	3	4	3	4	3	2	3	4	2	3	3	2	4	3	2
6	3	2	1	4	3	2	2	2	1	3	3	1	3	3	1	4	2	3
7	3	1	0	4	3	1	2	2	1	3	4	2	3	2	1	4	3	1
8	2	1	0	3	4	1	1	1	1	0	4	3	1	1	2	2	2	3
9	2	2	3	1	4	1	0	2	1	2	4	1	3	2	0	1	1	2
10	1	1	2	2	3	2	1	0	1	1	3	1	1	1	1	1	0	2
11	4	1	3	2	4	1	3	2	1	1	4	1	3	1	1	3	1	1
12	0	1	2	1	4	1	1	1	0	2	4	3	1	2	3	1	1	1
Avg. Likelihood	1.583			3.5			1.833			3.333			1.666			1.583		

The six technologies were rated on three criteria: Significance, S (0 – 4); Likelihood, L (0 – 4); Time Frame, T (0 – Never, 1 – by 2050, 2 – by 2035, 3 – by 2020)

Finally, interpreting non-response yielded another observation; several of the questionnaires that were returned unanswered showed signs that they were read, and even photocopied. Staples were removed, and the page corners had been folded. The later of the two observations are tied together, and have a reasonable explanation: The people who felt strongly either for or against the possibility of technological breakthroughs were the first to respond, as it took far less time for them to form an opinion on the specific technologies in this study. The responders who took the time to consider the implications and potential difficulties were the ones with the most helpful feedback, and this group took an extra week to respond. The final group, the non-responders thought the idea was interesting enough to make copies, but were not prepared enough to put their professional name behind the ideas. The NASA labs were the most likely to return the instruments unmarked – though sometimes saying it was against policy or that the appropriate place to send an idea with commercial potential was another location. Clearly they had read and pondered the proposal.

This suggests that if the team were to locate a credible source to look into the idea under his name not only is there potential for financial backing by NASA should the position be like that of Koelle, who declared PROFAC possible but not worth it at the time. Professionals and experts in the field may be more willing to see this invention as a possibility and not science fiction if one of their own says there is no reason to consider it impossible

Future Credibility work

A great deal of progress was made during the span of this IQP in the hunt for credibility, but it is just the beginning of the work that must be done. To begin with, a larger panel will need to be assembled to increase credibility of the results, a second wave;

increasing visibility of the idea will be a side effect and may play a large role in gaining credibility. The team has a few suggestions to teams that continue this work. A second wave of Delphi studies should be sent out with one difference. One week after the descriptions are mailed, follow-up calls should be made to every one of the correspondents to encourage the would-be non-responders to respond. Just showing that this study is important enough to warrant a call should be enough for most. Additionally, interviews should be conducted with professors and experts in the Worcester area. Personal interviews will yield even greater results in gauging people's reactions to the idea. Once approximately fifty responses have been gathered, 25 by main and 25 interviews, the more positive responders should be contacted again to see if they would be interested in becoming part of a consulting group to decide if a company can carry out the project. In the end Mr. Klinkman wants to select a member of the aerospace community to act as a technical overseer of the project to make the next proposal "credible."

The Role of Cognitive Styles in Group Dynamics

One of the major goals of this IQP was the determination of what makes an R&D team successful in innovation, and what type of personnel and environment one should assemble to increase the odds of success. Case studies of several of the most significant R&D teams ever to operate in the Aerospace industry were studied for recurring trends. The team's own experience was documented with respect to MBTI personality type mix and analyzed in comparison to the literature and other student teams to find out if there is an ideal R&D team makeup to use as a model.

Characteristics of Successful R&D Teams

Research and Development is an important aspect of many organizations, especially those operating in fields swept by regular technological change. An excellent innovation team puts you at the forefront of your field, in a position to grow and improve faster than the competition. In order to conceive the size and nature of the R&D organization needed to carry out Mr. Klinkman's project several book length case studies were examined: The China Lake Research lab (observed from Ron Westrum's *Sidewinder*), Lockheed's Skunk Works project (observed from Rich and Janos's *Skunk Works*), and NII-88, Sergei Korolev's space race powerhouse (observed from James Harford's *KOROLEV.)*

China Lake

China Lake, the Navy research base responsible for developing the best air-to-air missile ever created (the Sidewinder), was among the most efficient and finely tuned R&D organizations ever to exist. Bill McLean, the director of the base, had a gift for problem solving and a wealth of technical expertise. McLean's team was "small but full of energy and direction." The facility, the rapid response that McLean mandated in his (far from normal) R&D process, and his focus on producing a user friendly product made China Lake a remarkable R&D lab.

Bill McLean, the man behind the sidewinder, was described more than once by his peers as a visionary. His technical brilliance and unique view of how a research and development lab should be run gave China Lake a great advantage over typical organizations. The emphasis on experimentation was extraordinary -- McLean was often criticized for his tendency to perform an experiment rather than a work out complicated mathematic proof. But experiments were faster, and often math was inconclusive. Through his "Gadgeteering" or perpetual prototype philosophy, McLean and his team were able to keep the entire project in rapid progress. The strategy was to test an idea as soon as it was developed. The experiments lasted just long enough to get the minimal data required for the next step. The China Lake facility made this fast pace possible. Everything was available to the engineers: they had trained technicians, an airfield just outside their door, and planes and test pilots from the fleet who were very dedicated to the project.

McLean's model for an R&D lab differed greatly from the average. A typical R&D strategy is to formulate design requirements and working conditions early then carry out a vigorous prototyping and refining phase which eventually leads to an end product. The strategy implemented at China Lake was much more dynamic and focused on input from the user. While the former strategy has little input from the end user, McLean's kept a constant dialog open between the engineers designing; and the technicians building; and the test pilots firing the missiles. This was an innovative way of defining a design requirement. At the time of sidewinder's development there were aspects of air-to-air weapons taken for granted: Missiles were wildly expensive and difficult to maintain; Rockets inaccurate but inexpensive. McLean desired the best of both worlds - a self guided rocket, or a simple, inexpensive missile. McLean developed design requirements to remedy known problems from the field. In doing so he created an incredible, innovative product.

Skunk Works

The Skunk Works was formed in 1943 as a developmental branch of the aerospace company Lockheed. Their task was to build America a jet fighter to contest the German's new plane. Under the command of Clarence "Kelly" Johnson, the P-80 Shooting Star was developed and was the Air Forces main plane in the Korean War. Lockheed then decided to continue funding the new group, and the Skunk Works went on to become the most successful aerospace research and development team ever. Built at Skunk Works were spy planes like the U2 and Blackbird, as well as revolutionary stealth technology.

What made this R&D team so innovative and successful when other companies were not? Based on <u>Skunk Works</u>, there seem to have been four main contributing factors. The first and most important factor was the strong leadership of both Kelly Johnson and Ben Rich, his successor. They were very different in their mannerisms and need to be looked at independently. Kelly was a master of all aspects of aerospace engineering. He was involved in everyone's work and would tell someone when they were doing something wrong. He was known for his short fuse and bad temper. His character and technical genius made him loved, while his severe attitude toward people made him feared. Nonetheless, it was an honor to be invited to his team.

Ben Rich, on the other hand, was much more diplomatic than Kelly. As Johnson's first pick and trained successor, Rich was strong on theory, a great engineer, and a skillful team manager. Where he was better than Kelly was in his ability to deal with problematic people and act more diplomatically. Kelly had to be in charge, take on problems and be left alone. This contrast made Rich a more likable person, and he could negotiate more beneficial situations with the Military. Johnson and Rich were two different men with very different leadership techniques who both ran successful versions of The Skunk Works.

Another factor that gave the Skunk Works the edge was their team selection methods. There was no way to apply to the Skunk Works; you had to be invited there. This meant that you had to be excellent in your field and fit some kind of ideal for what a Skunk Works worker should be, as determined by Kelly, or Rich, or both. On top of these criteria, if you did not work well within the Skunk Works after a trial period you would be returned to normal Lockheed production without a word. What this led to was everyone on the team having a similar mindset, with loyalty to the project and team (and some elitism, as well). Being part of the Skunk Works meant you were on the cutting edge, in a demanding job, and from this confidence only the loyal remained. This loyalty also came from the close quarters where the engineers and workers lived. Everyone worked elbow to elbow to two other people. Privacy was abolished and everyone collaborated. This mentality extended farther than between inter-engineer relations. The construction shop for the planes was less than fifty feet from the office where everyone worked. This meant interactions between machinists and engineers were on a personal face-to-face level, with no bureaucracy or paper work getting in the way. There was a mutual respect between worker and engineer - It was understood they were both masters of their respective fields.

The final key to the success of the Skunk Works was the freelance nature of what they could research and experiment with. There were no higher ups telling Kelly to how to design his planes, everything was done based on what he deemed appropriate. This freedom extended an invitation to the individual worker to be creative and experiment. The freedom to go with a radical idea and take a risk leads to the creation of innovative stealth technology and the Blackbird – the fastest jet ever to fly.

NII-88

In October of 1957 the Space Age was fired into existence by one man: Sergei Korolev, the head of soviet space program. Despite the disadvantages that the soviet program was facing – A missing generation of engineers from the Stalin purges, a lack of support and funding from the government, and a general infrastructure gap when compared to the Americans – it was by all means a success. This success can be attributed to three things: Korolev's genius, his undisputed leadership, and the atmosphere of the lab.

First is Korolev's engineering genius. An excellent mathematics student from childhood, he crafted his intelligence into aptitude at Kiev Polytechnic Institute and Moscow N.E. Bauman Higher Technical School. During his schooling he independently developed a number of gliders and studied aviation extensively. Korolev was an ideal person to head the soviet space program based on his technical excellence alone. The benefit of having a multitalented genius (who can perform the technical tasks he is demanding of others) running your research team is obvious – momentum never slows. The development process continues to move forward because any particularly difficult engineering problems encountered by any part of the organization are tackled both by the engineers directly involved and their talented leader. Korolev was always willing to work late and tenaciously solve the problem encountered. Success after success came to the soviet team.

Korolev’s demeanor cannot be overlooked as it played a key role in the group’s success. Korolev was a firm, fiery leader who would threaten to demote and fire people every day. In the labs and shops this produces enough fear to keep the engineers and technicians working at the best of their abilities; the respect and admiration Korolev receives from them keeps the fear from being debilitating. This is worth reiterating – Korolev is respected enough so that his harsh demands for excellence are always met. The effect is amplified because Korolev surrounded himself with the elitist of scientists and engineers.

The atmosphere of the lab is the final key to its success. Physically, it’s demanding. There are no clean rooms and white robes, often the engineers have to improvise. Personnel sleep in barracks and rations are small and unappetizing. The hardship leads to a strong work ethic and camaraderie between everyone – from the machinists to the engineers and up to Korolev. This opens up a freedom to communicate between every member of every team, resulting in a tremendously productive environment.

Immediately the similarities between the groups become obvious, making it possible to determine what a successful research and development team requires. An extremely intelligent leader produces great work himself and breeds greatness in his personnel. Demanding leaders such as Kelly and Korolev inspire excellence with fear and loyalty, diplomats like Rich and McLean with admiration and cunning. Either style results in a productive environment provided the leader has the technical skills required to keep the team moving forward. The team you assemble must be elite and motivated. By ensuring every member is an expert, and breaking down the barriers between them, you create an environment that promotes communication, and thus promotes innovation. All three accounts report the open atmosphere of the labs and the respect every man had for every other. Finally, ensure you projects don't get tied up in bureaucracy. McLean, Johnson, Rich, and Korolev all gave their teams the ability to experiment and deviate from the norms. This is crucial to all three team's successes and can be the difference between an extraordinary team and an average one. No matter how elite the team and its leader, without freedom it has no opportunity to pioneer revolutionary new technologies. With the right combination of a genius leader, a proud team, and an open environment every day becomes an attempt to realize the impossible - and every attempt brings you closer to revolutionary success.

The Effect of Personality Type

In addition to the characteristics described above, the team investigated the effects of cognitive style (based on MBTI type indicators) on research and development in an attempt to determine the ideal R&D personality-type makeup. A short history of the MBTI test and interpretation of the results follows to provide the reader with the necessary background for the discussion of our R&D team and experience.

The MBTI

The Myers-Briggs Type Indicator (MBTI) is a psychological instrument used to determine the personality type of an individual, based on the cognitive psychology work of Carl Young. It was developed by Katharine Cook Briggs and Isabel Briggs Myers. It determines a cognitive type by locating a person on four dichotomous dimensions base on answers to 100 items dealing with personal preferences. The MBTI results in a score for you in four areas: Direction of energy (extraversion or introversion); preferred means of perception (Sensing or Intuition); preferred mode of Judgment (thinking or feeling); and dominant emphasis in lifestyle (judging or perceiving). The scores from each area assign you a letter, resulting in a four letter representation of your cognitive type, and a reliability estimate based on how consistent the pattern of responses was.

Direction of Energy

Direction of energy is represented by an E (Extraversion) or I (Introversion). It indicates if you prefer to be energized by what is going on inside your head, in a world of thought and ideation (I), or you prefer to be energized and stimulated by the outside world of interactions with people and things (E). Extraverts share thoughts freely and communicate well orally. They prefer to talk things over to deepen their understanding.

Introverts, on the other hand, prefer to reflect and then communicate in a written format, don't like to share their thoughts until their very well developed, and like working alone or with a single partner. They deepen their understanding by reflecting, rather than acting and experimenting in the real world, and work things out logically in their heads, before they are ready to talk about it.

Mode of Perception

Mode of perception is represented by an S (Sensing) or and N (INtuition). A sensing person prefers to deal with facts, the more concrete the better. They prefer to work with specific, objective, tangible, and if possible verifiable data. They are most at home dealing with specific and pragmatic details of a problem in the immediate future rather than the long term implications of different courses of action.

N-types, however, like to start with context, general theories, and concepts, not specific details. They trust they see where things are headed and can change the future with their creativity. They are insightful in about upcoming trends, but often underestimate the practical concern and obstacles in the present. They don't always manage all the relevant details well either. They read between the lines in terms of data gathering and focus on the possibilities. They flourish in difficult situations where they can explore the arising problems and expand their conceptual knowledge base before formulating a plan. N types are attracted to theoretical endeavors.

Means of Judgment

A preferred form of judge is indicated by a T (Thinking) or F (Feeling). This describes your preference for making judgments. Thinking types prefer to make objective decisions based on facts and truth, logical decision rules. They make decisions with their heads, not their hearts, try to be rational, and can miss the human-factor in decision situations and stress the principle rather than the immediate consequence in the case at hand. Thinking types tend to be attracted to technical and scientific fields; or anywhere that the process or procedure for making a decision is logical and specific rather than situationaly variable and subjectively contingent.

Feeling types are just the opposite, and seek harmony rather than justice (in the abstract sense) and try to connect subjectively via empathy with those who will be affected by the decision, trying to see things from their perspective. They insist on doing what is best for all there concerned rather than treating everyone equally. They get personal and seek to please and appreciate everyone in their decisions.

Dominant Lifestyle

The final letter indicator deals with how you live your outward life. It indicates the level of structure and closure you like as opposed to open ended situations that call for improvisation and adaptation. Turbulent task environments that evolve and change appeal to the Perceptive. Clear expectations, productivity, and settled decisions that are not likely to be reviewed and unsettled appeal to the Judgers.

Judging types (J) like to make decisions based on sufficient information and act upon them. They are goal-oriented and like closure. The will commit to ordered schedules with production oriented objectives.

Perceiving types (P) like flexibility. They like to remain adaptable and like to continue taking in new information throughout the problem solving process. They sometimes do not distinguish between work and play, while a J can’t enjoy play until the work is done.

Select Personality Types

Your 4 letter designation is greater than the sum of its parts, as more characteristics can be determined based on the collection of the letters than the individual letters. Of the 16 possible personality types our team contained only three unique types: INTJ, ENTP, and INTP.

INTJ

INTJ types are innovators. Intuition is their dominant trait, and they are introverted so the intuition operates in the internal world of symbols and they deal with the outside world as logical thinkers. They tend to be very independent, and when inspired they develop their (or others) insights into full ideas, concepts, and systems. They prefer to work alone and free of interference, and their judging preference makes them value time to carefully consider problems and courses of action before having to act. They tend to be non-emotional in work environments and like a restrained, organized outward persona, despite, perhaps, being intuitive and spontaneous, even playful, with their inward thoughts to manipulating ideas.

ENTP

ENTP's are extraverted thinkers who are also intuitive as their dominant trait. They are often visionaries whose enthusiasm and impulsive energy comes from their focus on what *could* be. They make good leaders as their energy supports and lifts the team; and they help catalyze the ideation process. ENTP's are often good at getting the most work possible from a team by making them believe something difficult is really possible. They champion change and new ideas. They tend to like fresh perspectives and are able to break complex systems down into simpler models which are able to provide apt explanations. They solve problems by looking at the big picture holistically, not by breaking down the problem and handling each individual factoid as a separate issue to be reassembled later.

INTP

INTP types are inquisitive. Their natural state is reserved and inward-looking, and they tend to focus their efforts into deep studies of whatever is at hand. They tend to be more naive about practical realities and human aspects in situations than other personality types. Sometimes this can lead to team conflict as they fail to consider everyone's opinion as valid if it does not follow logic. They enjoy exploring intellectual curiosities while free of emotional and personal issues, and quickly grow weary of members who take the work environment personally, other types, especially E_F_'s, are easily hurt by the INTP' often-blunt but truthful appraisals.

The LOXLEO R&D Environment

One of the chief objectives of this IQP was to examine ourselves as participant observers in an R&D organization, with particular attention paid to the interactions of personality type. Just as a successful sports team is made of specific players in specific positions which suit their abilities, a successful R&D team can be designed to fit a task environment if one is conscious of personality type interaction effects. Our personal case study enables us to propose a structure and cognitive mix for an ideal R&D team to work with Paul Klinkman (INTJ) in the future. A chronological look at the R&D experience also serves to demonstrate the volatile nature of an aerospace startup and describe the environment which future teams may be operating in.

Beginning: Development Support

The current team was brought into the LOXLEO startup to build on information from the How High, How Fast (HHHF) IQP team. Their project immediately preceded ours and concluded that the idea was feasible and technically sound provided some advances in a few key technologies occurred. The previous (HHHF) IQP team Brendan Malloy (ISTJ), Thomas Huynh (ISTP), and Brian Kolk (ISTJ) put it as follows;

> *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.*

Our LOXLEO team, which was assembled of 3 INTPs and 1 ENTP, seemed a reasonable group to further explore the technical details of Paul Klinkman's device. INTPs are sometimes referred to as "The Thinkers", and ENTPs "The Visionaries." A visionary; who generates ideas and promotes dynamic interplay in the team, supported by three thinkers; who relish in solving problems and developing concepts, was expected to be a highly successful R&D team, if we could agree on a specific plan could be selected and executed. P's tend to conceptualize too low and execute too late—in shout, procrastinate in the data gathering stage. INTP types tend to gravitate toward being engineers and scientists, a MBTI study of the WPI class of 2004 showed nearly 15% of students were INTP, the largest single group of all the 16 MBTI types. This is notable since it is a rare type in the general population about 3-4%. A similar MBTI distribution study by WPI student Gregory Doerschler (now in the Institutional Research Office at Clark University) showed that 43% of the WPI class of 2002 was –NP- type.

It is important to note here that the previous HHHF team starkly contrasts with our LOXLEO team, and that created difficulties in the early stages of the project. Paul Klinkman had gotten used to working with students who wanted him to set hard deadlines and suggest specific detailed tasks to the previous team. This group was a success but actually this was due to the effects of Malloy, who was highly committed and organized the effort, did the public speaking. The ISTP had work to do at the end on his own, but the two ISTJ's worked steadily on a schedule. Due to their more goal- and closure- oriented personality types they wanted to be directed and led by Paul—effectively to work for him rather than think for him with a critical edge. This approach proved less fruitful with our team, as our personality types are characterized by a resistance to deadlines and a desire to do our own independent thinking. Adjustments were required by the team to settle into a productive working cycle, as initially Paul seemed to think we'd want to help out with whatever specific priority came up each week, like a patent application deadline. In our view we were not ready to document a plan yet, as we'd not come up with one or committed to his yet.

The similarity of all the team members (who share the N, T, and P) is also worth analyzing. It is expected that rather homogenous groups quickly develop an understanding of one another and communicate easily, things that are beneficial to the work environment. This was true of the LOXLEO group, who all viewed the problems from the same perspective and attempted to solve them in very similar ways. However, the introverted preference of both the majority of the group and our technical advisor, Paul Klinkman, initially made communication difficult. INTP's are "thinkers" first. That is their dominant. INTJ's are intuitive first, as that's their dominant. He wanted to exchange ideas ad solve problems together. We wanted to understand and test his logic. That made him wonder if we were committed and contributing. Each individual made his own intra-team adjustment, set personal limits, and completed tasks that were not fully communicated to the rest of the group, much less the advisors.

This made it hard for both the advisors and students to judge the amount of progress made during this early part of the project while we were assessing—deciding whether we considered LOXLEO feasible and deciding how convincing Mr. Klinkman was, as well as how strong his case was. While it was our understanding this was the objective of the project at this point, Mr. Klinkman wished us to work more in depth with patent application duties. These specific tasks and deadlines were lost in the troubled lines of communication which connected Mr. Klinkman and our group.

This "rough start" cumulated in the realization that we had to readjust the group roles and the methods of communication to better insure everyone was seeing eye-to-eye. The value of this early period of the project is immense: it allowed us to see firsthand how valuable open communication is in the R&D infrastructure – a conclusion which had been previously drawn from the studies of Skunk Works and China Lake, but which we now truly understood via our own experience.

The similarity of all technical members also resulted in a tendency toward groupthink, where the mentalities ingrained in engineers (namely the paradigms that govern propulsion, spaceflight, and thermodynamic operations) limited the creative output required for such a forward-thinking project. The familiarity with traditional systems biased our thoughts on innovative ones. The solutions to many of these road blocks came from advisor John Wilkes, whose different personality type, extraverted, led him to talk about goals and organization, articulate explicitly when and why our goals changed. He brought new, unique ideas to the table and we managed the flank maneuver to a new plan, goal and division of labor fairly well. This starkly demonstrated the value of a variety of MBTI types.

The Team as Skeptics

After acting as a purely developmental team that was relatively uncritical and primarily supportive, the team switched to being friendly skeptics of the concept in order to prepare it for conference and personal presentations. Simulating a negatively biased technical audience was a surprising different role (but similar to the previous (HHHF) teams effort to break the concept to see how robust it is). The LOXLEO team had various strengths and weaknesses as critics that varied from the strengths they had as a technical team, but as a whole had a good "critical edge."

The chief strength the team had as skeptics was their dominant --T- trait. Recall that thinkers are critical, tough, and logical though they appear intuitive to an outsider. Klinkman is the one who is really Intuitive, though he looks logical in presenting to the outside would. He is actually more likely to invent to deal with a criticism of one of his ideas than effectively criticize himself. As -T-- dominant intuitive auxiliary types the team was both intellectual and imaginative in playing the devil's advocate. As -NT- types, then, the team was very well suited to being skeptics of the idea. Since the majority of scientists are also -NT- types, and so was the inventor the team was a fairly accurate representation of the cognitive preference of the aerospace industry skeptics. We just had to act like we believed their paradigm

There were two difficulties that the team had as skeptics. First was, again, articulating the doubts and concerns and ideas that were not presented convincingly among of a group made of introverts who “fix” things in their minds as they go along. This was expressed previously but remained a common theme throughout the support and skeptic periods of the project. The second problem experienced was the emotional interaction between the team and the technical advisor. The advisor is an INTJ, and that one letter difference (Judging, rather than Perceiving), meant our dominant was –T-, but Mr. Klinkman’s was –N--. Mr. Klinkman looked logical to an outside, but inside he was processing intuitively. We appear intuitive, but inside were governed by pure logic. It all had to fit together to work for us; Mr. Klinkman could overlook details without getting hung up but we could not. The P types find that a bit of stress brings upon better and quicker results. Ps like to move forward without a specific plan, while Js are very plan and schedule oriented. We had to propose a good reason to change a detail or plan, and Mr. Klinkman had to agree on its importance, keeping in mind the fate of his STTR proposal to NASA.

We discovered that Mr. Klinkman was not good at responding to criticism immediately. Initial, oral reactions did not seem to us well formatted and logical. We learned not to assume we had made a completely cogent device-changing critical observation until hearing from Mr. Klinkman a day to a week later. Often an email would come immediately after Klinkman returned home (after about an hour in the car to formulate his response thoughts in a way we would comfortably understand). Sometimes the response would come nearly a week later at our weekly meetings. These observations or objections that would result in design changes took a long time to iron out in this manner, and our difficulty understanding Mr. Klinkman's drawings, which lacked the technical details we had come to expect from more traditional formal sketched in our education, resulted in even more time delays. Ultimately the concerns and misconceptions were cleared up or the design of the device was changed to solve them, and we were able to move to the next stage of the project.

It's clear that this P-J dichotomy could bring about troubles in a team dynamics situation. It did, initially, but fortunately the technical team acquired an interpreter of sorts during the skeptic phase of the project. Peter Moore, who spent the first stage of the project doing a parallel outsourcing project, joined the LOXLEO R&D team during the skeptic phase. Moore is an INTJ, like our technical advisor Klinkman. Prior to Moore's arrival the team was made of only -NTPs (Fossett, Karasic, and Lincoln an INTP, and Roberts an ENTP.) The benefit of an INTJ on the student side of the table cannot be overstated. Moore took on an organizational role which helped bridge the gap between the technical team and its advisor. The MBTI Team Building Guide by Sandra Krebs Hirsh states that an INTJ "contributes to the team by scheduling and completing tasks in a timely and systematic way." This is exactly what Peter, the team's INTJ did, and further, he could naturally see things from Mr. Klinkman's perspective and explain why he was disappointed or upset. Often, in fact, he could tell in advance what Mr. Klinkman's reaction would be.

Visibility

As described in the 'Credibility' section of this document, the team shifted from building the technical case to conducting a search for visibility and technically-credible partners. This shift not only benefitted the Lox in Leo effort professionally and from Klinkman's perspective commercially, but also improved the team dynamics also under study in this report. The change in objective put Dr. John Wilkes in charge of the team more directly than before, changing the makeup of the main research body to three INTPs, one INTJ, and two ENTPs, one in the leadership position. Shifting the leader from an introvert-judger to an extravert-perceiver was ideal when switching from a technical to a social project. The project was initially working on a somewhat esoteric technical topic involving envisioning how systems that have never existed will function in an alien environment. This is the kind of task where the INTP type excels, and the INTJ leader an appropriate fit. They will prepare for closure in the ideation process as soon as the major details are worked out, whereas the INTP would prefer to work out all the details before switching into report mode.

In switching to a project with many social interactions and open communication with the outside world, with deadlines and lead-times required, it was crucial that the leader was an E-T-, that is, someone likely to communicate with others and who could lay out a plan that out INTJ task master could implement. It helped that he was an ENTP visionary, a new product champion, who could see the big picture of where the project is headed and know how the Delphi process works and what the results could mean for the company and technology as well as answering the immediate question. He was also unique in his ability to see the large goal of visibility and credibility in the LOXLEO startup, in the details of who is sampled in the study.

The member with the strongest INTP results was both excited by and apt at tallying and interpreting the gathered results. The student ENTP was soon at home following up the study with phone calls and emails, comfortable representing the group to strangers (as is expected based on his personality type). The ideal team in this social-based situation may not be the same as the technical team from the first stages of the project. Another extrovert (ideally an E-F- type) would have helped get the follow up done faster and more completely, but overall the team shifted into the new role without too many troubles.

The key was to do the necessary staff work and get a final version of the study into the mail by a certain date, even if it wasn't as perfect as Sterge Demetriades would have liked (regarding his PROFAC section). With what we had and when we had to act it was as polished as could be hoped for. This settling for good rather than stopping due to the criticism that it was not perfect is again a result, in large part, of having the task oriented extraverted leader of this stage of the process.

Ideal R&D Groups

A Small, Technical R&D Group

Analyzing the personal interaction of the team in its various situations affords many insights into what makes a successful R&D team. Many MBTI combinations can create a balanced and effective team, especially if the members are aware of their cognitive preferences and their roles in the team are taken on with this in mind. Based on the experiences of the team; focusing on the first hand experience of the personality types encountered; the ideal research group for an technical startup is going to be dominated in numbers by -NT- types, biased slightly toward introverts. There should be both judging and perceiving types, with a judging leader or manager.

A 5-person team made in this manner would be led by an ENTJ and contain one INTJ, one ENTP, and two INTPs.

An ENTJ in a leadership position is a natural fit, and makes an ideal executive type for an organization. The basis for this conclusion is mainly derived from observing our leader, who was an ENTP. The extraverted nature combined with intuition of situations makes an energizing, exciting idea champion who is able to communicate well both in and outside the team. Insuring that the ENTP is a technical expert who is deadline oriented is important, we learned from the various stages of our project. The judging trait is suggested rather than perceiving to help balance the team and create a more dynamic environment. Making the leader a J avoids alienating the single other J member.

The INTJ is a crucial part of the team. INTJ types are organized and goal-oriented, which is necessary in the ambiguous days of an early startup. Left alone, the INTP types may try to tackle a large breadth of things without enough focus. The INTJ is suggested to keep the team focused and productive. The similarity to the leader will benefit this role, as that important line of communication will remain open. Again, this is a role that the INTJ member took on in LOXLEO, and it benefited the team greatly.

The ENTP type is suggested to help facilitate the interactions between members, and provide a second body for extraverted work during shifts in objective. The E--P trait results in someone who is conceptually compatible with the INTPs, and also able to communicate with the INTJ and ENTJ. The ENTP type was determined most important because of the volatile nature of a forward-thinking startup. ENTP's are not necessarily good at getting things done, but are able to navigate in the turbulence that characterizes revolutionary startups.

Finally, the INTP pair form the scientific foundation of the team. Apt at dealing with vexing technical problems and revolutionary ideas, the INTP pair provides the everyday problem solving power to continuously advance the technologies. Alternatively, replacing one INTP with an ENFP gives the team the advantage of a harmonizer.

This team would be a powerhouse of the research and development process. It's technical enough to tackle the difficult problems of an early startup (due to the abundance of -NT- types), while at the same time remaining robust (with 2 extraverts and 2 judging types) and dynamic in the process of finishing tasks and pitching ideas to outsiders. Naturally, other combinations of types would work, but a group of competent and engaged people with the cognitive mix described above, both in terms of character (based on the case studies) and MBTI (based on the participant-observer study) is quite likely to be a small but solid, successful research and development unit.

Notes on LOXLEO Groups

The issue that is not clear to us, having not witnessed the experience, is how valuable it was to Paul to battle his way through his dealing, with dominated HHHF the ISTJ team that preceded us. Is it better to bring on the skeptics who will not read between the lines to push the inventor to clarify or give him people who can more easily understand what he means as long as it is logical? Which group would be more help in building a case to persuade the industry of the value of LOXLEO? In dealing with venture capitalists it would be wise to have an ESTJ, and dealing with venture capitalists is something the LOXLEO organization may very well have to do soon if NASA funding can't be found.

The idea of an ENTJ lab manager, serving an INTJ inventor, with an ISFJ on the team and either two INTP's or an INTP and an INFP, is a promising one to us as long as Wilkes (the ENTP strategist) remains in the picture to balance the issues raised by J's trying to micro-manage P's. The idea is to have an intuitive team with dominant T emphasis so that the case developed is logical. Sensing is required on the team to ensure that enough empirical and real-world data is incorporated into the case for LOXLEO.

There should be two sub teams of three people each one would attempt to uncover more about PROFAC's development and testing during Sterge's Northrop years, and one would try to build a more elegant LOX LEO design incorporating the tether for propulsion.

The hydrogen issue will require a third team. This team will work out the prototype concept for a gatherer that is larger (and more complicated) to operate at 800-1000km, where the hydrogen layer is formed in the atmosphere, or shift to designing a nitrogen gatherer if hydrogen is not going to be achievable.

Nine to twelve people in three to four teams: LOXLEO made of INTJ, INTP, and ENFP; PROFAC made of ISTJ, ENFJ, and INTP; and the hydrogen group made of ENTJ, INFP, and INTP; may provide the appropriate support needed next in the Lox in Leo story.

Next Steps in R&D

The LOX LEO team has speculated about what the most effective next actions for taking the LOXLEO corporate initiative and organization to the next step. The startup is at a critical phase, where technical advancement of the concept must be completed before a large amount of capital is available, but where technical advancement is prohibitively expensive without utilizing preexisting laboratories.

A closer relationship with the WPI aerospace department would benefit the LOXLEO initiative greatly. By utilizing the WPI project-based education system with aerospace engineering, physics, and chemical engineering students complete their MQP projects on several related problems and design questions, LOXLEO could make advances in the technologies required to prove the feasibility of the LOXLEO device to NASA and the aerospace industry. Our team suggests LOXLEO corp. provide $15,000 dollars to WPI to support 1-5 MQP teams whose combined goal is not to build the satellite, but provide a technical proof-of-concept. With this technical demonstration vouched for by faculty advisors of seniors at a reputable institution, the LOXLEO Corporation will be in a position to go to NASA or an aerospace company for additional financial support and organizational partnership.

A partnership between NASA, WPI, and LOXLEO manifested by a freestanding, academic based research center would benefit all parties. The Jet Propulsion Laboratory, a partnership between a university (the California Institute of Technology) and NASA should be investigated as a model. It is a NASA lab which Caltech runs under NASA contract. Locally, the joint WPI / Worcester Business Development Corporation venture Gateway Park is evidence of WPI's willingness to partner with the public sector and industry on such projects. This experience can provide much information on the ideal way to orchestrate the creation of a similar, space-themed center with NASA that also serves the aerospace industry. The vitalizing effect of the Gateway Park on the surrounding area, as well as the recently vacated vocational school adjacent to it (which provides the necessary floor space for the first, incubator-style laboratory), makes this an excellent time to establish this envisioned research center. In addition, Gateway Park may still contain available space for non-biotech startups.

A proposal (likely from a subsequent IQP team) is needed to get WPI and either NASA or the aerospace industry considering such a joint venture. Such a venture would make WPI again a pioneer in space propulsion technology, reminiscent of the era of

Robert Goddard. An IQP team could be investigating the details of creating such a center at the same time the MQP teams referred to above are working on the technical proof-of-concept. This would expedite the growth process of the LOXLEO initiative whether it is officially being taken "in house" by NASA or is a business venture that NASA is encouraging with some seed money.

Outsourcing

At the beginning of this project in October of 2007, the goals of inventor, Paul Klinkman, and project advisor, Professor John Wilkes, with respect to the outsourcing effort were different from what they eventually came to be. Originally my team set out to gain a detailed understanding of the current state-of-the-art, identify which components were appropriate to be outsourced and which would have to be fabricated 'in-house.' We were to locate adequate test facilities to experiment with some of Paul Klinkman's innovations. Eventually we were to get an idea of what the outsourceable components, including test facilities, would cost, and begin to generate the basis for a budget to go into a proposal to NASA.

Along the way there was a shuffling of team members in an attempt to improve team dynamics and output by responding to individual differences in cognitive and working styles. The original setup of the Outsourcing team was INTJ and INTP. The INTJ was incorporated into the LOXLEO team and the INTP was sent elsewhere. There were also separations and mergers of teams, and changes in leadership structure, in response to events and developments. Some new circumstances that developed around midway through the research and development effort necessitated the altering of the goals of the project.

Background

Previous work on the concept of gathering liquid oxygen (LOX) in Low Earth Orbit (LEO) was undertaken from the skeptical standpoint. The prior IQP team had tried to prove it would not work. The majority of experts surveyed had rejected the concept of gathering in the upper atmosphere out of hand, yet some were intrigued by it. So the previous IQP team (ISTJ, ISTJ, ISTP) set out to find just what made the concept of gathering gasses from the upper atmosphere not worth anyone's time. Their goal was to find evidence, even just one fatal flaw, and prove that this concept was not possible. Short of that, could they prove that it was not profitable, that it offered no advantages and was therefore not worth pursuing?

The previous team was ultimately unable to find any fatal flaw in the concept of gathering LOX in LEO. As a result the team members, the advisors, and Paul Klinkman, became 'cautiously optimistic' about the concept. Mr. Klinkman then designed a rough conceptual prototype and pursued a patent. Professor Wilkes and Mr. Klinkman presented this idea at the 2007 AIAA SPACE conference. They also began formulating the agenda for the next generation of IQPs.

The Outsourcing Process

In their original plan I was a member of a two man team. Our original assignment was to investigate manufacturing processes for spacecraft components. Then identify which systems could be constructed in-house and which would have to be purchased. We were to become familiar with the state-of-the-art of current spacecraft designs. In particular, investigate several key components upon which the gatherer would depend. We were then to locate vendors who would be able to supply the needed components, and who would be willing to work with Paul Klinkman to customize their designs when necessary. It was during this process that our advisor elected to assign my project partner to a different team.

The investigation into spacecraft systems was mainly accomplished online. This was my primary source of information because Mr. Klinkman and I believed it to be the most up-to-date. I conducted web searches for vendors, as well as looked for listings on industry websites and in industry publications such as *Aerospace America*, the journal of the AIAA. I was able to find several vendors who would be adequate to Mr. Klinkman's needs. A list of these potential vendors is attached. Another source of leads in the search for suppliers came from the contacts Mr. Klinkman and Professor Wilkes made at the 2007 AIAA Space conference.

After familiarizing myself with spacecraft design I had a better picture of what our needs were. The operations which would need to be accomplished by onboard systems are, basic spacecraft systems operations; station keeping; control of the solar cells; and communications with Earth based controllers. The mission-specific operations are as follows: capturing gas particles in the form of positive ions; neutralizing those particles; storing particles; separation of oxygen from other species; liquefying of oxygen; storing LOX; and transferring the LOX to another spacecraft.

The basic systems, such as power management; guidance, navigation, and control; retro-rockets for yaw control; gyroscopes; and oxygen tanks; are available 'off-the-shelf' and are adequate at the current state-of-the-art. Several companies have been located who can handle those requirements. However, I found that four crucial components would require capabilities not yet achieved at the current state-of-the-art. These components are the photovoltaic cells; the radiators; the electrodynamic tether; and the mechanism to liquefy oxygen. This setback led to the realization that the original goals of outsourcing major components, including the radiator, solar panels, and the tether, were premature.

It was known all along that the current capability of electrodynamic tethers was not nearly sufficient for the demands of the gatherer. It was iffy all along. The expected service lifetime of a tether, currently projected to be two years, was one-fifth what the gatherer would require. The propulsion workload a tether could handle was nowhere near what we needed. Paul Klinkman's proposed modifications would certainly extend the service lifetime, but his gatherer would demand much higher propulsive force than current tethers could provide. Without a significant breakthrough in tether technology, the Klinkman Gatherer would need an alternative form of propulsion. A strong step towards that breakthrough, an idea of Paul Klinkman's that could greatly extend the service lifetime of a tether has been explored. I established contact with an associate of Tethers Unlimited, an authority in the field, to discuss customization of their designs. I was assured that they will absolutely work with their customers to design tethers to whatever specifications are required. This was good news; the leader in the field would partner with Mr. Klinkman to extend the state-of-the-art of tether technology. Meanwhile, we started to scale back to what propulsion would be 'worth having' from a tether. At a minimum one needs to reduce the fuel requirements of overcoming drag to the point that it is not using more than half of one's rocket fuel product to stay in operation.

In theory, a tether that can provide thrust adequate to what our spacecraft will require to remain in orbit is possible. In theory the tether isn't a direct limiting factor. The tether is an indirect limiting factor because of its dependence on two other systems. First: power generation. A substantial amount of electricity would be needed to power a tether of the size we were looking into. Without a fairly clear design for the spacecraft an accurate estimate of required power was impossible. The very basic spacecraft concept that we were basing our rough estimates on would require electrical power on the order of one megawatt for the tether alone. At the current technological level of photovoltaic cells this would require many tons of power panels. Alternately, photovoltaic cells could be just one of several supplementary power-generation systems. Due to constraints on allowable power-generation systems in low Earth orbit, our options are limited; specifically a nuclear reactor is currently not considered to be an option. Different ways of maximizing the output of solar cells, such as constellation arrays of satellites transmitting generated power via laser or microwave to the central spacecraft have been discussed. These concepts would add significant amounts of controls requirements, complexity, and cost. They also have the effect of pushing the gatherer further into the dreaded realm of 'science fiction.' Every time we introduce further complications, and make the overall concept less elegant, I feel we lessen our credibility.

As an aside, the team frequently brainstormed on how best to reach goals from a pragmatic standpoint. My opinion was that as we are still in the stage of selling an idea to the space community, which can be less than hospitable to ideas from 'outsiders,' our solutions had to be as elegant as possible. I felt any gross unnecessary complications in the design could be detrimental to our chances of being taken seriously. The group eventually came to a consensus that this was true, but we should nevertheless investigate any and all options. Thus power generation constitutes another area where significant progress, essentially a breakthrough in lightweight deployable space solar arrays, is needed.

The radiator problem was approached qualitatively as it would have been impossible to make an accurate prediction of the amount of thermal energy the spacecraft would need to radiate. The heat generated by the electronic components would be no more than that of a typical spacecraft and easily manageable with current technology. Problems arise from the high amount of power demanded by the tether, and the fact that the particles being gathered would have temperatures in excess of 2500 Kelvin (approximately 4000°F). This would accrue to a tremendous amount of thermal energy to dissipate.

Lastly, and perhaps most prohibitive, cooling, compressing, and liquefying of a gas in space has yet to be accomplished. Apparently this problem simply has not been solved. This is an issue that needs to be resolved before the concept of gathering gas particles in Low Earth Orbit can become a reality.

Other components, which were expected to be built in-house, turned out to be impossible for the task of gas gathering due to physical reasons. For example the highly corrosive nature of positive oxygen ions in the extreme upper atmosphere necessitated a complete rethinking of the collector mechanism. The original idea of using a molecular turbopump was discarded due to the problem of 'quantum tunneling.' This phenomenon results from the gas particles impacting pump-vane surfaces at orbital velocities.

The collector mechanism would essentially be a dissipative inlet. The team casually referred to the inlet as 'the maw.' The objective was to design an inlet that could capture all the particles it encountered. The problems derived from the impact velocity of the particles. The second generation concept of using a mercury diffusion pump was abandoned with the realization that using mercury in orbit is currently considered unacceptable due to the extreme toxicity of mercury to ecosystems. Oil is an alternative to mercury in a diffusion pump, which Mr. Klinkman is considering. The other likely possibility for the inlet, one which has strong support from experts, is a cryopump. Unfortunately a cryopump, likely cooled with liquid nitrogen has never been tested in space.

In the meantime interim patents, to protect Paul Klinkman's intellectual property, were being pursued with the support of other team members. They were generating Computer Aided Drafting (CAD) drawings, and filing paperwork to fill the requirements for a patent application. It was soon apparent that patents were premature, and the patents thus far pursued were better than the first set, sought after the work of the prior team, but still based on the mercury diffusion pump. Thus they are already made obsolete and overtaken by the continuing process of reconceptualization. The spacecraft, in its current conception, is not yet viable. It was closer technically, but not acceptable yet as it needed a nuclear reactor and mercury.

Outsourcing Summary

Outsourcing efforts would remain valuable and should be continued. The team felt it was important to locate sources for critical components and, by process of elimination, find what the limiting technologies would be. Another benefit of outsourcing efforts would be the networking value. There was a second aspect to outsourcing also; Paul Klinkman is in a position where he could benefit greatly from partnering with professionals from within the aerospace community. The difficult truth remains, as we have elaborated on, Mr. Klinkman's lack of credibility within the aerospace community proved to be a major stumbling block for the effort, and we turned to promoting the general concept rather than the particular process.

An allegory to this is Bessemer's invention of a method to make steel. He developed a technique as far as he could, and when he found himself unable to find the final missing element in a process to make high quality, consistent steel, he went public with his work. Within a short period of time a separate patent on an additive which solved the puzzle was filed. In the end the Bessemer process was fully realized. The LOXLEO story hopes to eventually have a similar story.

Social Implications

An integral aspect of the ideal Interactive Qualifying Project is to consider the social impacts and ethical issues raised by the development of a new technology. Social implications are often unclear while a technology is new, and the advocates are typically biased in favor of the advantages. This is not surprising, as they are focused on the problem they are trying to solve rather than the unanticipated side effects that are likely to emerge later. Therefore the task of assessing how society and this technology will interact is rather difficult and a positive bias is likely to be evident in our interpretation at this early date. Still one can see if there is a strong case to be made on the benefits side and note potential drawbacks and tradeoffs that come up.

The process for predicting whether a technology will have a positive, negative or, on balance, no effect on society requires a broad understanding of the technological context as well as knowledge of that technical field's relation to society. A full entire understanding of the range of potential impacts is impossible and it specific impact will depend to some extent on application choices made later. If the actual impact is unpredictable as no one can foresee the number of offshoots that will inevitably arise, one can still often tell what direction this capability will tend to move the affected system toward. Despite the difficulties, the process of trying to cautiously consider second and third order effects and look for potential negatives is still worth doing.

One goal of an IQP is to address and try to draw conclusions about the technology—society interface based on one's technical knowledge combined with an analytical understanding of at least some social system. In our case the most important social system is the economics of space, but political implications are also important in the context of a space race. In addition we were called upon to be reflective about the small group dynamics that lead to success in R and D teams.

The social implications of success in developing the oxygen harvester in low Earth orbit are surprisingly far reaching. The primary benefit that would accrue to the U.S. space industry utilizing the oxygen harvester is that it would reduce costs associated with operations in space and reduce the cost of lifting material beyond LEO to GTO and especially to the Moon.

The current paradigm in the space industry requires fuel for missions to be carried from the Earth at the site of the launch. The possibility of gathering propellant in LEO for the purpose of refueling is not currently accepted in the space industry. Such a device can be developed only if at least part of the community changes its views on this matter, or the major come to view it as an open question worth investigation. If developed and utilized such a capability would drastically change the economics of space. The current generation of chemical rocket technology will become much more capable, SSTO (Single Stage to Orbit) rockets become worth considering and until such time as nuclear drives, solar sails and space elevators obsolete rocket technology for reaching orbit and traveling around the solar system, there will be a new socio-technical balance that revolves around the cost of filling fueling depots as much as launch costs to LEO.

The notion of creating orbiting propellant depots in space has been discussed by Jeff Foust, but the discussion almost invariably assumes that propellant will be lifted to space. Foust, in Space Review (5/12) claims that the extra room made by not needing to carry fuel to orbit "would have major effect on mission's designs, capabilities, and cost."[2] Anything you could get to LEO could go from there to almost anywhere in the inner solar

[2] Foust, Space Review (5/12)

system after refueling. If refueling does not involve fuel lifted from orbit, doing that becomes much more affordable.

Klinkman's means of gathering the fuel in space has the potential to be much more efficient and cost effective than filling a depot from Earth. Therefore the benefits associated with depots become much greater when they are combined with the capability he wants to create.

Given refueling depots and off world sources of volatiles for fuel, many things that were not expected to happen until new drives were created become possible with current chemical rocket technology. However, this same removal of the technology bottleneck will also reduce the incentive to devote resources to the creation of the next generation of space drives. There will still be pressure to reduce the cost of reaching LEO, but the ability to work around this problem will lessen the sense that launch costs are the only and most important question holding back space exploration and commerce. Indeed, the incentive to develop mining colonies and bases off the Earth will be increasingly strong to the extent that the cost of reaching LEO remains high and unyielding.

In summation, the LOXLEO technology sidesteps the question that is the current focus of the field and produces an economic incentive to produce in space and on planets and moons with substantially less gravity than Earth. This is an interesting moment as it makes the moon more valuable and its resources more important so long as lunar production has a substantial economic advantage over Earth production to support activities in near space. This advantage will probably end in the era of the Space Elevator, but during the rocket era it will be important, and this technology will tend to increase the level of activity during the rocket era and extend its length. This situation creates a window of opportunity for off world entrepreneurial opportunity, and an economic rationale for building a colony on the Moon. The question is whether this economic advantage is large enough to offset the cost of living and working there, as well as developing a production infrastructure on the moon? That question is beyond the scope of this inquiry.

Immediate Benefits to NASA

There are three major benefits that the gatherer concept offers NASA: cost savings, increased available cargo space in spacecraft, and fuel for long missions without large heavy fuel tanks having to be lifted to LEO. Currently it seems that a two or three stage rocket is required to carry one fuel tank to orbit that is substantially smaller than either of the one ejected getting the payload tank into space. Indeed, the payload is typically 5-10% of the ELV rocket on the launch pad and the percentage yield is substantially smaller if the destination is GTO rather than LEO. Under these conditions the cost reduction implications for NASA are tremendous if the tanks designed for future space craft can be made smaller, sent to orbit and filled or refilled there. Of course they will have to be designed to be refueled.

As NASA takes on a new program to return to the moon and government funding is reduced, any technology advances that reduce costs for NASA would be of great benefit in fulfilling its missions on the cheap. Michael Griffin, the Chief NASA administrator, remarked in a review of the value of a fuel depot in LEO during an American Institute of Aerospace and Astronautics address:

> *There are several ways in which the value of the extra capability might be calculated, but at a conservatively low government price of $10,000/kg for*

payload in LEO, 250 metric tons of fuel for two [lunar] missions per year is worth $2.5 Billion at government rates. … [T]his is a nontrivial market, and it will only grow … We may well witness a 21st century 'Gold Rush' of sorts …[3]

The question is whether one can get that much fuel up there for less than that cost and still profit?

One can question the value of building space infrastructure if one has to carry fuel from Earth, but with this technology one might be able to reap a 75-85% profit. How much of the great fiscal savings should go back to NASA and how much should go a refueling company to build capacity and develop new sources of volatiles possibly on the moon itself? If NASA's costs go down the savings could be used for funding of new projects, strengthening the US space program, carrying out more complex missions, and numerous other possibilities. However, if NASA is to gain control of the profit margin, it must earn that privilege by taking LOXLEO technology program in house for development. If NASA is not willing or able to make this investment, the profit will go elsewhere, presumably to aerospace suppliers who will charge what the market will bear, pricing it just under the cost of lifting LOX from Earth until competitors emerge and drive down the price closer to actual production costs.

Let's assume for now that NASA is forward looking and sets up a center dedicated to developing this capability (or assigns it to an existing center) and reaps the savings. However, not being a business it does not expand capacity and sell the excess fuel but limits productions to US government mission requirements. In effect it will spend the savings on expanded capability, i.e. deliver more equipment to the Moon for the same budgeted money. Klinkman estimates that by taking this course NASA could

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3 AIAA address on November 15, 2005

deliver two and half times as much mass to the Moon to build its base at the south pole of the Moon between 2020-2030, and that is just one NASA mission.

Not only would the fuel costs be saved for NASA, but space on the craft would be increased. Because the act of merely getting the spacecraft into the exosphere is so expensive, payload capacity on each craft is maximized to reduce the number of launches. The weight and space available from not needing to carry propellant for maneuvers in space after reaching orbit will allow for a substantial amount of extra equipment to be brought into space with each spacecraft launched. This means that more satellites, International Space Station Equipment, and tools for lunar base construction and later colonization will be delivered far faster (with fewer flights) than would have been possible without a refueling capability.

On the other hand, the overall level of activity in space would grow faster if NASA paid higher prices and let the supplier company profit at its expense for a decade—if the profit is poured back into expanded capacity. The price will come down much more slowly but the supply will be much greater and NASA would benefit in the longer run. One way to have its cake and eat it too might be for NASA to partner with a company to develop the capability and absorb the risk, in return for a fixed lower fuel supply rate (and priority in times when supplies are low) but let the company have the rights to the technology patent and allow the market determine the rates paid by others active in space. Letting its corporate partner profit so long as there is a steady increase of capacity, might be a good compromise.

The ability to refuel with all of the propellant needed for missions leaving Earth orbit will surely benefit NASA as longer and longer space missions are carried out. The trip to Mars takes 6 months. Then one is committed to a year on the ground. Martian atmosphere is heavily CO2 and can be processed into LOX. Zubrin's MARS DIRECT mission concept proposes that an unmanned system be landed to produce the LOX for the return trip before the astronauts depart for Mars.

Returning to Earth will require a large amount of propellant. If a backup supply gathered in LEO could be sent along as well, one has an interesting option. One could avoid landing the interplanetary space craft on Mars to refuel, and hence avoid having to get it back up into space. If one can bring fuel gathered in space for the return trip then the whole mission logic changes. If the spacecraft is left in space it is not necessary to shuttle all of the equipment on the craft that is used explicitly for space related tasks to the surface and back. Who needs a robotic arm that services satellites on the Martian surface? The spacecraft could theoretically remain in space, and ground equipment would go on a one way trip to Mars from orbit. Only people and life support would be lifted back to the exosphere with their Martian samples in a craft specialized for surface to orbit and vice versa shuttle transport only.

Even the shuttle would stay in Martian orbit and not return to Earth. The multiple benefits would change NASA's whole perception, logic and set of procedures procedure for space travel, and incidentally reduce the cost of a trip to the Moon or Mars. That means that these voyages of discovery can happen sooner. If there are more options and backups that probably means that safer mission strategies can be employed as well.

Extended Satellite Lifetime

A problem with the current method of using satellites is the lack of a process for proper disposal. In Artificial Space Debris, a book discussing the issues with human created space debris, it is noted that "95% of all known Earth satellites can be classified as space debris."[4] This means that nearly all satellites are just left in orbit after their useful service lifetime has run out. Typically the only problem is that they have run out of propellant. Satellites that have spent all of their fuel can no longer maneuver or maintain orbit, but are not removed from orbit; instead the old satellites are left in space as junk in decaying orbits that could eventually collide with other valuable spacecraft. If the satellite does not collide with any other spacecraft, the orbit will decay until the satellite eventually reenters the atmosphere. The satellite can sometimes come crashing down to Earth but will normally burn up in the atmosphere. Clive Hamilton the Australian Institute Director commented in an Australian Associated Press news article discussing the issue of space debris:

> *There are over a million pieces of space junk orbiting the earth, and some of them are going to come crashing to earth sooner or later… There's certainly a lot of alarm about it in space circles. They now have to put extra armor plating on satellites and space stations and so on because of collisions with space junk.* [5]

As of today there are no good ways to deal with the trash in space. Space is only becoming more cluttered, vastly increasing the chances of serious collisions with valuable equipment.

> *In the United States, current policy (issued in 1988 by President Reagan) states that "all space sectors will seek to minimize the creation of space debris…consistent with mission requirements and cost effectiveness.*[6]

The problem of space debris is decades old. The LOX gatherer could help alleviate this problem. The main goal should be to prevent this problem from getting worse first by extending the design life of satellites, second by allowing them to be repaired, serviced and retrieved, and third by attaching drive units to space junk capable of boosting them

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4 McKnight (p 23)

5 AAP Newsfeed December 7, 2000

6 Orbital Debris: A Technical Assessment (p 188)

into trajectories that will result in their hitting the sun or burning up in the atmosphere over the ocean right away. One can also prevent the problem from happening with new satellites designed to be refueled in the first place. The Ecological Society of America could develop new protocols for refueling satellites with the propellant collected by the gatherer. Teaming with the ESA would help the organizations reach their objectives.

> *[The] ESA's current policy is "…to reduce to the maximum possible extent the production of space debris and promote exchange of information and cooperation with other space operators…"* [7]

The cost of putting a satellite in orbit being so high, and the need for more satellite communications to support interconnectedness that has become essential in modern society is evident. Hence, a cheaper "greener" recycling or retrofitting method for dealing with satellites is needed. If a satellite was not designed to be refueled a new "clip on" propulsion unit will be needed to re-boost them and move them around. Hydrogen that was lofted to orbit or mined from the lunar regolith could be combined with the oxygen gathered by the proposed LOXLEO system to make fuel. The oxygen gatherer provides most of the gas needed to refuel the clip on units that will be retrofitted to old satellites which would extend satellite lifetimes, reduce space debris, and save money for the organizations paying companies to put their satellites in space.

Recycling spent satellites is not the only benefit to the environment. The fuel required to lift satellites to orbit is extravagant and the exhaust is expelled into the Earth's atmosphere. This pollution per launch cannot be changed unless the mass being lofted is reduced. However, the number of launches necessary to carry out the program can be reduced. The real gain is that new satellites will not need to be put in orbit to replace a

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[7] Orbital Debris: A Technical Assessment (p 188)

satellite that is out of fuel. It would simply be refueled with space based supplies. New satellites will be utilized for different tasks. Are there fewer launches? Probably not, especially as the cost of space operations would be coming down – but much more will be accomplished with the same number of launches. The yield and benefit side of the cost/benefit equation would be increased.

Commercialization of Space

Congress is urging NASA to encourage the creation of privately owned companies to take part in space commerce by contracting with them for services. Unlike in the past when the notion of traveling to space meant droves of government funded engineers working on enormous and expensive projects, privately owned companies have taken interest in space exploration and especially tourism.

The X Prize Foundation is an organization that supports the process of innovation in the private sector. Competitions are held that require innovative new ideas to compete, such as: The Google Lunar X PRIZE, which is a $30 million competition for the first privately funded team to send a robot to the moon, travel 500 meters and transmit video, images and data back to the Earth. Another competition is the Northrop Grumman Lunar Lander Challenge which is a two-level, two million dollar competition requiring a vehicle to simulate trips between the moon's surface and lunar orbit.[8] Competitions such as these are causing a new space based sector of the economy to develop. Clearly the commercializing of space is soon to come. The ability to refuel in space will further aid the commercialization of the space economy by reducing the expense of space travel.

[8] http://space.xprize.org/

The most notable development in the new space based sector of the economy that will benefit from the orbiting oxygen gatherer and its associated infrastructure is the emerging space tourism industry. The notion of an entire economy emerging from a currently nonexistent area may seem fantastic, but John Spencer, a well known space architect would disagree. In Space Tourism: Do You Want To Go? Spencer comments:

> *There was once no cruise line industry, no airline industry, no movie industry, no computer industry. In 1950, there was no communication satellite industry. In 1980, there was no commercial Internet industry. Now they are all multibillion-dollar industries.*[9]

There is no reason this could not be the case for the space tourism industry.

One aspect of the space tourism industry has already begun and is rapidly developing; this is the area of quick flights into space. A few companies are pursuing the goal of bringing passengers briefly into space. A company known as Virgin Galactic is at the forefront:

> *Virgin Galactic, part of businessman Sir Richard Branson's Virgin Group, will fly its passengers on sub-orbital flights aboard its SpaceShipTwo, built by Burt Rutan's Scaled Composites. The first 100 passengers… have already paid the full $200,000 fare…*[10]

A very lucrative market for space tourism is clear from the fact that Virgin Galactic technology is still being developed, but passengers have already paid over two-hundred million dollars. There passengers will experience a mere 4 to 5 minutes of microgravity, but it will be the trip of a lifetime. If their spacecraft could be refueled, the length of time a tourist would have in space would dramatically increase as sub orbit tour hops could

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[9] Spencer (p 158)

[10] July 9, 2007 Space Daily, Distributed by United Press International

become orbital. The oxygen gatherer will allow for an infrastructure of fuel ‘stations’ in space, which companies like Virgin Galactic would utilize to extend their space flight times, thereby enhancing the space tourist’s experience. Spencer forecasts in his book that by 2010 orbital yachting will become a reality.[11] If this is to happen the network of ‘gas stations’ set up by the gatherer would also provide fuel for this new industry, and massively accelerate its development.

The journey to space will likely not be the ultimate goal of space tourism. Plans for hotels in space have already started. Hotels in space will be a large market for the oxygen gatherer as they will need a substantial amount of oxygen and water, yet cannot go anywhere to get it. They will need to be serviced by spacecraft that have been refilled at a fuel depot. The freight tender will probably not be much like the spacecrafts designed to carry passengers quickly and safely. Companies such as Virgin Galactic could provide transport to space hotels like:

> *"Galactic Suite", the first hotel planned in space, expects to open for business in 2012 and would allow guests to travel around the world in 80 minutes. [T]he space hotel will be the most expensive in the galaxy, costing $4 million for a three-day stay.*[12]

Oxygen will be needed to create a breathable atmosphere in the hotel, as well as produce propellant to burn to keep the hotel in orbit and it will also be turned into water for plants, people and radiation shielding. It is to be expected that the hotels will ship equipment from Earth to reprocess CO_2 to make a breathable atmosphere, but they will still need to make up gas losses into space. The oxygen gatherer could, at a minimum, save a

[11] Spencer (p 51)
[12] August 13,2007 ChinaDaily.com.cn

substantial amount of money for the hotels, but may actually be necessary to make the business concept work at all.

A growing a thriving tourist industry will need to bring down costs to expand the pool of potential tourists. First one wants those few who can afford $4 million each but then one wants to serve a family of 4 in one cabin for the same price. A truly mass market will require fares of about $100,000 each. However, returning to the question of reprocessing CO_2, one might want to avoid doing that if there is an alternative source of oxygen in space. Carbon dioxide is very valuable in space, as plants need it. Hence, a lucrative business picking up CO_2 for agriculture units on the Moon and trading for oxygen pulled from the lunar regolith will probably develop one day.

In the meantime, the oxygen will have to be gathered in LEO and used to produce water.

H_2O and CO_2 will go to agricultural units associated with the hotels or their support sites on the moon to support plant life. But, initially, the plants in the hotels are more likely to be decorative or biosphere balancing bacteria than a major source of food. It seems likely that the Earth and the moon will compete to be the support base for the orbiting hotels. Luna will increasingly have the advantage ultimately taking over agricultural production of the bulk staples (corn, rice, potatoes) too expensive to lift from Earth. Earth will retain the edge on high value luxury items like beef and tree grown fruit.

Implications Summary

The scope of NASA projects, satellite technology and the space tourism industry would undergo significant developments as a result of the successful development of an orbiting oxygen gatherer. If NASA develops it, the agency would save billions of dollars, which can be used to fund new projects. If it does not it will pay suppliers to increase its mass delivery capability who will end up slowly bringing down the cost of space activity as soon as there is competition (based on price) among them. Satellites will become refuelable, and hence reusable so fewer more durable spacecraft will be built. They are a primary means of transferring information now, and will become more cost effective. The space tourism industry will benefit greatly from cheaper operating costs as a result of a local source of oxygen in space. Implementation of the device and the ‘gas station’ infrastructure will revolutionize how society views and utilizes space. No longer will space activity be planned and experienced by only a handful of elite pilots and scientists, but space will become accessible to the super rich at first, and then the public via a lottery system. At the point when a ticket is about $100,000.00 something like a mass market will emerge and there will be important economics of scale.

The reduction in the cost of access space could create a multinational unified space community. Currently the International Space Station has only very few nations participating in its development and use. This will change when not only the world’s richest nations can afford to send astronauts, but due to the relativity low costs to get to space the average nation will be able send astronaut and scientists to space. The International Space Station would truly become international with scientists from all over the world working together to advance knowledge and develop technology.

With many nations being able to cheaply access space, via commercial carriers issues of ownership will likely take place. Disputes over who owns mining writes on the moon will require new laws and regulations for dealing with space exploration and development. This topic has been fully examined in a parallel Interactive Qualifying

Project titled “Who Owns the Moon? Property and Mining Rights Issues.”[13] We note that many of our cost estimates assume the need for an infrastructure to support regular trips to the Moon. There will be at least 20 from 2020-2030, 2 per year, just to build, man and operate the proposed lunar base at the South Pole of the Moon.

A previous IQP titled “Harvesting the Atmosphere,” written by Port, Scimone, and Verbeke summarizes the benefits for the moon base:

> *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.*

A full analysis of the benefits of a moon base can be found in “Harvesting the Atmosphere.”

This project examined many of the likely implications that would evolve from the ‘hunter-gatherer’ space economy which Paul Klinkman’s invention would create. All of the implications of the oxygen gatherer cannot be foreseen, but the clear benefits of the gatherer will change the fundamental manner in which space is perceived and used. At this point the case in favor seems so overwhelming that it is hard to see the downside of

[13] Miller, Joseph and David Coit. WPI IQP

removing the bottleneck to space which has constrained the space program thus far. However, we are not unaware of the challenge of managing a massive flow of traffic to and from LEO. It will require a massive regulatory and monitoring system much like what not exists to make air travel safe and predictable, scheduled and channeled. Further, there will probably be more robotic spacecraft than there are aircraft, and in LEO there may have to be manual override controls so that a human on the ground can take over. However, the aircraft industry has had to manage these challenges in the region reaching up to the stratosphere in the 100 years since the Wright Brothers first flew and will be up to the challenge of bringing order and control to the Near Earth Space Region in the next 100 years.

Project Future

Project Future

Developing a spacecraft is a major challenge that we knew would span a much longer amount of time than a three-term IQP. This effort could easily last a decade. As such, conclusion of our portion of the effort must ensure a smooth turnover to the next team who will be picking up where we are leaving off. Having read this report the next team will know exactly what we have accomplished in terms of technology, organization, visibility, and credibility; and hence, where we are leaving the overall Klinkman project. Our job was really to explore and try to describe the nature of the task at hand. Some resolution was gained during the course of our IQP about what still needs to be accomplished before Mr. Klinkman's goals can be reached. We certainly have a clearer idea of what is at stake and think that the discovery of Sterge Demetriades' work suggests that Mr. Klinkman is on the right track, and suggests that there is more than one way to reach their common goal. Through close examination of the technical requirements of the spacecraft and an informal consultation with numerous experts in the field, we were able to better define what developmental stage the gas gatherer was in.

NASA is expected to have a finalized plan for their return to the moon within about seven years from now. Paul Klinkman is taking that to be an effective deadline. NASA currently does not include the capability of refueling in LEO in their plans for returning to the moon; Mr. Klinkman wants to change this. He wants his concept to be tested and proven in time for NASA to take notice and incorporate it into their plans. Mr. Klinkman is not alone. Others, such as Dallas Bienhoff at Boeing, with his designs for in-orbit fuel depots, are suggesting novel technologies and techniques to aide this latest goal of space exploration.

A loose end in this effort is reestablishing contact with the former member of the National Institute for Advanced Concepts (NIAC) who had participated in the previous IQP team's Delphi study. NIAC was recently defunded and no longer exists, but the former members can still make valuable contributions.

The Defense Advanced Research Projects Agency (DARPA) could be a very useful group to establish contact with. Sterge Demetriades' later work on PROFAC was classified by the United States Government, mainly to silence Mr. Demetriades. The next IQP team will decide whether or not that information will be necessary. Should they choose to seek declassification of the documents, DARPA may be their best help. During December of 2007, when our team was going to establish contact with DARPA, the decision was made by Mr. Klinkman not to. For the time being he would prefer to not involve the military in the developmental stage of his spacecraft; however, DARPA should be at least remembered as a potential help in making this classified information available, should Mr. Klinkman change his mind. Should the next team choose to pursue this, the recommended point of contact is Lieutenant Colonel Fred Kennedy (USAF). His telephone number and email address are (571) 218-4372 and fred.kennedy@darpa.mil. Col Kennedy is associated with a group that has experimented with on-orbit fuel transfers. Clearly the Air Force wants the ability to refuel their costly satellites, and is willing to make multiple launches from Earth every year to do so. Information on this experiment can be found at http://www.darpa.mil/orbitalexpress/.

As a side note, Mr. Klinkman does not want to involve the military in the developmental stage of the spacecraft, but he is not against the refueling of military satellites and anticipates the military to be a major customer.

The extent to which Professor Wilkes and Mr. Klinkman would like to keep Sterge Demetriades informed of and involved in progress was a large discussion the team held. This is further elaborated on in the section of this report about Mr. Demetriades. Briefly, he is an asset in that he has a lot of contacts still active in the aerospace community, and can show us faster channels of making contact with those people. In the interest of maintaining a good working relationship between the current WPI IQP team and that gentleman it would be prudent to choose a liaison and introduce Mr. Demetriades to that individual.

If the next team needs to search for alternative sources of funding, or vendors, or potential consultants, the proceedings from the upcoming SPACE 2008 conference will be useful. There will be lists of names and organizations which could help with group efforts.

An aspect of Mr. Klinkman's vision is a detached fuel depot, used to keep refueling operations to the customer separate from the gatherer. A Boeing manager, Dallas Bienhoff, has led a team that already designed a sizeable fuel depot. Boeing has taken the position that they will not further develop the depot until they are guaranteed that it will be bought by NASA, or another space agency. NASA has taken the position of saying, essentially, 'you build it, we'll use it.' The problem is not the 10 flights to build it, but the 20 flights per year to fill the depot just once. Still, Boeing persists that an economic case is there, even at that price.

At the close of our IQP we were told that a man named Kenneth Cox, of the Aerospace Technology Working Group (ATWG), has taken an interest in the Klinkman gatherer concept. Cox worked at NASA during the Apollo era. Basically the ATWG is a group of scientists and engineers, originally initiated by NASA, who investigate new ideas they think would open up access to space. Capturing the attention of just such a group was essentially the ‘reach-goal’ of the Delphi study that we conducted. Based on our work Mr. Cox has approved the idea of distributing our description PROFAC and LOXLEO to the thirty to fifty people expected to attend the first day of the conference, and asking them to fill out the Delphi instrument overnight.

If they do so, and data is collected on a few basic variables such as their age, highest degree and field of expertise, it will be possible to sort the responses and identify our ‘expert panel’ out of this pool of participants. It is expected that Mr. Cox will correspond with Mr. Klinkman, Professor Wilkes, or both in the near future regarding the amount of involvement they are willing to have in developing Mr. Klinkman’s concept.

If this goes as planned it is possible that a full panel of 25 experts or even a panel of 25 ATWG experts and 12 other current NASA and University experts can be assembled and compared on this concept. That would go far toward achieving the goal of making sure key influential people had heard of the idea and had a reference to consult. This is visibility, the first step toward credibility. We wanted Mr. Klinkman to have a body of data before he decided whether and how to approach the Aerospace, Physics, and Chemical Engineering departments at WPI to look for people to help assess the latest version of the refueling concept.

Conclusion

Mr. Klinkman’s current conception of the LOXLEO gatherer is not feasible at the current state-of-the-art of the enabling technologies. This is a situation where the ultimate goal is currently an impossible reality, so the team must do everything it can do and then reevaluate the situation.

The hope of this IQP team with respect to the Delphi study was to expose Mr. Klinkman's idea to a large audience of experts and to gauge the extent to which the aerospace community feels the technology is worth pursuing. As expected those who responded positively were in the minority, but we received more positive responses than we had hoped. The results of the Delphi study are encouraging.

The previous team concluded that the concept of gathering gasses in orbit was sound. Our team determined what the concept needs from aerospace technology to be feasible, and roughly where Mr. Klinkman's concept is in the developmental process. We devised a way to market the concept in order to generate 'buzz' within the aerospace community, which resulted in Kenneth Cox reaching out to us with the potentially huge opportunity represented by the ATWG.

The next team will hopefully not encounter the setbacks and direction-changes this team endured. Due to the long-term nature of developing a new concept for a spacecraft, each successive IQP team does all they can to advance the effort and conclude by facilitating as smooth a turnover to the next team as possible. Ultimately Mr. Klinkman's vision will be realized.

Addendum

A presentation was made by Professor Wilkes and Paul Klinkman to the Advanced Technologies Working Group and the International Space Development Conference. A handout given to the audience and the PowerPoint slides are included in the appendix.

Appendices

Appendix A: Delphi Study

Dear Panelist,

Below is a list of possible breakthroughs. Under each breakthrough there is a category for you to gauge each breakthrough's significance on the future of space travel should it occur, the likelihood that such a breakthrough would occur, and the time frame that would occur in. Beneath each breakthrough there is also room for some brief comments, should you wish to elaborate on your opinion. Once you complete this questionnaire, please return only the two questionnaire pages to it to:

Space Technology & Technology Institute
Division 46, Interactive Project Program
c/o John Wilkes
Dept. of Social Science & Policy Studies
WPI
100 Institute Road
Worcester, MA 01609

If you would prefer to complete the questionnaire electronically email DelphiStudy2008@wpi.edu to request the document in electronic format.

A.) PROFAC- A 1959 paper by Sterge T. Demetriades outlines a system for spaceflight not fully reported in the only paper to which we have access. At the heart of it is the Propulsive Fluid Accumulator (PROFAC). PROFAC is an orbital device that remains at an altitude of roughly 100km, gathers atmosphere, and stores oxygen-enriched air. This creates a refueling station for both nuclear spacecraft drives (where the air is used as a propulsive fluid) and chemical (hydrogen) rockets (where the air is used as an oxidizer). A moon-bound vehicle which is refueled in earth's orbit requires roughly 5% of the fuel mass required for one launched directly from the earth to the moon.

The two orbiting components of PROFAC are the Orbital Vehicle and the Accumulator. The Orbital Vehicle functions as a ramjet powered by nuclear or solar energy and provides the thrust required to overcome it's, and the Accumulator's, drag. The Accumulator, which is located concentric or parallel to the Orbital Vehicle, gathers atmosphere and stores it as liquid in an attached tank, which can then be detached to connect with the outbound space vehicle. The final piece of the PROFAC system is the spacecraft itself, which launches from earth and refuels at orbit. Mr. Demetriades's 1959 paper proposes nuclear drive ships as the most ideal companions to the orbital components of PROFAC.

B.) Space Tethers- Space tethers connect two main bodies with a long conducting wire. The arrangement, once brought to orbital velocity, is deployed into a self-propelled equilibrium. Tethers operate in two different designs. The first design is called momentum-exchange, which operates using the principle of differential gravitational pull, coupled with their difference in centrifugal force (a product of their different angular velocities) produces a stable vertical orientation. These tethers are known as "bolos." The longest tether proposal we have seen of this type described as a capability within the state of the art and ready for deployment was ESA's YES2 satellite at 30km. This deployment was not a success, due to an electrical anomaly which released the brake after 3.4 km were successfully deployed.

The second tether application works using the magnetic field of the earth. A current is induced in a conducting tether via magnetic flux as the tether moves perpendicular through earth's magnetic field. Alternatively, solar panels could induce a current through the tether, which would propel it via electrodynamic force from the earth's magnetic field. This is still very experimental but a plan to deploy an electrodynamic tether from the ISS that can produce .23N is noted in the literature. Electrodynamic tethers along these lines are also expected to be able to propel orbiting, ~100 kg satellites to higher orbits. Development in this field would result in propulsion systems for large stations in earth's orbit which would counteract drag and have long "on station" lifetimes.

The following LOX in LEO system proposal incorporates an electrodynamic tether in its design. The largest model calls for one over 50 km long that can deliver 76 Newtons of force to overcome drag. If skepticism about that feature is the only problematic element in the proposed system please comment on the availability of a tether with that capability in this item. Don't let it color your opinion of the other non-tether claims made in the next item.

C.) Gathering LOX in LEO- One of the chief expenses in the current system of space launch, and one of its foremost limitations, is the large amount of fuel expended carrying liquid oxygen to orbital altitudes. Inventor Paul Klinkman has proposed a method to reduce the amount of fuel required to launch by collecting oxygen from the atmosphere in low earth orbit (LEO) at an altitude of 350 km. He thus creates a supply of liquid oxygen (LOX) and of other gases for spacecraft to refuel without the expenditure of lifting it from earth to LEO.

Mr. Klinkman's design uses a maw and molecular pump to harvest gases from the predominantly (90%) oxygen layer of the thermosphere at 350km in altitude. The system is constantly in orbit passing through this very high vacuum layer of the thermosphere, near the orbit of the International Space Station. Collection of incoming oxygen is aided by sweeping through the near vacuum at orbital velocity and is performed via a mercury vapor diffusion pump that is mounted to the front of the craft, utilizing a mercury curtain to capture the high speed molecules. The mercury molecules condense on the sides of a rotating conical surface, where they will be forced by the pseudogravity of rotation into collection tubes. The most elegant and efficient version of the spacecraft is propelled using a single massive electro-dynamic tether over 50 km long, though other solutions are possible, as noted in the prior item. It should also be possible to reduce the required thrust of any tether by deploying two or more of them.

LOX in LEO System Details**-** There is a considerable gap between a proven electro-dynamic tether that can produce about a quarter Newton of force, and the largest proposed spacecraft that will require at least 76 Newtons of force to overcome drag. A jump to robust multi-strand tethers is not inconceivable. Tethers Unlimited Inc. (TUI), the main company active in this field, is moving toward multi strand tethers to make them robust enough for a design life of ten years. Though Mr. Klinkman claims that tether propulsion is not an absolute necessity for his system, he is drawn to the elegance of the approach. The possibility of utilizing multiple smaller gatherers, each with a single tether, is also being investigated.

On other challenging fronts, more than one way of radiating heat from the craft and storing and transferring the collected gases is still under consideration, but Mr. Klinkman claims that at most only modest incremental extensions beyond the state of the art are required in these areas. Only the tether area would call for something like a supporting breakthrough.

One proposed system avoids having spacecraft rendezvous with the gatherer by offloading the tanks to an orbiting fuel depot. Dallas Bienhoff's team at Boeing proposed such a depot to NASA two years ago. Mr. Bienhoff's team at Boeing envisioned 20 launches per year to fill the depot, thus enabling it to support 2 lunar delivery missions per year while the moon base is being built, 2020-2030. They estimated that being able to refuel in LEO would increase the annual tonnage that could be delivered to the moon by those two missions by 250%. The Klinkman team may leave their depot connected to the gatherer, saving one rendezvous step.

Mr. Klinkman claims that the LOX in LEO approach that he advocates could re-supply the LOX portion of the fuel requirement at a fuel depot for a decade using a single orbiter with a 20 meter diameter maw. The spacecraft would gather full time except when the maw is closed during solar flares. The idea of taking the 5% nitrogen which would be taken in at that altitude and forming nitrogen tetroxide (N_2O_4) or nitrous oxide (NO_2 is a possible monopropellant according to Peter Schultz at Brown University), is under discussion.

Two annual launches delivering hydrogen to the depot would still be required, if one was to avoid cutting into the Boeing delivered payload estimates. This is probably a temporary impediment. Mr. Klinkman considers a parallel LEO hydrogen gathering system operating at 800-1000 KM in altitude to be a possibility, though the Van Allen belts are a complicating factor at that altitude.

D.) Reusable Single Stage to Orbit (SSTO) – The use of a SSTO as a launch vehicle has been abandoned by NASA since 2001 when the X-33 project was put on the back burner. However, since such a launch vehicle is still capable of reaching Low Earth Orbit (LEO), the only major problem is its fuel capacity. If the vehicle was redesigned so that it could be refueled in orbit, then fuel capacity would not be an issue when traveling beyond LEO. The rocket would launch as it has in the past, from a tower on Earth, and once it reaches LEO it would rendezvous with fuel canisters or a refueling station in orbit. These canisters could be launched into LEO by the Ram Accelerator described in the next item in this section. Due to the extreme g-forces in the Ram Accelerator launch, transport of materials and supplies is the only viable use of this launch system. People and fragile cargo would go up in the SSTO vehicle. The two in tandem would create a capability worthy of being called a breakthrough.

E.) Ram Accelerator – The ram accelerator concept was developed by Abraham Hertzberg at the University of Washington in Seattle. It works as a stationary ram-jet engine by accelerating a launch vehicle inside of a steel pipe. The pipe would be built into the side of a mountain, measure about 750 feet long, and be filled with a yet-unknown combustible mixture of gasses. When the gas is ignited, it projects the launch vehicle upward at about 30,000 G's. The launch capsule must be designed long and slender to prevent drag in the atmosphere, and have a sharp point at the top to prevent the force of the launch from igniting the gases above the launch vehicle in the pipe. To prevent friction against the pipe, the launch vehicle is slightly smaller in diameter then the pipe, and uses the gas in the tube as a cushion. The extreme g-forces make this style of launch impossible for humans, but could be used to transport various types of cargo and especially fuel to LEO.

F.) Nanotube Polymer Space Elevator - The space elevator is a 60,000 mile, three-foot-wide ribbon anchored on one end to a platform on Earth and to a counter weight in space on the other. First an initial spacecraft will have to be launched with the ribbon into geo-synchronous orbit. Once in orbit, the ribbon will uncoil as the spacecraft moves higher to keep the center of mass at the same point. When the ribbon reaches the Earth's surface, the craft will unroll the last 10,000 miles of ribbon, moving up to its geo-synchronous station. Once constructed, 13 tons of cargo can be moved up the "ladder" at a time. The vehicle that moves the cargo would use a couple of tank-like treads that tightly squeeze the ribbon. It will take about a week for cargo to reach geo-synchronous orbit at 22,300 miles up. The ribbon will be constructed out of carbon nanotubes (explained below), which are lighter and seven time stronger than steel. Currently the longest nanotube ever made is just a few feet long. However, if a nanotube-polymer breakthrough occurs, it will be possible to build the 60,000 mile ribbon.

Questionnaire Rating Section – Page 1

Please enter your name:	

The rating scales are as follows:

Significance:	Likelihood:	Time Period:
1 – Trivial	1 – Impossible	1 – Early (2020)
2 – Marginal	2 – Improbable	2 – Middle (2020-2035)
3 – Small	3 – Unlikely	3 – Late (2035-2050)
4 – Moderate	4 – Likely	4 – Never
5 – Major	5 – Probable	
6 – Revolutionary	6 – Expected	

PROFAC		
Significance:	Likelihood:	Time Period:
Comments:		

Questionnaire Rating Section – Page 2

Space Tethers		
Significance:	Likelihood:	Time Period:
Comments:		

Gathering LOX in LEO		
Significance:	Likelihood:	Time Period:
Comments:		

Reusable Single Stage to Orbit (SSTO)		
Significance:	Likelihood:	Time Period:
Comments:		

Ram Accelerator		
Significance:	Likelihood:	Time Period:
Comments:		

Appendix B: Outsourcing Vendors

General Spacecraft Systems and Components

Space Systems/Loral
3825 Fabian Way
Palo Alto, California 94303
(650) 852-4000
(800) 332-6490
http://www.ssloral.com

From the website:
"A subsidiary of Loral Space and Communications, SS/L designs, builds, and tests satellites, subsystems, and payloads; provides orbital testing; procures insurance and launch services; and manages mission operations from Mission Control Center in Palo Alto."

SpaceDev
13855 Stowe Dr
Poway, CA 92064
(858) 375-2000
(877) 375-1004
http://www.spacedev.com

Specializing in deployable structures, electromechanical systems, hybrid propulsion, small satellite design, integrated 'plug and play' systems.

Orbital Sciences Corporation
21839 Atlantic Boulevard
Dulles, VA 20166
(703) 406-5000
http://www.orbital.com

Specializing in engineering and test services, launch systems, radiators and thermal control, fabrication and testing of satellites.
Orbital Sciences employs over 3300 people, around 1600 engineers and scientists.

Surrey Satellite Technologies Limited
Tycho House
Surrey Space Centre
20 Stephenson Road
Surrey Research Park
Guildford, GU2 7YE
United Kingdom
44 (0) 1483 803803
http://www.sstl.co.uk

Mission Statement:
"To be the recognised world leader in providing customers with affordable access to space. Leading the small satellite market across the full spectrum of missions in Earth orbit and beyond. Tailoring price, performance, schedule and risk to meet each customer's requirements. Stimulating and exploiting research into advanced small satellite systems. Fostering a culture of team-spirit, innovation and excellence. Generating consistent and robust financial success for shareholders."

Surrey offers consulting services which could benefit future work. They also do business in space-ready photovoltaic panels.

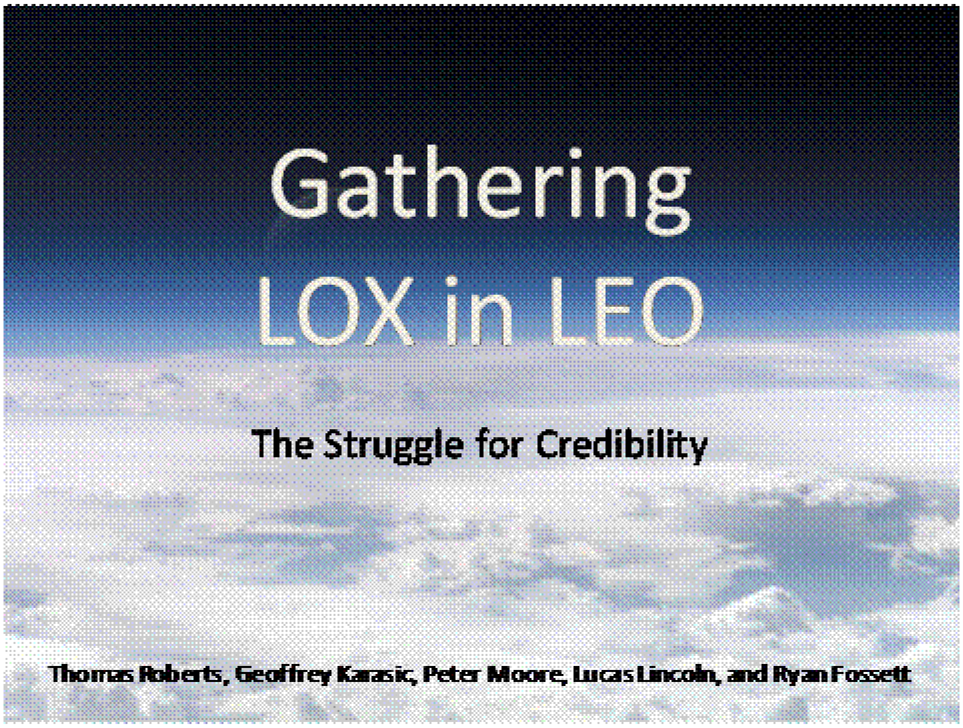
Tethers

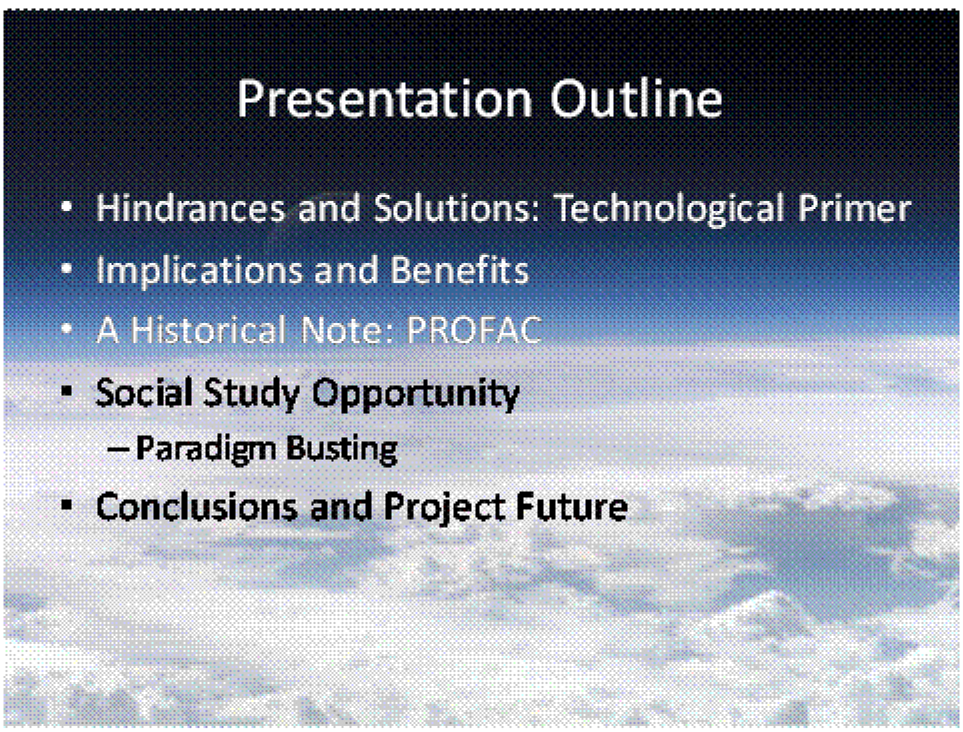
Tethers Unlimited, Incorporated
11711 North Creek Parkway South, Suite D-113
Bothell, WA 98011-8804
(425) 486-0100
http://www.tethers.com

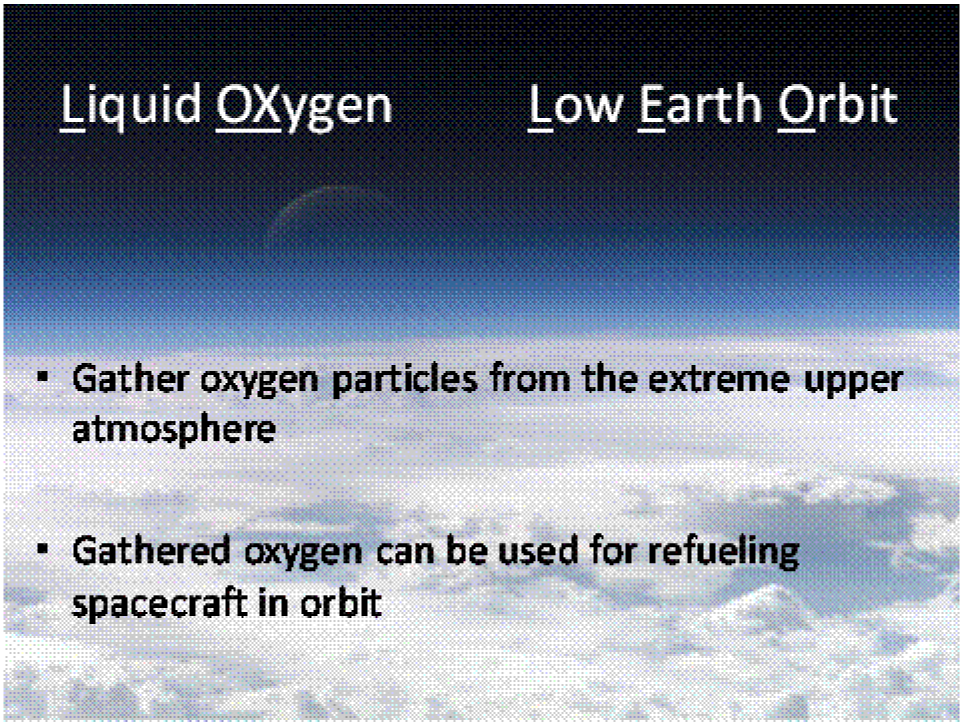
"TUI develops advanced technologies to solve the most difficult challenges in space missions."

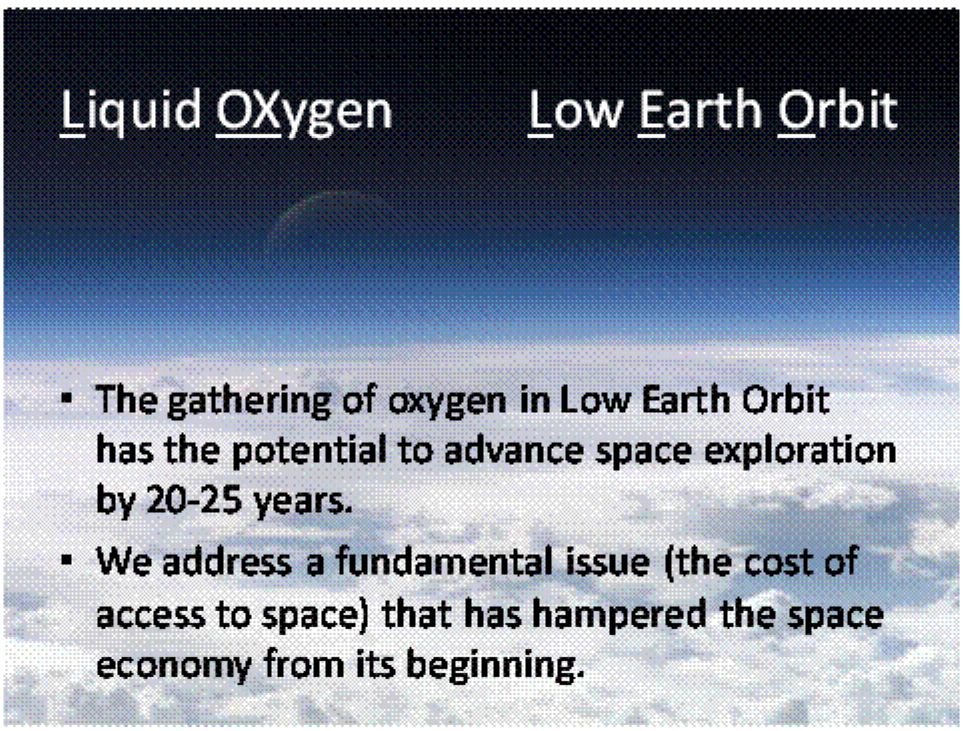
Specializing in propellantless propulsion, satellite cluster formations, radiation remediation. This vendor may also be useful for general satellite subsystems as well.

Appendix C: Holy Cross Power Point Presentation






Liquid OXygen Low Earth Orbit
Gather oxygen particles from the extreme upper atmosphere
Gathered oxygen can be used for refueling spacecraft in orbit

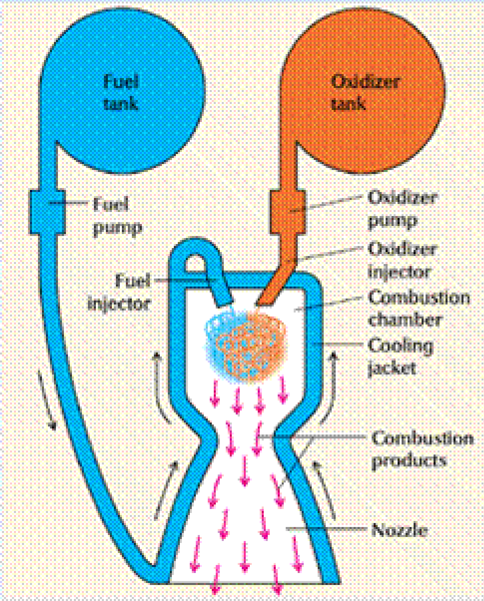

Liquid OXygen Low Earth Orbit
The gathering of oxygen in Low Earth Orbit has the potential to advance space exploration by 20-25 years.
We address a fundamental issue (the cost of access to space) that has hampered the space economy from its beginning.

Ares V Rocket, part of NASA's Constellation program to return to the moon

- Solid-fueled boosters propel payload into orbit
- Significant portion of payload is oxidizer
- 90% of the fuel on this rocket will be used just to get the payload into orbit.

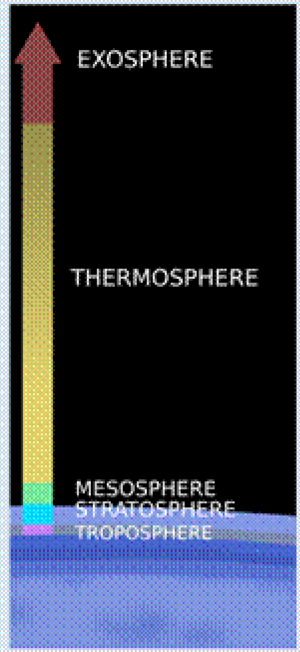
Liquid Rocket Fuel

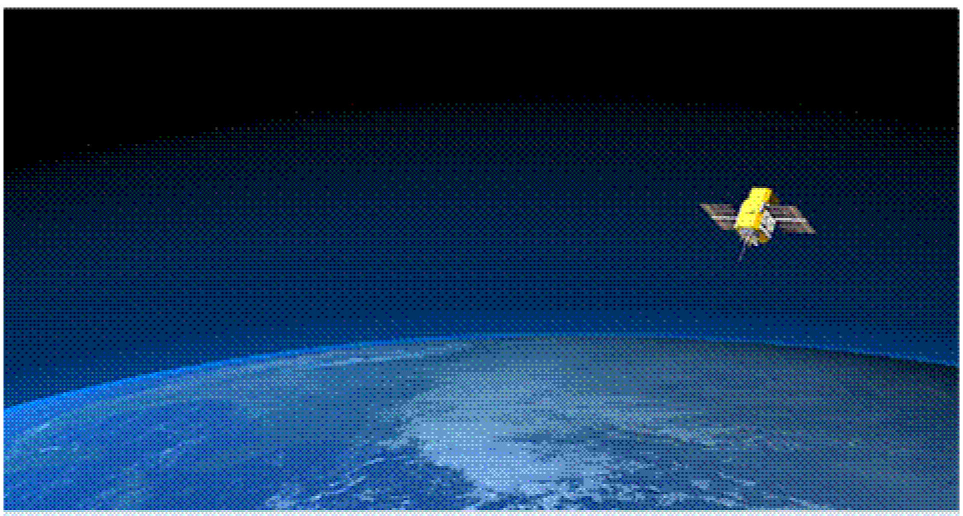
- Not used until orbit
- Payload weight is *the* hot commodity on any trip into orbit
- Eliminating the weight of the oxidizer from the launch vehicle makes room for more mission-related equipment
- Running out of oxidizer will not end the mission



Layers of the Atmosphere

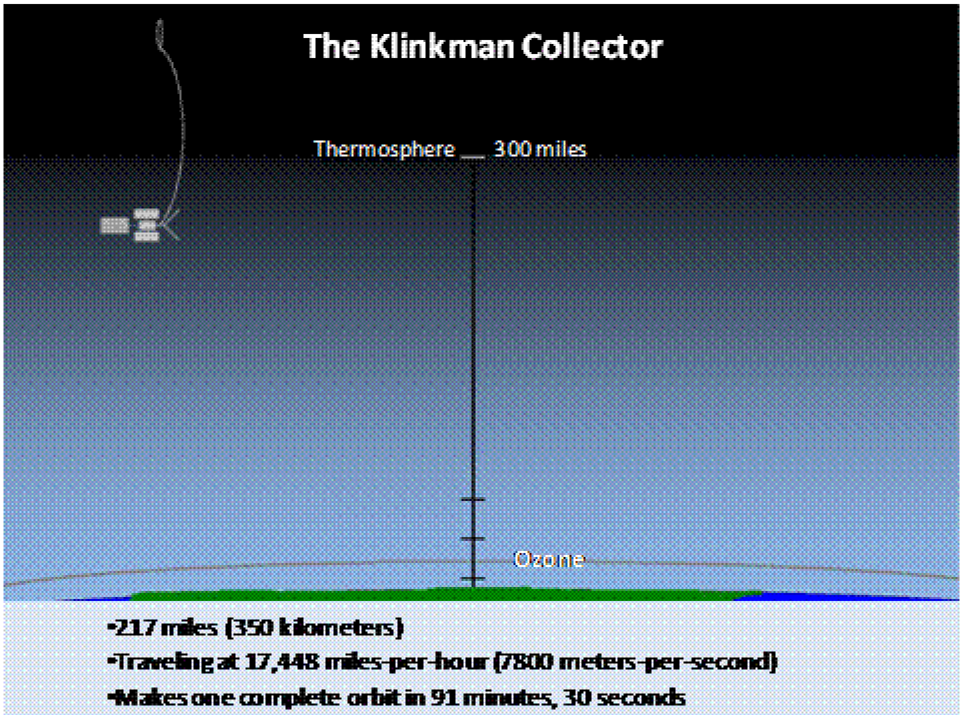
- Low Earth Orbit (LEO)
- Approx 62 – 435 miles (100 – 700 kilometers)
- International Space Station orbits at approximately 211 mi (340 km)
- Thermosphere, individual particles can reach temperatures in excess of 4500°F.
- Thermometer would read well below zero

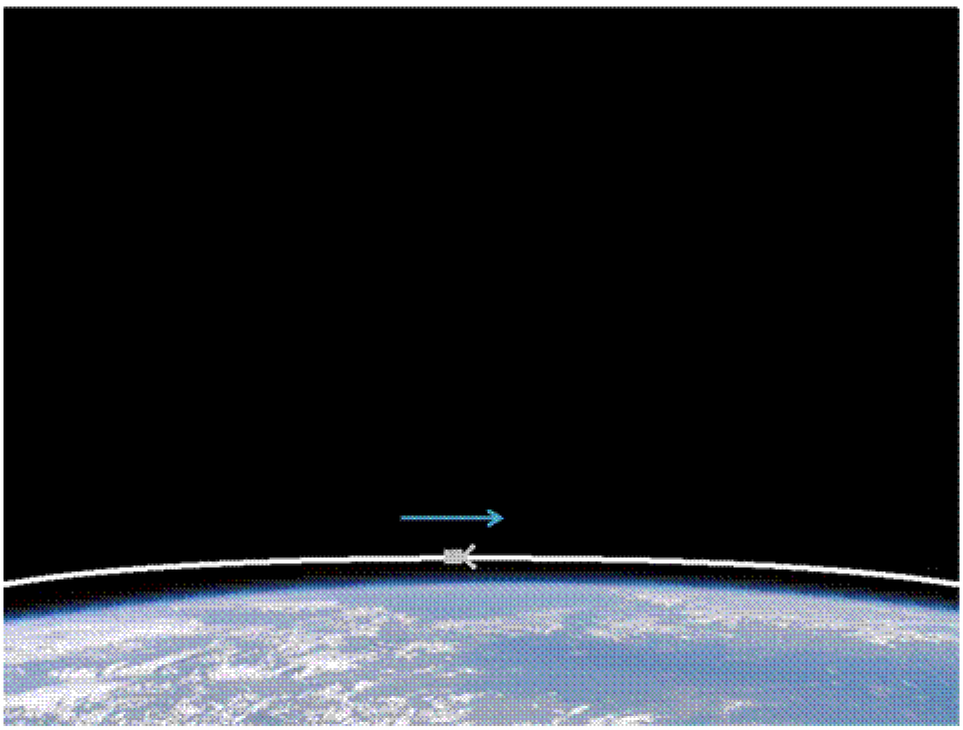




'Space' in LEO is not empty, just mostly empty

- The Karman Line at 62 miles (100 kilometers) is recognized by some as the 'beginning' of 'space.'

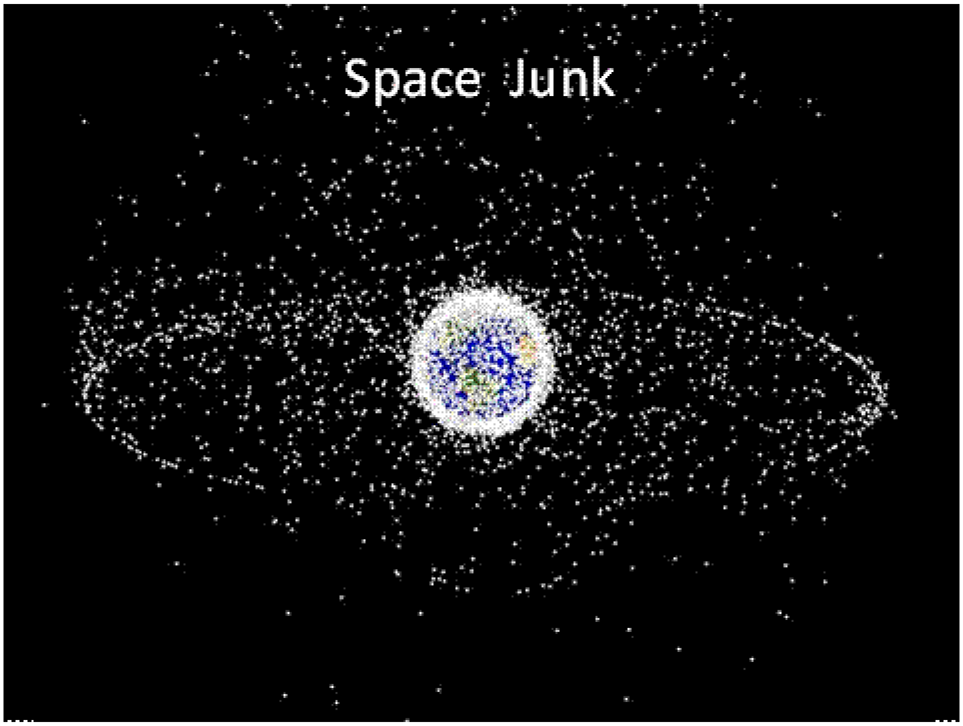

The Klinkman Collector
Thermosphere __ 300 miles
Ozone
•217 miles (350 kilometers)
•Traveling at 17,448 miles-per-hour (7800 meters-per-second)
•Makes one complete orbit in 91 minutes, 30 seconds



What are some of the impacts of this technology?

NASA Cost Savings

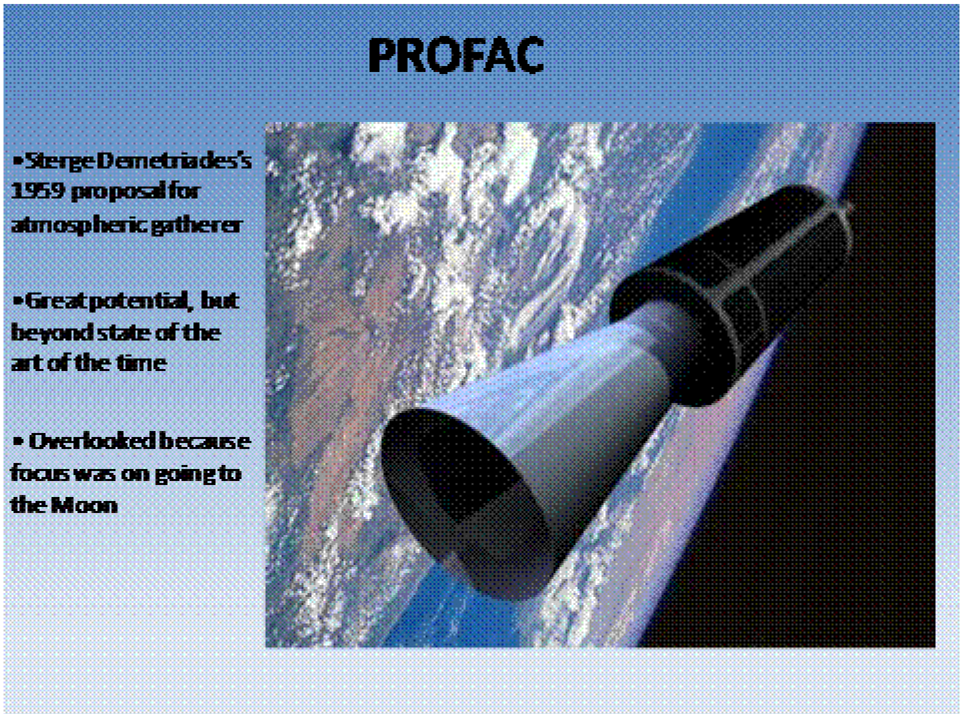
"There are several ways in which the value of the extra capability might be calculated, but at a conservatively low government price of **$10,000/kg** for payload in LEO, 250 metric tons of fuel for two [lunar] missions per year is worth **$2.5 Billion** at government rates. ... this is a nontrivial market, and it will only grow ... We may well witness a 21st century 'Gold Rush' of sorts ..." — *Michael Griffin, NASA Administrator, AIAA address, 11/15/2005.*



- Refueling in LEO increases the payload delivered to the lunar surface from ***19 tons*** of landed mass to ***48 tons***.

- LOX in LEO opens space to commercial enterprise.

- NASA can become regulatory agency.


PROFAC
•Sterge Demetriades's 1959 proposal for atmospheric gatherer
•Great potential, but beyond state of the art of the time
• Overlooked because focus was on going to the Moon


PROFAC
•Lack of interest from U.S. aerospace industry lead to publishing in G.B.
• To prevent Russia from pursuing PROFAC the U.S. Air Force classified Dimetriades's work
TOP SECRET!

What is the difference?

	PROFAC	LOX in LEO
Gathered Gases	Atmosphere	Oxygen
Propulsion	Nuclear Drive Air-breathing	Electrodynamic Tethers
Operational Height	~70 miles	~190 miles
Controls	Habitable/ Manual	Remote/ Automated

Where We Started

"...[assuming] that breakthroughs are going to be made in electrodynamic tether and radiator technologies, we believe that an atmospheric gas harvester operating in Low Earth Orbit is feasible."

-Previous Team Assessing Feasibility

Our Initial Goals:

1. Expand upon the technological details of LOXLEO.
2. Experience the effect of cognitive style in a R&D Team.
3. Examine the implications of success.

A Shift in Focus

- NASA's review of the device:

"This proposal is very intriguing and if the concept were successfully developed the benefits to NASA would be tremendous. It is advised that the proposers **team with credible engineers and scientists** to truly explore the feasibility of their idea to gather oxygen in space".

- Even a fully developed idea would not be considered when presented by an industry outsider.

The Hunt for Credibility

- Assemble a Panel of 15 Experts to:
  - use as a forecasting tool
  - disseminate idea in aerospace industry
- Looking for 1 in 5 positive response rate
- Panel was assembled via mail correspondence

Interpreting Responses

- Study in progress
- Currently have 10 of 15 desired expert panelist's reviews
- Positive response rate is ~30%

Interpreting Non-Responses

- Several potential panelist deferred from the study
- Even in non-responses there were sign of interest
- Initial backing could lead to further support (snow ball effect)

Conclusions

- We began the hunt for credibility
- Spearheaded the efforts to increase visibility
- Initial credibility leads to self sustaining system
  - Additional credibility gained due to visibility

Appendix D: ATWG Breakthrough Survey

Reference Sheet for ATWG Findings – Breakthrough Comparative Survey

By John Wilkes, Ryan Fossett, Geoffery Karasic, Lucas Lincoln and Peter Moore

Comparison of 12 current respondents to past averages

	Previous study	2008 Study
Single Stage to Orbit	3.4	3.33
Ram Accelerator	1.7	1.66
Space Elevator	1.4	1.58
Space Tether	3.8	3.5

Based on the 12 initial respondents, all of whom were experts in University or NASA positions, how did the Demetriades and Klinkman proposals fare compared to one another? The Advanced Technology Working Group (ATWG) sample was collected in May of 2008, well after the other data set. The ATWG panel is on the one hand more representative, as half of the 24 attendees present responded. The response rate for the other panel is about 10%. On the other hand, it is not strictly an expert panel. Only 4 of the 12 were willing to call themselves experts by degree or long experience. Six preferred to call themselves “Knowledgeable but not Expert” and two called themselves “Interested but not Knowledgeable”. Hence the Expert and Non- Expert rating will be compared to see if this difference in expertise accounts for the differences in average ratings of the technology.

Starting with the NASA and University based expert panel, on significance, 6 rated the ProFAC device as more significant, with 4 rating them the same and 2 rating the LOXLEO device as the more significant proposal, if realized.
The average rating was 2.17 for ProFAC and 2.00 for LOXLEO

The ATWG panel did not see it that way, as only one (an expert) rated the ProFAC device as more significant, 5 rated them the same and 6 (one of whom was an expert) rated the LOXLEO as more significant. So the Experts split but the rest of the panel was more impressed by LOXLEO.

On likelihood, seven members of the NASA/University panel rated them the same, 4 considered LOXLEO more likely and one considered ProFAC more likely. The average rating for LOXLEO 1.83 and the average for ProFAC was 1.58. The four ATWG Experts split with two considering ProFAC more likely, one considering them equally likely and one considering LOXLEO more likely. However, the panel as a whole included 5 who considered LOXLEO more likely, 5 who rated them the same and 2 who considered ProFAC more likely.

Contrasting the two panels over all the ratings, the ATWG panel was considerably more optimistic about the first three technologies, which were the controversial ones (ProFAC, LOXLEO and the Sapce Elevator) but rated the more familiar ones about the same way that the University/NASA panel did. They even rated one, SSTO as a bit less likely than the other panel. Again, ProFAC is treated about the way the Space elevator is and LOXLEO fares a bit better.

The pattern of likelihood ratings is interesting:

	University and NASA Panel			ATWG Panel 5/08		
ProFAC	111111122233	Mean	1.58	111222222445	Mean	2.22
LOXLEO	001111223344		1.83	122222333444		2.62
Elevator	001111222333		1.58	111222223335		2.22
Ram. Acc.	011111222333		1.66	011122222333		1.84
SSTO	223333444444		3.33	122233344445		3.00
Tether	333333444444		3.50	333333334455		3.50

On which one was likely to appear sooner, 5 rated them the same, 4 thought ProFAC would appear earlier and 3 considered LOXLEO more likely to appear first.

In summary, ProFAC was considered the more significant development, LOXLEO the more likely to appear and they split on which one could appear first.

One the other hand, the differences between the way these two technologies were perceived seems to matter less than the similarities. Both were considered about as likely as the space elevator (average 1.58) or Ram Accelerator (average 1.66), i.e. unlikely, as opposed to average ratings of 3.5 and 3.33 , ie. quite likely, for the tether and SSTO respectively. LOXLEO was a bit more controversial, with two ratings of zero (impossible) and two ratings of 4 (expected) than ProFAC, which received no zero or 4 ratings, but had seven ratings of 1 and two of 3. They were perceived much as the space elevator (two zero ratings and three ratings of 3) was being viewed, i.e. as controversial.

The spread of averages was nowhere near as great on the question of significance, but the patterns of ratings differed substantially. All six of the technology's average ratings fell between 2.00 and 2.5 (moderately significant) with SSTO and LOXLEO tied at an average of 2.00 on the low end and the Tether (average 2.5) and Space Elevator (average 2.41) on the high end. However, ProFAC (average 2.17), LOXLEO (2.00) and the Space Elevator average 2.41) hit this middle range as extreme scores cancelled each other; two zeros and three 4's for ProFAC, two zeros and two 4's for LOXLEO, one zero and four 4's for space elevator. Again these are the controversial technologies about which there is little consensus. By contrast SSTO got eight ratings of 2 or 3, only one zero and no 4's, and the Ram Accelerator got 7 ratings of 3, only one zero and no 4's.

Turing to the ATWG panel, the striking finding that jumps out at you is that across the board they think these technology breakthroughs would be more significant than the other panel does. These are a bigger deal to them, even SSTO which they were less optimistic about. Indeed, SSTO ranks right up there near the space elevator in importance. LOXLEO and the Tether are essentially tied for third. ProFAC trails for some reason, possibly due to the need for a nuclear reactor, but even in this case and that of the Ram Accelerator they still see these ways of getting things to LEO as more important than the other panel. They seem to immediately see the potential implications of these developments for the socio-economics of space. For them there is more at stake.

The Pattern of Significance Ratings

	University and NASA Panel			ATWG Panel 5/08		
ProFAC	001122233444	Mean	2.17	111122333445	Mean	2.50
LOXLEO	001111223344		2.00	223334444444		3.41
Elevator	011122334444		2.41	133344555555		4.00
Ram Acc.	011113333333		2.08	011333333455		2.84
SSTO	011122233333		2.00	223444444555		3.84
Tether	112222333344		2.50	133334444445		3.46

In terms of when they were likely to appear, ProFAC got 5 "nevers" and 2 near term estimates of "by 2020". The Space Elevator had only 2 "nevers" to go with its 2 "by 2020" estimates. LOXLEO had 3 "nevers" and no near term estimates of "by 2020". Only the Tether did not get a single "never" rating., but only two raters out of the twlve expected to see it by 2020. There was considerable scatter in the timing ratings.

Turning to the ATWG panel the pattern is again greater overall optimism about when the Technologies are likely to appear, especially on the part of ProFAC and LOXLEO, which they tended to see as coming a soon as the other panel expected to see SSTO. However, there was one glaring exception, and that was the Space Elevator, which they rated as coming substantially later. The ATWG average for the Elevator was about where the average of ProFAC and LOXLEO, or the Ram Accelerator, was placed in time by the other panel, i.e. quite late.

Timing ratings (0=never, 1 by 2050, 2 by 2035, 3 by 2020)

	University and NASA Panel			ATWG Panel 5/08		
ProFAC	000001122233	Mean	1.16	011112222223	Mean	1.58
LOXLEO	000111111122		0.92	011112222223		1.58
Elevator	001111222233		1.50	011111111122		1.08
Ram Acc.	000011112223		1.08	001111122223		1.33
SSTO	001111222333		1.58	111122222333		1.75

Tether	111111222233	1.66	122222233333	2.33

At this point it is time to consider the impact of the "Non-Experts" on the ATWG results. Aside form the fact that they preferred LOXLEO to the ProFAC concept which the experts were more divided, were they overall more optimistic than the experts in the group? A comparison of the whole panel average to that for just the 4 experts in the panel should answer that question.

Likelihood Ratings

	ATWG Experts only (Mean)	All ATWF panelists (Mean)
ProFAC	3.00	2.22
LOXLEO	2.75	2.62
Elevator	3.00	2.22
Ram Acc	2.00	1.84
SSTO	3.50	3.00
Tether	3.75	3.50

Invariably the non expert ratings are lower and more cautious on likelihood of a technology being developed than those of the experts. The non-experts are not inflating the average ATWG rating but rather deflating them, especially on the controversial ProFAC and Space Elevator technologies.

Significance Ratings

	ATWG Experts only (Mean)	All ATWF panelists (Mean)
ProFAC	3.00	2.50
LOXLEO	3.25	3.41
Elevator	4.00	4.00
Ram Acc	2.50	2.84
SSTO	3.75	3.84
Tether	3.50	3.46

With the exception of the ProFAC device, the striking thing about the expert and non-expert ratings in the ATWG group is how similar the averages are. The Non-experts are lower twice a bit higher three times and exactly tied on the Space Elevator.

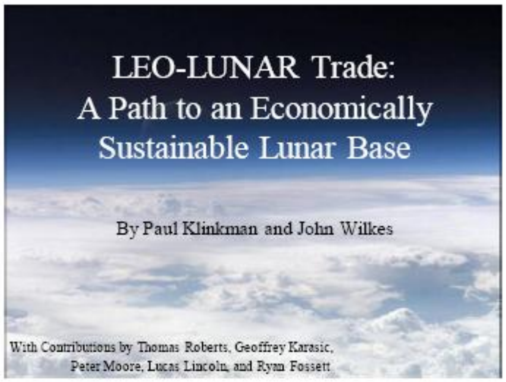
Timing Ratings

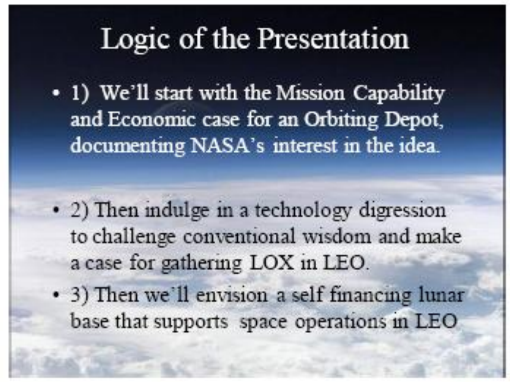
	ATWG Experts only (Mean)	All ATWF panelists (Mean)
ProFAC	1.5	1.58
LOXLEO	1.5	1.58
Elevator	1.25	1.08
Ram Acc	1.75	1.33
SSTO	2.25	1.75
Tether	2.50	2.33

If anything the non-experts are more cautious about how soon the technologies will appear than the experts in the ATWG. They are basically tied on ProFAC and LOXLEO. Clearly it is not the case that the higher ratings of the technologies in significance, likelihood and expected delivery date on all but the space elevator are due to the non-expects in the ATWG panel.

Professor John Wilkes, Dept. of Social Science and Policy Studies, WPI
Worcester, Mass 01609 (508) 831-5578   jmwilkes@wpi.edu

Appendix E: ATWG PowerPoint Presentation





"–at a conservatively low government price of $10,000/kg for payload in LEO, 250 MT of fuel for two missions per year is worth **$2.5B**, at government rates. If a commercial provider can supply fuel at a lower cost, both the government and the contractor will benefit. This is a non-trivial market, and it will only grow as we continue to fly." –Michael Griffin, AIAA Speech, 11/15/05

- Propellant Costs $7,000/kg if Launched on a Delta IV.
- These Costs Vary Worldwide Because They Are Typically Subsidized

A Technology Bottleneck

- Chicken and Egg problem, needing lunar oxygen mining to support LEO operations.
- More to it… according to Jonathan Goff, a propellant depot "is one of the key technologies for turning our civilization into a space faring civilization instead of just a space visiting one" (Foust, 2008)
- We agree, and would go farther.

Advantages of a Refueling Depot

- Foust and Goff: orbit the mission fuel tanks empty, extend life of satellites, extend mission range and duration. Reduce costs by using less expensive launchers.
- We would add: move, upgrade, replace and service satellites and other spacecraft. Provide LEO to GTO ferry service, clamp on units to retrofit spacecraft to be refueled.

The Conventional Wisdom…

- Jeff Foust, (editor and Publisher of SPACE REVIEW) calls "Propellant Depots: an idea whose time has *almost* come". (5/12/08)
- "In Situ resource utilization isn't an option for Earth orbit, but creating orbiting depots for propellants hauled up from Earth is an alternative".

…is probably wrong!

- We contend that propellant gas gathering in LEO is possible, and potentially lucrative.
- If Boeing could make a profit using 10 launches to build a 300 MT depot (enough to support 2 Moon missions) and 20 more a year to fill it (Bienhoff, 2007), imagine the profit margin on 2 launches per year to boost LH and the LOX gathered in LEO?

We aren't alone.

- A Propulsive Fluid Accumulator (ProFAC) was first proposed by Sterge Demetriades in 1959. then a grad student at Cal Tech, he developed the idea under government contract at Northrup.
- NASA declined the idea during Apollo for some reason , but a published rationale was offered by Heinz Koelle of Marshall SFC.

Von Braun's Protégé on ProFAC

- "A propellant accumulator in Earth orbit (Profac) does not seem to offer any economical advantages over a nuclear ferry vehicle if it is limited in its applications to chemical rockets only".
- He clearly expected nuclear drives soon.
- He did NOT say that it wouldn't work.

Likelihood ratings

	mean 1	expert	all
ProFAC	1.58	3	2.22
LoxLEO	1.83	2.75	2.62
Elevator	1.58	3	2.22
Ram. Acc.	1.66	2	1.84
SSTO	3.33	3.5	3
Tether	3.5	3.75	3.5

Significance Ratings

	mean 1	expert	all
ProFAC	2.17	3	2.5
LoxLEO	2	3.25	3.41
Elevator	2.41	4	4
Ram. Acc.	2.08	2.5	2.84
SSTO	2	3.75	3.84
Tether	2.5	3.5	3.46

Timing

	mean 1	expert	all	never	soon
ProFAC		2.38	2.38	1	1
LoxLEO		2.5	2.42	1	1
Elevator		2.75	2.91	1	0
Ram. Acc.		2.25	2.67	2	1
SSTO		1.75	2.09	0	3
Tether		1.5	1.67	0	4

Independent (Re)invention

- More than 50 years later , Paul Klinkman a WPI graduate and inventor, teamed up with 9 WPI students in 3 teams to re-examine this question.
- Three prior WPI students had tried to come up with a system that would gather gas below 100 KM in altitude. It wasn't in orbit and used as much fuel as it gathered,.

Klinkman's High Alt. Approach

- Klinkman heard of a new WPI team forming and decided to "recruit" it to evaluate some higher and faster strategies.
- He didn't know that Demetriades had operated at 100-120KM, barely in orbit, gathering dense (mostly Nitrogen) air.
- The 2nd WPI team ,initially skeptical, was won over by a proposed 350km gatherer.

The Technical Digression

- 1) How the gases distribute in LEO, and what kinds of fuels one can produce there.
- 2) Compensating for diffuseness of gases at the altitude of ISS with time and speed
- 3) How oxygen ions are expected to behave on impact with a collection surface.
- 4) Overcoming drag without using more than half of the fuel that has been collected

The Thermosphere Has Layers

Hydrogen
- 800+ km

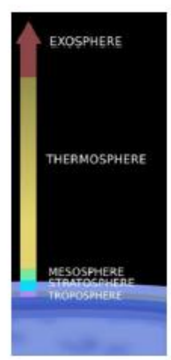
Helium
- 500km

Oxygen
- 350 km

Nitrogen
- 0 km

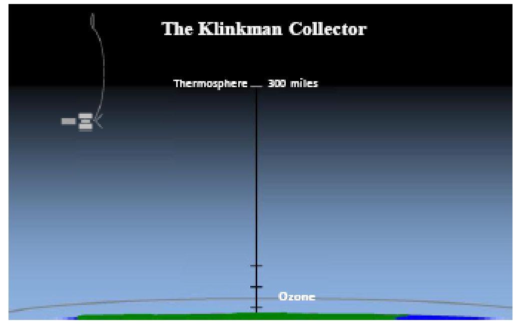
Layers of the Atmosphere

- Low Earth Orbit (LEO)
- Approx 62 – 435 miles (100 – 700 kilometers)
- International Space Station orbits at approximately 211 mi (340 km)
- Thermosphere, individual particles can reach temperatures in excess of 4500°F.
- Thermometer would read well below zero



'Space' in LEO is not empty, just mostly empty

- The Karman Line at 62 miles (100 kilometers) is recognized by some as the 'beginning' of 'space.'



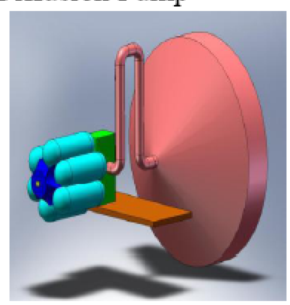
- 217 miles (350 kilometers)
- Traveling at 17,448 miles-per-hour (7800 meters-per-second)
- Makes one complete orbit in 91 minutes, 30 seconds

A Small Collector Surface Will Carve Through a Huge Volume

- At 8 Km/sec, 1 Square Meter of Surface Gathers 8000 Cubic Meters/sec.

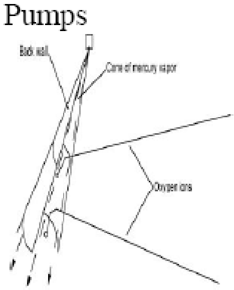
Circular Diffusion Pump

- Many cones of vapor push inward
- Merging vapor streams push gases downward in center of cone



Quantum Tunneling and Vapor Diffusion Pumps

- Oxygen Ions Penetrate Anything
- They Penetrate Through the Top Atoms of Vapor
- Slowed Atoms Stay Inside Long Enough for Capture



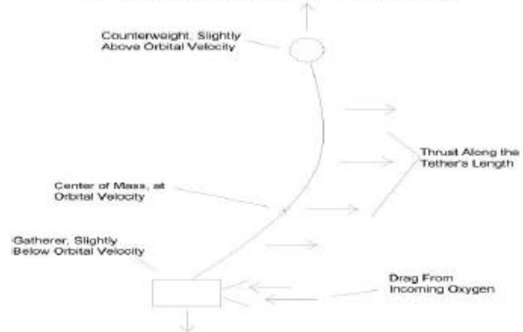
Daffodil Collector:

- Liquid is Vaporized at Points
- Vapor Condenses on a Surface
- Spacecraft Slowly Spins
- Liquid Flows Back Up Bottoms of Cones to Cone Tips
- Liquid is Vaporized

Plan A: Hall Effect Thrusters

- Uses Oxygen
- Specific Impulse of 1200-1800 Seconds
- At 1600 Seconds, Requires 50% of Collected Oxygen for Thrust
  - So We Must Double the Intake Capacity

Option B: Electrodynamic Tether Thrust



Electrodynamic Tether Issues

- Still Useful with an Inefficient Gatherer
- Metal Erosion (Spalling)
  - Replace Tether Every 2 Years?
- Space Junk

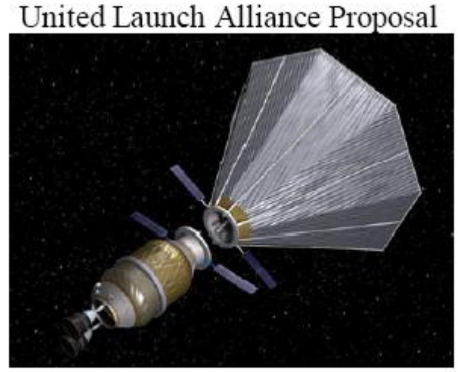
Optimal Gathering Altitudes

- Varies: Solar Max vs. Solar Min Weather
- Below 300 Km: Exponentially Adds Atmospheric Drag on the Solar Array
  - Is More Nitrogen Useful?
- Above 500 Km: an Exponentially Larger Collector Is Needed
  - Is More Helium / Hydrogen Useful?

Demand

- Hall Thrusters use LOX
- LOX/LH and Water
  - Import LH
  - Gather Traces of Hydrogen in Orbit
- N2O4 Monopropellant
- Helium –Tank Ballast Gas, in Telescopes

United Launch Alliance Proposal



Simplest Possible "Depot"

- Frank Zegler of ULA proposes a single unit of a single propellant (LOX) orbited in a single launch using a variant of the Delta 4's hydrogen tank.. It would hold 25 Metric tons, about what the Altair lunar landing craft would require. In short, one small EELV, a sun shade to control boil off rates ; the Altair LOX tank goes up empty.

A More Ambitious Plan

- Retrofit 3 space shuttles to be refueled in space, one of which carries a unit designed to liquefy oxygen concentrated to sea level densities.
- Instead of scrapping them in 2010, launch them into LEO-one way, on a 3-5 year mission to close the "gap" , until ARES I Ares V and Orion are operational.

Their last launch payloads

- Two Shuttles would each carry and deploy unmanned gas gathering systems rated to gather 50 MT of oxygen per year and empty tanks of that capacity. The gatherers would be 5 interconnected ten ton units.
- One Shuttle would carry two of ULA's proposed modified Delta 4 LH tanks and a sunshield- loaded with liquid Hydrogen.

Their 3-5 Year Mission

- The fuel gathering and storage units are deployed in orbits crossing near the one where the Constellation missions to the Moon will be reconfigured.
- The still fueled Shuttles go into storage orbits – serving as 3 Skylabs until sufficient LOX has been gathered to fully refuel them. They can go on missions.

ISS/Lunar Mission Support

- The shuttles can operate so as to enable ISS to pay for itself as a staging area for retrofitting satellites to be refueled. (The risk and expense is in going up and down.)
- A gatherer designed to attach to the ISS would be used to move the ISS to the vicinity of the Lunar Mission staging area. This would be over a period of 5 years.

Powerful New Capabilities

- This scenario illustrates the value of the refueling based on local sources being developed to end the scarcity of one gas.
- The value of past investments is enhanced by being able to move them around .
- The ISS and Shuttle become retrofit, repair and upgrade facilities until facilities better suited to the task can be built and launched.

Socio-Economic Consequences

- In-Space Transport Costs Drop About 80%
  - U.S. Nearly Monopolizes the World's In-Space Transportation Business?
  - New Space Tug Industry
- The ISS becomes a valued asset.
- Refueling Becomes an Accepted Practice
  - Orbiting Refuel/Repair Services Start
  - Standalone satellites give way to massive man tended space platforms -serviced annually.

Back to LEO- Lunar Trade and a Lunar Base that can pay for itself.

- An Image of what is going on in LEO at the time the Moon Base is built 2020-2030 is now clear.
- Having 300 tons of LOX/ year on orbit greatly increases the mass that can delivered to the Moon in 10 missions. The base is 2-3 times as large.
- That new capacity is used to put space support infrastructure on the moon, increasing the supply of LOX for Earth and Lunar Orbiting fuel depots.

A New Class of Space Craft is Built to Support the Trade System

- Tankers : Competition in the LOX trade
- Lunar Hydrogen enters the refuel picture
- The Helium-3 question- a sleeper gold rush
- Metals –especially iron and titanium
- Silicon/Steel &LEO Solar Energy Platforms
- Tourism: Hotels and Cruise Liners in Space
- Freight Depots, Service Facilities and Food

Where Will they Be Built?

- The case for lunar construction is good
  -- Construction is easier in due to having some gravity
  -- Lifting objects 6 times as large is possible with the same boosters
  -- A Space Elevator for the Moon is feasible with existing materials.

The Division of Labor

- Bulk and heavy freight is where Luna has an economic edge over Gaia.
- Cheap staples (potatoes) will probably come to LEO from Luna first, higher value meats and fruits that grow on trees later.
- Metal and Silicon Spacecraft hulls and tank shells would come from Luna, but precision interior fittings and instruments from Earth.

The Long Shots

- Klinkman thinks one might be able to get the gases one wants out of lunar regolith without actually mining and processing it.
- Klinkman also suspects that metal might be placed into Lunar Orbit by spraying vaporized metal or filings over a form layer by layer orbit by orbit. (no launch needed)

Where is the Labor Force?

- Humans working under a dome buried under 10 meters of regolith is not impossible.
- Use Telepresence for 90% of the labor force. The command-response-feedback lag is about 2.6 seconds, as commands travel at light speed.

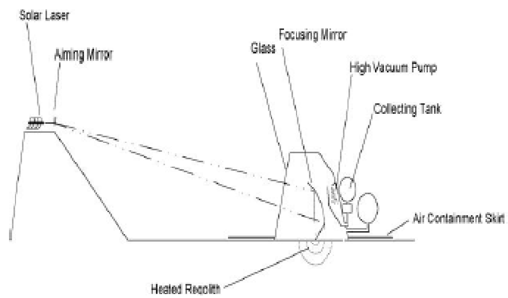
Top Lunar Issues

- The Hydrogen Question – Propellant, Water, Agriculture
  - Refueling a Lunar Shuttle
- Getting Products Off the Moon – Preferably Without Using Rockets
- Solar Power and the Long Night

Hydrogen Tenting

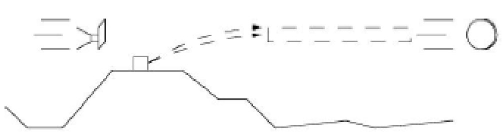
- Ilmenite releases Hydrogen at 400°C – 600°C
- Moving Ore is Avoided
- 50 ppm, Keep Moving the Collector
- He, He_3 Bonus
- Perhaps Electrostatic Particle Attractor Wires Can Reduce Dust

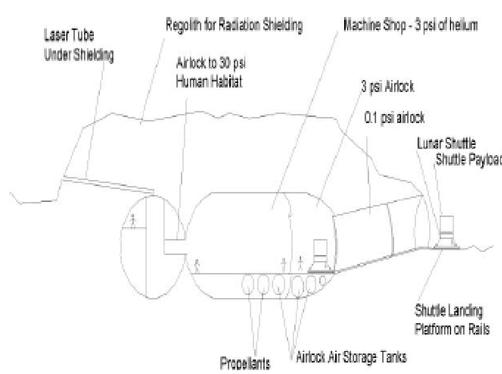
Lunar Hydrogen Extractor



Growing Metal Objects in Very Low Lunar Orbit

- Vaporize Metal Atoms/ Grains From the Surface Into Paths of the Many Objects
- Atoms/Grains Stick Onto Surfaces and Build Up Over Many Orbits
- Large Scale Efficiencies





Solar-Powered Lasers

- Positioned At L-1 or L-2
  - Power Anywhere on Moon All Night
  - Up to 5 Hours of Total Eclipses/Month
- Or, Put Lasers on Hills at the Lunar Poles

Summary of Three Phases

- Phase I- Recycle Available Scrap Space Craft to Demonstrate the Refueling concept and start retrofitting satellites to use it.
- Phase II- Reorganization of LEO activity to gather existing and new infrastructure at the departure point for the Moon.
- Phase III- Lunar Resources and Production bring down the cost of LEO operations

Conclusions

- In situ LEO gas gathering is possible and the easiest gas to gather, oxygen, is also the most valuable- until lunar production starts.
- Hydrogen can come from Earth until lunar infrastructure to pull it out of solar wind can be developed. (Will be like growing trees.)
- LEO demand for relatively cheap fuel and metal will support a substantial Moon Base.

Leo-Lunar Trade:

A Path to an Economically Sustainable Lunar Base

Large Volume Financial Breakdown, Per Kg. of Propellant

- Solar Cells, Gas Processing, Tanks $500/Kg.
- Gatherer Surface $100/Kg.
- For Hall Thrusters, Double the Gatherer Surface. Add $100/Kg.
- For Tethers, Replace Tether Every 2 Years, Add $500/Kg.
- Many Solutions, Minor Price Changes

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