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Harvesting LOX in LEO: Toward a Hunter-Gatherer Space Economy

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[Abstract] One of the great impediments to using traditional chemical rocket technology to support space activity over the long run is the need to boost oxidizer (and other parts of the rocket fuel package) to Low Earth Orbit. The key to operating in space over the long run will depend on the ability to refuel in space, especially if one wants to move to SSTO technology. Thus, the proposed Oxygen Harvesting System promises to kick open the door to space well before the next generation of space drives is available and massively reduce the cost of reaching destinations in the inner solar system. It will also probably also be the first profitable product oriented space industry that is not based on an information product. Certainly it paves the way to the first interplanetary trade system as gases in short supply or completely lacking on the Moon and abundant on or near the Earth are delivered to the Moon at low cost.

This invention, for which he has submitted a patent application, promises to remove several constraints on space activity and may well accelerate the process of space exploration about as much as the Wright Bros.' invention of he wind tunnel. That has been estimated to be about 50 years worth of trial and error avoided. In this case, the implication may be even greater as it makes the existing generation of space technology much more capable and reduces the need for new ways to reach LEO to bring down the cost of access to space.

Who says the day of the lone inventor is behind us? On the other hand, part of the story of this invention is tied to Klinkman's continuing relationship with his Alma Mater. He graduated from WPI in 1976 and developed this idea with the help of 3 current junior year undergraduates and a space buff sociologist interested in creative cognitive mixes and small group dynamics on innovation teams. Wilkes is also interested in Aerospace R and D organizations and in the system of project based education at WPI could get participating undergraduates academic credit worth 3 courses each for their contributions.

I. Introduction and Overview

THE best known example of the hunter-gatherer approach to space operations is the Mars Direct Proposal by Robert Zubrin.[1] He proposed that the fuel for a return trip from Mars be created out of the Martian atmosphere by an unmanned system before the astronaut team to explore the Red Planet was launched from Earth. While there was a prior proposal to gather oxygen from lunar oxide rocks, that was expected to be a later development after a base was set up, i.e. an oxygen production facility at such a high energy cost was part of the manufacturing base for an industrial society. Zubrin was talking about "living off the land" on arrival as it were, a first step extraction method with robots paving the way for humans. While there is some material processing going on, this is not the same as a permanent mining or agriculture economy in terms of its socio-economic implications. The idea of following the materials that you need to support your life support system, finding and processing resources in space as we need them is quite appealing. It is so appealing that we propose to start with the Earth's own upper atmosphere as a propellant source and thus remove a major barrier to the capability and effective range of current chemical rocket technology.

What do we mean by being hunter-gatherers in space? Certainly it does not mean that you are going to find food ready to eat. However, unlike Earth, which is rich in carbon, nitrogen, hydrogen and oxygen, space is lean and thin

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on one of more of these key elements in most places. Metals are also precious, and for a population dependent on robots to go do the actual gathering and scavenging, silicon will be prized as well. The Moon is iron, oxygen and silicon rich, but carbon and hydrogen poor. That means that agriculture will be hard to establish there, yet it must be done for a self sustaining colony to emerge. LEO is harder to describe in these terms, though it is clearly where the space economy has started and a case that Earth/LEO and the Moon are complementary enough to support a trade system based on relative scarcity can be made.

Science fiction portrayals of the emerging space faring society generally start with some way to refuel in orbit, or just presume departure from an orbiting space station and posit some sort of shuttlecraft to get to it. Michael Flynn's novel *Firestar*[2] posits a SSTO craft that uses about 95% of its fuel to get to LEO and then has to be refueled. He used a ram accelerator to "shoot" fuel up to the "plank" orbiters in LEO and then executed a rendezvous to refuel. There was no explanation of how the space junk of empty fuel containers would be dealt with. Thus, his novel reflects the prevailing view that nothing is going to happen to move the development of space technology along until some means of less expensive access to orbit than rockets, for freight, is developed, since everything is going to have to come up from Earth.

Thinking in terms of more immediate markets, Dallas Bienhoff of the Boeing Company's "in Space and Surface Systems" Division recently described (at the ATWG 2007 in Dallas Forum May 19th.) the Boeing effort to make a case for a refueling capability for NASA as part of the return to the Moon.[3] His numbers for the massive increase in payload delivered to the lunar surface (from 19 tons landed mass to 48 tons) for the same cost were thought provoking. On the other hand his estimate for the number of launches (about 10) needed to get the tanks and other system components they envisioned into orbit and then the idea that 20 more launches would be needed to fill them once a year, was daunting. Even at that high cost it looked like it was worth doing. However, Boeing was not prepared to go ahead on the basis of a promise from Michael Griffin, NASA Administrator, that if the company built it NASA would use it.

> 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…[4]

Still, Boeing wanted to build this facility under contract. Given NASA claims that it was not necessary to have a refuel capability, just desirable, the refueling depot looked destined to stay on the drawing board despite the strong case to be made for it. It is clear that Griffin's speech was meant to encourage space entrepreneurs to look again at this opportunity.

> We may well witness a 21st century 'Gold Rush' of sorts when entrepreneurs learn to roast oxygen from the lunar soil, saving a major portion of the cost of bringing fuel to the lunar surface. Will a time come that it is more economical to ship LOX from the lunar surface to LEO than to bring it up from the Earth?"[5]

It was evident from these cost estimates why Flynn had turned to a non-rocket technology to get freight of this kind into orbit in his fictional account exploring the implications of a SSTO system. However, Bienhoff's bottleneck of needing 30 launches in the first year was not the part of his proposal that interested Paul and I. We had already been working for a year with the idea of gathering gasses out of the upper atmosphere. We thought we knew how to fill the six oxygen tanks in Boeing's cluster of 8 connected fuel tanks. To us the important thing was that there was an existing and detailed design for an orbiting fuel depot already costed out and converted to a given number of launches by specific kinds of existing rockets, and NASA officials were interested in having it built. Indeed, 28 possible propellant depot architectures were assessed. Bienhoff's team already knew that LOX/LH was under consideration by NASA for the trip to the moon and more stable LOX/Methane for the trip back. Zubrin[6] seemed to have hydrogen-oxygen propulsion in mind for Mars Direct as well, and it certainly was an appealing choice to us, since in principle hydrogen was another gas one could gather in space and which separates and gathers into a layer around Earth. However, as a practical matter it was hard to tap that hydrogen layer with a simple orbiting device.

Based on our research it seemed much easier to gather nitrogen, oxygen and helium in LEO than hydrogen. Hydrogen was the problematic but necessary key to turning the oxygen into water and rocket fuel. Propellants and life support were what we really wanted, both to sell in orbit and to support agriculture on the Moon. However, we reasoned that 89% of the mass of the propellant is in the Oxygen, (LOX), so, if necessary, one could liftoff (or shoot, a la Flynn) the hydrogen from the water drenched Earth, and still be well ahead of the game. Further development of the hunter gatherer approach to space would involve searching for ways to gather hydrogen in space, possibly from the layer around the Earth or even from the solar wind as it streams against the Moon, but the first gas product of value as part of a fuel system would clearly be oxygen.

Wilkes arrived at the conclusion that one would have to gather it from the thin atmosphere in space at orbital altitudes and velocities after a WPI student team[7] worked for about 7 months with the idea of gathering the denser lower atmosphere about 50 Km above the surface of the Earth. Their gathering device started from LEO at 17,000 mph, entered the atmosphere and returned to orbit. They figured out how to enrich the oxygen yield in their returned load from 22% to roughly 66% and jettison considerable nitrogen. However, to do it they needed processing time in the atmosphere with a heavy gas separation device, i.e. they had to slow down, cruise and then change direction to boost back to LEO. In short, they somehow used at least as much fuel as they could hope to gather.

The breakthrough came when WPI alumnus Paul Klinkman proposed to a second team consisting of the Malloy, Huynh and Kolk[8] that was going to try to skim the atmosphere at about 100 km (still in the level where the atmosphere is about 22% oxygen) that they move up to a layer of atmosphere that was already about 85% oxygen atoms. This proved to be very roughly 400km, not far from the current International Space Station, which meant that an existing substantial orbiting platform was probably already moving through at least an 85% oxygen layer of space. This would make a test of the concept and obtaining estimates of how much could be gathered traveling at orbital velocity for a year much easier to carry out. Furthermore, any oxygen slowly but steadily gathered might offset a known oxygen leakage at the space station, reducing the demand for resupply missions to the station and helping to defray its operating costs.

Once the simplistic ideas that space had a sharp edge and that the atmosphere was uniform in makeup were banished from our brains, a new paradigm of a layered and differentiated space with a density gradient took hold. This image had some interesting implications for people thinking in hunting and gathering terms, looking for the stuff of life support and propellant. Our new problems were more specific and technical than before, and as they now seemed soluble, this idea seemed to have promise. How could one stay in orbit given the drag that would be encountered gathering atoms? How could one hold the atoms for gathering? How could one dissipate the considerable heat that would be generated and power the system of liquefaction involving compressors? How could one deliver the products to a more robust refueling depot suitable for rendezvous with manned spacecraft from our orbiting unmanned gatherers? How could LOX be delivered to unmanned systems needing to be re-boosted or moved to extend their operational life? There would be many customers if we could deliver the product to them.

The project of the Malloy et al.[9] WPI student team became one of technically assessing and elaborating the Klinkman concept to see if there was any reason to think that it would not work in principle. One of the team members focused on the social and economic implications of such a device operating in space and the other two did the technical feasibility study, constantly pushing Klinkman to consider or reconsider various issues and answer questions about details. They ended up provoking several design changes over time. In the end Malloy et al. were satisfied that it would work but vague on the both the size and economic value of the product yield. Still, Paul decided that he (and they) had things worked out well enough to apply for a patent.

It was not until their project was complete that we learned that the lunar requirements and scale issues had been addressed by the group at Boeing. By then we had already begun speculating about the implications of being able to refuel high value satellites needing to re-boost or move to another orbit. Just how much satellite longevity could be increased by a refueling capability was not yet clear. However, we had noted how nicely this new capability would meld with the development of large unmanned space platforms designed to be man tended (periodic visits) rather than permanently manned. Once the instruments distributed over 20 satellites were concentrated into 1 or 2 platforms, the case for service calls to a platform to refuel it, repair components and carry out instrument upgrades would be considerably strengthened. The case for carting away space garbage to free up space for more instruments on the platform would also be more compelling. At some point removing or recycling spacecraft that are no longer functioning will be likely to emerge as a side business associated with satellite servicing, but until a space authority emerges that can require it this will not be a regular practice.

Thus, our purpose today is to show what we envision is required to gather valuable gases in near space, how the idea emerged, and why it is important. Our gas gatherer will then serve as an illustration of the kinds of things that a hunter-gatherer mindset toward space might produce in terms of local exploration and extraction activities. It is also of interest how gathering would set the stage for an exchange economy, especially between the Earth and the Moon. Wilkes has come to see these two heavenly bodies as having the potential to be complementary trade partners. Klinkman is less convinced that a balanced trade relationship is possible, or necessary.

As part of the discussion of broader implications of this invention, a discussion of how the institutional model it suggests might foster innovation in aerospace will also get some attention. Space is not an area in which the lone inventor in their garage can operate very effectively, despite the recent niche invention of an improved space suit glove by a lone inventor. This is an area in which institutional resources are required and the collaboration of Paul Klinkman with his alma mater, WPI, is atypical as he is an inventor, not a specialist. Further, he was not working in an area where he could draw on established credentials to marshal resources. The way in which he is relating to the WPI project system requires a bit of explanation.

The WPI project system itself is a maverick idea in academia as it involves not just a senior design project in one's major, but a junior project that is not necessarily at all related to one's major. Even the faculty advisors need not stick to their area of expertise. Hence, it has thus far been the junior project, which is designed to explore the way technological and social change interact, that has spawned the WPI space technology and policy initiative. This initiative has annually (for four years) involved 20 to 40 students and 3-8 faculty members in an effort to try to understand the social implications of a new space race. Thus, it was initially focused on the Moon.

In three years, the Space Initiative has evolved from modest efforts at technology forecasting and assessment using Delphi methodology and expert panels to see what areas of technology we most likely to experience breakthroughs. There were also a series of student efforts attempting to envision a moon base and its social implications back on Earth. Soon the WPI students wanted to look further into the technologies considered most promising by the expert panelists. Now they want to push one of the “long shot” technologies to breakthrough stage.

Next year the Klinkman proposal will be the focus of a three team effort by a total of 7-9 WPI students to specify the key subsystems of the gas gathering device. The goal is to try to take them to the point of a proposed prototype that could be the basis for a funding request. Thus far, no Aerospace faculty members have been directly involved in the project advising or in the discussions with NIAC about the gas harvesting concept. Hopefully the level of specificity reached by the teams this year will entice a team of Aerospace majors to recruit a faculty member and take the next step toward a definitive technical assessment of promise and credibility of the proposed system.

Whether or not that occurs, this year a team dynamics experiment on how to enhance the yield of R and D teams through the use of cognitive styles data will be carried out by a team of juniors. Another team of juniors will be assigned to explicitly look into the social implications of the proposed LOX from LEO device. Their report can feed right into the proposal generation process. The students signing up for these projects can be space buffs in any major, or indeed people interested in managerial issues and only peripherally interested in space. Thus, the WPI projects system can support interdisciplinary teams with a variety of missions and can even reach out over the years to support alumni with interesting ideas that they probably could not develop on their own, (at least not without obtaining significant funding). It was not designed for this purpose but is flexible enough to be adapted to support the incubation stage of invention and entrepreneurial activity.

Thus, the space project initiative is a many leveled collaboration supporting both critical thinking about the social implications of technological change, technology policy and forecasting and some actual efforts to solve organizationally strategic technological problems for NASA. In addition, the students get to think about team dynamics on innovation and assessment teams and read about the greatest labs that ever existed in the field of aerospace, like China Lake, the Skunkworks, as well as Energia and NASA in their heyday during the 1960s space race.

II. Technical Questions Regarding the LEO Gas Gatherer

A few general assumptions are required to support the molecular pump idea.

First, atmosphere can be collected in LEO with a high-vacuum molecular pump.

Second, an orbital altitude can be found where significant amounts of atmosphere can be collected. For testing purposes, a reasonable altitude is conveniently near the altitude of the current space station. Our preferred target altitude for large-scale mining is around 325 km above the earth. At this altitude, 300 metric tons of raw atmosphere gathered in orbit per year would break down into 270 tons of oxygen, 21 tons of nitrogen, 9 tons of helium and a fraction of one ton of hydrogen. The gathered hydrogen will probably bond to our oxygen atoms when the mixed gases are first compressed and hot, creating approximately five tons of water per year.

Third, although momentum is lost when atmosphere is collected, methods exist for regaining momentum in orbit without burning more propellant than can be gathered. We think an electrodynamic tether is the most elegant answer to this problem.

Fourth, once collected, oxygen, nitrogen and water can be refined, liquefied, stored and pumped into propellant tanks for later use, and delivered to diverse strategic locations.

If all of these statements prove to be true, then economically profitable gathering of locally available gases in orbit is theoretically possible.

NASA’s future market demand for propellants in orbit for the Moon missions starting in about ten years will be 250 metric tons per year according to NASA Administrator Michael Griffin[10] and at least 300 tons per year according to Dallas Bienhoff of the Boeing Corporation.[11] Assuming that 8/9ths of the hydrogen/oxygen propellant will be liquid oxygen, one can assume a minimum NASA demand of 222 to 267 tons of LOX per year. The commercial market for LOX related to other NASA activities focused on the space station, earth sensing and communications could make the actual demand greater. See figure 1 for an illustration of the Boeing concept of a fuel depot in space that would have to be kept stocked mostly with LOX.

The current cost to launch one kilogram of propellant into orbit, or one kilogram of anything, is at least $4,000 by conventional rocket launches. As noted by Griffin, using the shuttle requires a figure of $10,000/kilogram. Thus, 250 tons of liquid oxygen per year costs between 1 and 2.5 billion dollars per year to lift into orbit. Assuming that a gas gathering technology would continue to pay dividends indefinitely, a $5 billion NASA investment in a space-based source of liquid oxygen would offset a 10 to 25 times greater expense in launch costs over the next 50 years, even assuming a zero percent growth extrapolation. Any fundamental reductions in propellant launch costs will equally lower the gas gathering satellites' launch and deployment costs, so we can reasonably expect to keep liquid oxygen production costs proportional to launch costs as these costs come down. Given a radically different lift technology such as a space elevator, the launch costs of our collection equipment will still be less than the launch costs of liquid oxygen.

Based on these estimates, we propose that an effort be made to fairly quickly deploy a series of satellites that can gather and process the very thin oxygen dominated atmosphere at this altitude. One has to learn enough to be able to scale up in capacity to 300 tons of atmosphere per year in a decade with an emphasis on manufacturing liquid oxygen. Such an effort would at least be both cost effective and probably a good investment.

Making inferences based on the Boeing proposal, we suggest that the additional 30 tons of liquid hydrogen needed per year for an oxygen/hydrogen propellant mix can be launched from the Earth, at least initially. Liquid hydrogen is relatively difficult to manufacture in orbit and is relatively lightweight for launching from the hydrogen rich Earth.

At an altitude of 325 km on a normal day, a cubic meter of sparse atmosphere contains 3 x 10^17 atoms. An efficient molecular pump at this altitude with a one square meter mouth, orbiting at 29,000 kilometers per hour, will capture 29,000,000 cubic meters of sparse atmosphere per hour, or about 1.1 metric tons of atmosphere per year. To capture 300 metric tons of mixed gases per year, a molecular pump with a round mouth roughly 30 meters in diameter is required at this altitude. A 30 meter molecular pump won't be easy to deploy, but it is something on a scale that we can probably launch and deploy, and it would meet the demand of the largest declared customer so far, NASA's lunar return program. Can the challenges be mastered in time for this to be part of the system planning for launches in the 2018-2020 time frame, when construction would begin on the lunar base? We think so. Following are the technical challenges to be met and the schedule necessary to meet that deadline.

A. The Electrodynamic Tether

The gathering of 300 tons of mixed gases per year will create a steady 60 Newtons of drag on the gatherer while in orbit. To compensate, we propose to marry the molecular pump with an electrodynamic tether rated to generate 60 Newtons of thrust. Such a system does not yet exist, although it seems possible in principle. No tether generating greater than 0.23 Newtons has yet been designed. We expect that this technology can be scaled up in the next 10 years. We hope to see the development of a more fault and failure-resistant multi-strand tether capable of surviving 10 years in space. We also hope to see the development of somewhat longer tethers, which will enable our molecular pump to gather in relatively thick atmospheres at slightly lower altitudes.

One tether manufacturer, TUI, rates their electrodynamic tethers for use between 350 km and 700 km. Due to the increased atmospheric pressure found at lower altitudes, a tether placed between 325 and 350 km probably won't generate much net thrust minus the air friction on the tether. However, one might expect that the length of a 60 Newton electrodynamic tether would be at least 50 km, and so the tether would reach from a productive thrust generating altitude down into an altitude with a slightly thicker atmosphere, where the act of capturing gases is more optimal. The two constraints which position our atmospheric gatherer at around 325 km are the lower limit on electrodynamic tether effectiveness, and a desire to gather as thick an atmosphere as possible, where oxygen is the predominant gas found at almost any nearby altitude. Hopefully the deployment cost of large molecular pumps will be a temporary constraint and one can move higher, to gather a higher percentage of hydrogen, as the technology advances.

B. The Molecular Pump

At this point we favor a combination of two standard high-vacuum molecular pump designs: the turbomolecular pump and the mercury vapor diffusion pump. In a currently promising design, a turbomolecular pump on the front of the gatherer will have spinning turbine vanes pitched quite steeply to absorb atoms entering the pump's mouth at orbital velocity. The turbine will also successfully admit most space dust particles and occasional pieces of space junk. Any slower moving atoms rebounding inside the turbines will be pushed back downwards by the vanes. Behind walls of these turbine vanes, a lightweight mercury vapor pump may be operated without fear of many mercury atoms leaving back out the mouth of the pump. A mercury vapor pump is easy to construct. Mercury vapor is an excellent choice for compressing atoms, as the fast moving oxygen and hydrogen atoms and the hard radiation of space won't ever decompose individual mercury atoms as they might decompose, say, a special oil.

C. Cooling and Refining the Gases

At 325 km, gases normally come into the molecular pump's mouth at 600 degrees to 2000 degrees Kelvin. However, they also enter the molecular pump at orbital velocity. The relative velocities of these incoming atoms need to be reduced. The gases then need to be compressed. The individual oxygen atoms will combine to form oxygen molecules, releasing heat in the process. All of the above operations release heat. To then take away a great deal of excess heat, the compressed gas mixture is pumped through radiator pipes. Later on, a heat pump may be used to further cool the gas mixture.

One method of refining our gaseous mixture is to cool it within a slowly turning centrifuge. At specific temperatures, different factions of the gaseous mixture such as trace amounts of water, liquid oxygen and liquid nitrogen will condense into droplets, and these droplets will be pulled downward out of the gas mixture by the pseudogravity of the centrifuge. This particular industrial separation process also delivers the purified end products that we want – liquid oxygen and liquid nitrogen. Oxygen liquefies at 90^oK at earthlike atmospheric pressures, a temperature which isn't quite as hard to reach in space as it is on earth. Klinkman isn't firmly committed to this form of refining oxygen, but the liquefaction idea does make a good deal of sense. Factional refining is a well-known method of separation.

D. Storing and Pumping Liquid Oxygen

It's reassuring that the Boeing Corporation has designed a 180 ton storage and transfer facility for low earth orbit and justified that to the mission requirement of one of the larger single customers. However, should the lunar base program be cancelled there would be ample demand to justify developing this capability up to the same scale of operations. Satellite movement and re-boosting, supplying the space station and transfer from LEO to GTO would be a sufficient market to support a company in this field even if nothing exciting (like going to the moon and Mars)happens in the space program for 20 years. However, the moon program is likely to go forward and the proposed capability makes SSTO technology much more interesting. Commercial space ventures are talking about space tourism, space hotels and cruisers that will never land but just operate in space. Any of these developments would vastly increase demand for in-space refueling.

If they all happened in combination, it is not clear whether scaling up fast enough to meet demand for LOX in LEO would be possible. At that point taking on some LOX in LEO and using it to go up the Geosynchronous Orbit and then to the Moon the completely refuel on LOX "roasted" out of Moon Rock, as Griffin put it, might start to make economic sense.[12] We think that lifting LOX supplies off of the Moon and bringing them to LEO, as he envisioned, will not make sense in this century. However, when the demand in LEO is massive and the traffic moving through LEO is so great that congestion is an issue the bulk of refueling operations may have to move to lunar orbit. Then the logical source of LOX would be moon rocks.

This technology is something that NASA should invest in, and says that it wants, but will probably develop with or without NASA support in the next 20 years. With solid support from NASA we can surely have it in 10 years or less, and design the return to the moon around this capability. Then the delivery capability of the current generation of rockets will be greatly increased.

III. Device Construction

Constructing a solid 30 meter wide cone with high-velocity molecular turbine blades in its mouth won't be easy. The device needs to survive impacts with occasional pea-sized objects. As such, the unmanned gatherer is likely to consist of a ballpark 10 tons of mass and will produce at least 25 times its weight in LOX annually. Design life of about 10 years seems like a reasonable goal.

We expect to use automated deployment methods in orbit. Solar arrays are currently unfolded in orbit like an accordion. Our goal is to design turbine blades and cones that unfold and expand into place through centripetal force when the turbine is slowly rotated. The outside edges of the turbine blades may be held in place with cables, and the blades may be supported in the front and back with guy wires. Unlike jet engine turbine blades, the main stress on an orbiting molecular pump will be centripetal force and not air pressure or occasional birds sucked into the turbine.

E. How Rapidly Could a "Crash" Development Be Carried Out?

The basic component designs that are under consideration will probably work. Our molecular pump design should work in a vacuum, in microgravity, and will probably absorb nearly 100% of incoming atoms. Other people's tether designs will probably work. The manufacturing of liquid oxygen will probably work. Boeing's spacecraft propellant depot system will probably work, though we expect that not all the potential customers will be able to come to it, so a delivery system will need to be designed as well as a way to move product from the production unit to the depot.

The 2007-2008 academic year will be devoted to settling on designs and considering the need for backup designs. We also need to do more detailed research on the weather 325 miles up, as our device may be sensitive to air pressure and to trace elements in the input stream.

In 2008-2009 Klinkman plans to build tiny test models of most critical process and run them in a vacuum chamber using WPI or NASA laboratory resources. One can test the molecular pump's absorption of atoms by spraying atoms at the pump with an ion propulsion engine. The required budget should be about $100,000 if volunteer graduate and undergraduate student labor can be recruited. These will have to be specialists in training advised by experts, or a paid staff will be required and the budget will be 3 times as large. No major testing of a tether is possible on Earth, but NASA has plans to deploy one soon.

If everything works, we'll be able to send a micro-version of our collector up sometime in 2010, again without a tether. Hopefully we'll be able to gather, to return to Earth, and to analyze a ballpark 1 gram of assorted gases with maybe a grain of space dust or junk. Given the device's complexity, this stage will require research assistants, graduate students who are part time and being paid as well as doing thesis work, thus a $200,000 budget would be the minimum requirement.

In parallel with this development effort, we will encourage the leaders in the field to undertake the development of better, more robust tethers. The goal is to marry a tether to our satellite for the first time in 2011 and if that part can't be outsourced, but has to be developed in house it will be hard to hold to that schedule. The goal for that test year would probably be to gather on the order of one ton per year of oxygen. Ideally this would be a test with a system attached to the ISS. Then the resulting LOX could be used by the international space station to replenish the space station's atmosphere and the gas gathered would not have to be liquefied to be of use. Currently, Russian Progress space vehicles deliver almost half a ton of water to the international space station every eight weeks, and much of this water is used for oxygen production. Our test device's budget would run about $5 million.

The next step up, in 2012, would be a launch of the largest possible molecular pump that doesn't need final assembly in space. Right now the largest items in space are about five meters in diameter. Such a pump would gather 20 tons per year of product. This satellite could cost $50 million, but it would displace $80 million dollars of refueling launches in its first year alone. For NASA, it would have a payback period of less than a year, given current plans.

Scaling up to the gathering of 300 tons per year of gases could be accomplished by launching and tethering together 15 such molecular pumps. These could be launched in the years 2013 through 2015. However, a single molecular pump is more efficient in many ways than 15 small pumps. A construction design team will have to start work in 2010 to be ready for launch and assembly of our 300 ton per year target model in 2014. The approximate launch budget will be $500 million with a $20 million per year maintenance budget, over a 10 year period. NASA's payback period would be approximately 6-12 months; certainly it would pay for itself in the first year.

At this point the fundamental costs of buying and selling propellant in orbit would change. Systems would not be designed around the need to launch liquid oxygen into space, other than to reach LEO itself. If NASA sponsored this effort, NASA or another US agency would be charged with managing the problems of liquid oxygen market prices and maintaining federal reserves of liquid oxygen in orbit. NASA would still get a government rate and private organizations and other countries would pay more. If private enterprise sponsors the development of this critical infrastructure technology and the alternative is $4000/ kg competition will develop and the current generation of chemical rocket technology will prove to have been more capable than expected. Many things that were expected to require a new drive such a nuclear or ion could be done with existing technology.

IV. Other Resource Possibilities and the Technical Challenges Involved

Nitrogen and oxygen both have potential value as a propellant in ion propulsion engines. Nitrous oxide is a fairly stable monopropellant which can be 100% orbit-gathered, possibly giving nitrous oxide a huge cost advantage. A group at Brown University seems quite determined to make the case for using it as a fuel. If they succeed, abundant nitrogen and oxygen that can be gathered from the upper atmosphere becomes a competitive fuel, and hydrogen boosted from Earth is less critical. Nitrous oxide does not seem likely to be a fuel of choice for tertiary rocket stages on high delta-vee missions, but it would be a useful and potentially cheap first stage capability. Another use for tons of nitrous oxide is as ballast weight for tether applications such as our own electrodynamic tethers.

Thus far we have identified few profitable uses for helium in orbit except for balancing pressures in liquid oxygen tanks, so most of the helium gathered around the Earth will probably be jettisoned. Helium mined on the Moon would be another matter since it would be deposited there by the solar wind and would include helium-3, a potentially valuable fuel for fusion reactors of the future. In his book *Entering Space,* Zubrin stresses the importance of a spacefaring society mastering this technology to have solar system-wide reach and to have dreams of travel to other solar systems.[13] Helium gathered around the Earth is much less interesting unless it can be demonstrated to have originated from the solar wind and did not rise from the Earth.

The emergence of fusion reactors on Earth that could use a combination of deuterium from the seas and helium-3 from the Moon might actually set off the 21st or 22nd century 'gold rush' to the moon envisioned by Griffin when he was speaking about oxygen. The gas trade that would foster interdependent civilizations on these two heavenly bodies would be helium-3 for hydrogen. When the Moon has both a powerful local energy source based on both fusion nuclear and solar power, it will also have the means to draw oxygen in bulk from its oxide rocks. Then at last there will be serious competition between lunar and LEO sources of oxygen. What the Moon will need before then is a local source of hydrogen or something to trade for it in bulk to make water to support agriculture.

Zubrin[14] himself thinks that the Moon is too limited a supply of helium-3 to be meaningful to an interplanetary society and that Saturn will ultimately emerge as the energy source that drives the solar system wide social system that he envisions. Others estimate that at present world levels of energy consumption the helium-3 deposits on the moon could power the Earth for 1000 years, far longer than the oil era will last. In short, helium sources are not interesting yet, but helium-3 might just become the most valuable lunar resource of all, and the Earth has little to none, while accessible deposits exist locally on the moon. That would make the moon a location as important to a future fusion energy economy as the Persian Gulf is to the current fossil fuel based energy economy.

In the meantime, the Moon's economic value will be based on its proximity to Earth, a relatively shallow gravity well, an easily collected metal supply similar to that of Earth and an abundance of regolith that can be used to ward off cosmic radiation by covering inhabited structures with 20-40 feet of regolith. We think that telepresence will allow 90% or more of the lunar workforce to stay safely on Earth and operate robotic devices that mine and fabricate on the Moon. One day, large orbiting structures around the Earth may be assembled and launched from underground workshops on the moon. However, at that point there will not longer be a hunter gatherer economy in near space, but a full scale trade system making good use of the differences between the Earth and its moon.

At this point the space faring nations and private organizations of Earth will have evolved into propellant-rich and iron-hungry hunter-gatherers in Earth orbit. We'll soon be hunting for cheaper extraterrestrial sources of both carbon and metals, our building blocks for habitat shielding and construction in earth orbit and elsewhere. Can we move carbonaceous asteroids into low earth orbit via slow propulsion systems? Can a small moon colony launch pig iron into lunar orbit at a fair price? Can we somehow gather carbon from the Venusian atmosphere? A propellant versus carbon and metals trading system would be the starting point for an off-earth discovery program driven by the economy rather than pure science. What is interesting about our proposed gas gathering system is that it just might be the first space based activity that produces a product other than information that can both pay for itself and enable an expansion of other space activities.

V. Invention and the University: Can Group Process and Self-Knowledge Be Taught?

A technological breakthrough has occurred here and the players are an unlikely crew. One is an inventor operating outside his field, the person giving the engineering and science students' credit for their work is a sociologist and the rest are undergraduates; the three most closely involved being Mechanical Engineering majors, one of whom has an interest in management and might change majors. Why them, and how we might best replicate the conditions that led to the breakthrough in other organizations?

The context of the effort is an unusual project program that was described earlier, but what of the specific team? As it terms out, Wilkes has been tapping the pool of WPI undergraduate talent interested in space for several years and been profiling the student teams that work with him using the Myers Briggs Type Indicator to describe the mix of cognitive styles on the various teams. Some teams "click" as a partnership, others never jell and only a few are standouts in terms of getting a potential innovation to work. The cognitive mix of the teams that click and the intellectual leaders that emerge in the highly innovative teams is something that Wilkes has been on the lookout for some time. He and his students have studied about 100 WPI student teams in these terms over the last 5 years, 80% of these being the Senior year project teams that WPI students form to do a project worth 3 courses in their major. Only 2 years ago was this type of study been extended to the Space Initiative junior year IQP teams.

Before Paul Klinkman, an independent inventor, approached WPI, Dr. John Wilkes had been running project teams on issues of space development for two years. Previous research teams had identified a general need to find a cheaper source of propellant gases in orbit or on the moon, even if they hadn't identified an economically viable source. Dr. Wilkes had this critical piece of information at hand when Paul Klinkman presented a rudimentary method of collecting gases as a guest speaker in one of John's classes. Paul talked in terms of bounds and limits, showing only that the possibility of slowly gathering gases in orbit could exist. John grasped the possibility and asked for further information. In a short time, Paul responded with further research and invention and John said it felt right that this could work. John then emerged as the organizational champion of the project.

In MBTI terms one has had a meeting of the minds between two "intuitives" who prefer to read between the lines rather than spell things out in detail. Paul was an INTJ and John an ENTP, different and complementary, but also overlapping in how they process information and come to decision.

A study by Douglass Wilde[15] of the Stanford University ME Department indicated that the ME design teams created at Stanford with an ISTJ as the anchor person were unusually likely to win Lincoln awards, but only if balanced by an EN "synthesizer" who thought out of the box and pushed the consideration of unusual approaches and perspectives. A creative tension emerged between the two roles when they were played by "naturals" who had personal preferences to operate in the fashion called for by these roles. The Stanford findings have been replicated in part at WPI in a study of students on their senior projects in their majors. Having an ISTJ or INTJ on the team did increase the chances of a successful and innovative team outcome though the ISTJ's were not especially likely to be perceived as "creative" themselves. They are the finishers, but the projects that they prefer to take on tend to be innovative in incremental ways, not big step function risky innovations of the breakthrough variety. The big step projects tend to be started by the intuitives (NJ or NP) and they have a mixed record on carrying through, especially the NP's.

In this case of the Gas Gatherer developed at WPI the anchor role of the person who demands the logic and specifics and talks to be spelled out was played by all three WPI students, who were ISTJ, IST(J?) and ISTP respectively and tended to have a cognitive clash with their ENTP advisor. John wanted to be general conceptual and flexible when they needed structure, specifics and clear expectations to be comfortable. Paul was more sympathetic to their need for task specificity and closure and found that they were pushing him in directions that would be useful when it came to filing a patent. He became technical advisor and organizational buffer and took the intuitive leaps that the students were resultant to take and let them prove him right or wrong as the case may be.

As Paul describes it, he was constantly driven to present a coherent project with achievable milestones to the students at weekly meetings. This meant that he had to keep ahead of the technologists. The invention grew in scope and in robustness week after week. The students were hard-pressed to keep up with the changes at first, but eventually gained a good enough understanding of the invention to ask some good questions about the invention and perform some independent research on these questions. The result was a careful document about a conceptual breakthrough that was quite convincing and outlined the remaining holes quite well. Two of the three oral presentations also went well.

Achieving cognitive balance and diversity without raising the level of conflict of the point that is pathological is really quite a feat. But these students did close ranks against the speculative tendencies of the advisors and though they went beyond their comfort zone they were a useful back pressure as well. Sometimes Paul could not articulate the connections he saw intuitively until the next group meeting a week later. Other times he really had skipped a logical step and the interaction was complementary and positive. Meanwhile, the ENTP social scientist visionary and project champion learned more and more about the technology over time. Soon he could play a useful role in noting what was really important and could change things in an important way and what was really not worth a spirited exchange as it really did not matter. The time and effort to spell out something in detail was not worth is at this stage so long as no one doubted that the problem was soluble.

Next year the dynamic will be different as the 4 students who will be working most closely with John and Paul on the continuation of the R and D process are not at all like the students in the last team. They are much more like Paul and John than their predecessors. Three of the 4 are friends and cognitively very similar to one another. Myers-Briggs researchers report that successful invention often relies on a balanced interplay between inventive people, champions who can recognize good ideas, and somewhat skeptical technologists who ask logical and penetrating questions. Optimally, these three types of people tend to feed off of each other's best qualities.

The question to be addressed next year is whether these people are too alike to perform well as a team? They will be very comfortable with each other and communicate more easily with one another and their advisor but will a creative tension be there? How can they be complementary? Paul will be the only J as the students are all P's like John this coming year. Can they consciously compensate for the lack of natural diversity?

As one compensation, the teams have been asked to self consciously document their experience next year and be aware that certain team roles will have to be played by people who are not naturally inclined to take them on by personal preference or cognitive inclination. Managers self conscious about the cognitive diversity on their teams and aware of the tendencies for certain types to attend to some things and let others slip may be able to see trouble coming and carry out mid course corrections. On the other hand, perhaps Wilde's procedure of forming the student groups so as to assure cognitive balance is wiser than trying to compensate for known group inclinations. A group dynamics experiment is under way. The results will find their way into Wilkes' course on Conflict and Accommodation in the Process of R and D. It deals with creativity and innovation at the group level. John and Paul met when he came to WPI to address that class.

VI. Conclusion

In summation, a case has been offered that inventors and universities, especially those with projects programs and that try to stay in touch with their alumni, have a considerable amount to offer one another. Good educational experiences for students can be produced by projects designed to test the viability of potentially patent worthy ideas. In this case the group dynamics at the micro level were interesting as students one would not normally have considered particularly creative as individuals contributed greatly to a larger ongoing creative process.

The idea itself emerged out of prior studies of potential breakthroughs that framed the question and set the stage for Paul's inventive insight. The solution is technically interesting, sets things off in a new direction and has potentially large implications in terms of dramatically reducing the cost of space operations. It is also promising in that be may make money in space in a new way and set in motion a next level of economic activity in space. We have dubbed that the hunter-gatherer stage in space and hope that it will soon set the stage for the agricultural revolution in space. That is what will be needed to pave the way to self sustaining colonies. Mankind is not going anywhere without its plant partners.

While this innovation does not change everything, it does sidestep the problem that is holding back the development of space, the cost of lifting a key part of the freight manifest to LEO, the bulk of the fuel supply. The general hunter-gatherer, "live off the land" approach which is evident in Zubrin's ideas as well as our own proposal could allow things to happen in this generation that otherwise would have to wait for major technological breakthroughs in drives and other areas. The proposed gas gatherer innovation enables an expansion in space by making the current generation of chemical rockets more capable despite their limited lift capacity.

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