Harvesting Gases in Lower Earth Orbit to Propel Spacecraft

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Abstract

Over the last six decades, spaceflight has been growing of interest to humanity. With increasing costs to launch scientific, military and commercial missions, aerospace companies are looking for ways to fuel or refuel spacecraft in orbit rather than having to carry payload and fuel together. Launching them together severely limits the payload delivered; since only 5-15% of the total gross lift off weight gets to orbit.

If part of that percentage needs to be fuel to maneuver in space or soft land on the moon, there is little payload mass available for instrumentations and cargo to be delivered. The best solution would be to use resources accessible in space for refueling - called in situ resources. The conventional wisdom for 50 years has been that the key to bringing down costs of missions staged from LEO is to minimize the cost of getting a pound of freight to LEO down. There has also been some interest in getting LOX from the regolith of the Moon (1/6\textsuperscript{th} Earth gravity well to overcome) to LEO. Currently, almost all propellant that is to be used by a spacecraft has been launched from Earth. Carrying this extra mass during launch limits the total payload capacity of the spacecraft. Clearly, an orbiting refueling depot is needed, but without a lunar base to supply LOX, the cost of lifting it to LEO to keep the depot supplied is prohibitive. Hence, the bottleneck remains.

However, Boeing has proposed to build a depot (ten launches) and fully fuel it (twenty more launches per year) enough to support two Lunar missions a year. NASA rejected the proposal, as it was considered not necessary, though desirable. Therefore, refueling in space is not considered part of the critical path back to the Moon. On the other hand, Chief Administrator Mike Griffin promised, in 2005, to use such a facility if Boeing built it with
corporate funding. Boeing was not prepared to take the implied risk and progress is stalled, though the US Air Force has “practiced” the rendezvous, docking and fluid transfer maneuvers necessary to service and refuel a satellite in space as part of the March 2007 “Orbital Express” mission (Malik, 2007). ASTRO and NextSat were the DARPA funded prototype satellites (built by Boeing) that demonstrated the ability to refuel in orbit, though ASTRO did not actually refuel NextSAT. They returned the fuel transferred to ASTRO the next day. Therefore, a lack of a fuel depot to support this emerging fuel delivery capability constrains missions and reduces the ability to run a more effective mission and efficient program. Various solutions have been proposed to overcome this situation. This project will focus on one potentially elegant solution, the gathering of LOX in LEO using unmanned satellites on the scale required to refuel spacecrafts, something that has recently (Foust, 2008) been described as impossible.

Interestingly this concept was originally proposed and largely proven in 1962 – but the field lost sight of this idea and it was not seriously proposed to NASA until 2007. The NASA Glenn reviewers of that proposal did not fund it primarily due to the lack of credentials on the part of the “marginal” outsider who claimed that it could be done but had never designed a spacecraft before. The reviewers met this claim with both skepticism and excitement, but actually, an expert who had very much the right credentials answered most of the objections to the idea in 1962. How the idea was lost, and whether a case can now be made for trying again to develop such a system is the subject of this paper. I will examine its feasibility of harvesting useful gases in low Earth orbit in hopes of removing this impediment to space and much more efficient era of space operations.
Introduction

The significance of the case of the loss of the 1962 PROFAC concept used component of it. Ion rockets and the whole concept of gas gathering in LEO are as much of interest to the management, technology policy and social organization communities as they are to the aerospace community. Serious organizational memory lapses and losses of promising, and even revolutionary, ideas and designs do happen. It is not my purpose here to prevent such lapses in the future, but just to document one well enough that it is clear how it happened and that the consequences for my technical field of Aerospace engineering were and are serious.

In this paper, I will offer a preliminary technical review that shows evidence from experts concluding that the concept to be discussed could and probably will work. Further, a few relatively recent Delphi studies that brought this concept back to the attention of modern experts revealed that the idea was not dismissed out of hand and the handful who got briefed on the idea were optimistic about the possibility.

There seems to be a consensus in line with my position that the economics of space would be tremendously improved if this technology were successfully developed. Even the anonymous NASA reviewer from inventor Paul Klinkman’s SRTT proposal submitted to NASA Glenn came to this conclusion. Given the broad consensus that this would remove a key technical bottleneck with large economic implications, this is a project worth attempting in the next decade.

Refueling in orbit using mostly in situ resources is a smart, simple solution to cut down launch expenses and gain more yield on investments in space systems. This concept will benefit various scientific, commercial and military applications. It will start to save millions of
dollars as soon as it is deployed and operational. There should be no shortage of demand for its product. Two systems designed be different people roughly 50 years apart to accomplish this task have been proposed. Both independently state that this concept is feasible, and in combination, they are convincing. Further, with two approaches to explore the chances of ultimate success are increased.

The report will comment on findings and provide some background information from previous IQP teams in the “Overview”-section. Following a historical orientation section, the technical report will describe concepts designed Mr. Demetriades and Mr. Klinkman, stressing PROFAC, the first designed and the one that was once lost and then found. Various aspects of feasibility will also be analyzed. Next, there will be a discussion section that will be followed by some concluding statements and comments regarding the report.
Overview

Economics play a vast role in space travel. The cost of getting payload to low Earth orbit greatly limits the full potential of space activity. However, in the late 1950’s, a fascinating concept was published by Sterge Demetriades, a Greek immigrant who had attended Bowdoin College and MIT, as well as Cal. Tech., that sidestepped part of the problem. Though it pushed the state of the art at the time, it was clearly worth a try and probably would have been if Sterge had been working as an insider at the newly formed NASA. The new space agency was then gearing up the Apollo program, charged with carrying out a lunar landing “by the end of the decade” (and before the Russians). However, he was not working on the inside and had extensive contacts in Europe. He wanted to talk about the idea there but the US government preferred that he not do that, at least until it was clear whether the US would be actively pursuing the idea.

The concern was that the Soviet Union might learn of this possibility and develop the concept before the US could and get another advantage in the Cold War space race. There was history of technical secrets that got to Europe and ending up in the hands of the Soviet Union. The US State department had struggled with the question of whether to let Sterge go to Stockholm to give an invited paper at the International Astronautics Federation meeting. The invitation came from Leonid Sedov, a Russian who was a leader in that organization. Initially, Sterge was denied a passport to attend and present, but in the end was allowed to go. Meanwhile, his general concept papers on PROFAC were starting to appear in a British journal.

The result was problems between Sterge and the US government. He was given a warning regarding the potential consequences of attending international technical conferences
to display the details of his idea. He knew he could have more passport problems and suspected that security clearance might be revoked, and he needed that to make a living. If he worked on any of his ideas regarding nuclear power or space technology for a foreign government, including Greece, he was told that a jail sentence up to 10 years was possible.

The message that he got was that if he were to work on nuclear power and space projects in the future, he would have to be working for the US government. This would require him to become a US citizen. In his case, changing citizenship was a serious matter; this act was viewed by the Greek government as a way for Sterge to escape the Greek military draft. His family warned him not to come home until this matter was resolved as draft dodgers could be executed in Greece. If the goal was to keep Sterge in the USA, it worked quite well.

At this point, it is important to clarify the time line. Sterge initially got onto a “watch” list of the US government, given his interest in nuclear devices and particularly explosives while still an undergraduate at Bowdoin. When he went to MIT for graduate school, the message about who he could and could not work for was delivered. In accepting the offer to work for the US government in this field, he was assigned to the ordinance center at Aberdeen, Maryland. Therefore, he stopped work on his Doctorate at MIT, took a Masters degree instead and went to Aberdeen. He was not happy there and arranged to leave Aberdeen on being admitted to graduate school in a new field, this time at Cal Tech. He started out wanting to work in aerospace, being interested in the problem of launching rockets out of tubes.

However, after Dr. Tsien, got in trouble with the US government and had to leave Cal Tech and return to China because of accusations of disloyalty, Sterge went looking for a dissertation topic that did not involve national security. He settled on a topic in Mechanical
Engineering involving the flow of fluids through veins, (essentially health work on blood) which was unlikely to be considered controversial. However, his real interest was still spacecraft propulsion and rocket design, so it was during those years at Cal Tech that he was consulting for several aerospace companies in the area, especially Aerojet. It was during this period that he had the insights that would lead to PROFAC. In its first version, the PROFAC system was powered by a nuclear reactor, clearly a carryover from his previous interest in nuclear devices, now elegantly combined with his new interest in aerospace. He was a cross-trained hybrid and thus, unusually likely to look at problems in a new way.

This period in Sterge’s life at Cal Tech was complicated by conflict with another student (Turkish) that started with an unprovoked attack in the first week that he was at Cal Tech. (See Appendix A for the details). The Cal Tech administration handled the matter so poorly that Sterge lost interest in becoming an academic, wanted to leave Cal Tech. as soon as possible, and ended up departing after 3 years without a Doctorate, having completed all but his dissertation. Actually, he felt he had completed it, his advisor disagreed, and so Sterge left without the degree. He then published the work that would have been his dissertation in an elite journal in the field. At this point, he felt he did not need the degree, since he was not going to be an academic anyway and had proved his point about the value of his biomedical research.

Taking full time work at Aerojet, where he had already been consulting on problem with the Titan rocket, Sterge found the private industry job market unstable, and in September of 1957, he was told that he would probably be laid off in December of that year. Actually, before December, Sputnik was launched and suddenly there were many new opportunities in the field
of aerospace. Aerojet did not lay anyone off, but Sterge left anyway for a new job at Northrop. It was here that he would assemble a team to work with him by day on plasma thrusters and on their own, at night, on the PROFAC concept. He declined to make PROFAC a Northrop project or proposal, though one of his managers, Ludwig Roth, (who was an associate of Wernher von Braun) wanted to handle it that way. Therefore, PROFAC was never an official proposal to NASA or Northrop as a funded project.

Sterge started publishing on the idea just before arriving at Northrop and when he became head of the Space Propulsion and Power laboratories at Northrop, he could hire people into his lab and assemble the team that would work on the PROFAC idea unofficially. In the end, they had assembled research reports comprising about 2000 pages of material. It was at that point that Demetriades et al. submitted a series of 4 papers for presentation at ARS (American Rocket Society) meetings, starting with the one at Berkeley in 1962. The ARS was the forerunner of the current AIAA.

Only one of these papers would be presented before the whole body of work was classified by the US government and removed from the open literature. The US government had been watching him since 1960, due to the passport incident and was ready to move immediately once he started publishing the details of PROFAC.

Four glimpses of the idea he called PROFAC, (the Propulsive Fluid Accumulator) appeared in the open literature before he was shut down. In 1960 and 1961, he managed to publish articles on the subject in the Journal of the British Interplanetary Society. Then in March of 1962, it is mentioned in an article called “Plasma Propulsion” that appeared in
Astronautics. That same year he presented that first paper in the intended series of 4 papers at the American Rocket Society meeting in Berkeley, California.

There was never a second, third or fourth ARS paper. However, in 1963 Sterge wrote an article called “The Propulsive Fluid Accumulator Engine” which appeared in the McGraw-Hill Yearbook of Science and Technology. In this document, he mentions that power sources other than nuclear could be used and gives examples. At this point, Sterge decided that as an immigrant, he could not function in fields that were militarily sensitive, left the field of aerospace and dropped his interest in nuclear power as well, to begin a career in a company working on coal plants, plasma physics and lasers.

The next time one sees mention of PROFAC in the American aerospace literature is when it is mentioned by Heinz H Koelle in his chapter 5 “ Evolution of Earth-Lunar Transportation Systems” in an edited book called Astronautical Engineering and Science. Koelle was, at the time, head of the future projects office at the Marshall Space Flight Center in Huntsville, Alabama, having been recruited from Stuttgart in 1955. This was two years after he organized the third International Astronautical Congress held in Stuttgart. He had come to the attention of Dr. von Braun through correspondence in 1948, but this event came when he was the secretary of the German Rocket Society and he impressed Dr. von Braun. They met at the conference and Koelle received a formal invitation to be Chief of the Preliminary Design Section in Huntsville in 1954. Hence, his article can be taken as the assessment of the von Braun team influential in NASA policy at the time.

In effect, Koelle et al. concluded that PROFAC would work, but NASA did not need it for Apollo. He also thought that it would be made obsolete by the development of a nuclear rocket
before the level of traffic between the Earth and the Moon would justify its development. “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” p 92. This is an interesting comment since PROFAC was not limited to chemical rocket applications, but the point is clear. The Huntsville group did not see any need for PROFAC and did not favor its development, at least at that time.

Partly as a result of the lack of enthusiasm for the idea in Huntsville, the development and testing of PROFAC did not begin at NASA’s instigation during the Apollo program. It is important to note that Sterge had not sent a proposal to NASA prompting this review. It was done at the initiative of the Huntsville group, and Koelle was presenting on this subject at the same ARS meeting in which Sterge was presenting his first detailed paper on the subject. Presumably, this was an effort to forestall, or at least vote against, its development, by an influential group in NASA. Since Sterge did not provide Koelle with any documentation, he must have heard about the idea from Roth and operated based on published materials.

Why this proactive negative stance? It was not Sterge’s position that Apollo should be based on PROFAC technology. He had concluded that it would take 20 years to develop and not be available in time to support the Moon landings; though it would be valuable later, when there was regular traffic back and forth to the moon. Construction of a lunar base was expected to start with the Apollo 20 mission. Years later, Demetriades was discussing the science politics of the period with James Gehrig, a staffer for a US Senator on the Senate Committee that oversaw science and space. He reported that the problem with PROFAC from the standpoint of Redstone Arsenal (Huntsville) was that it was built around a nuclear reactor
as a power plant. Hence, its development would not be under their control in NASA but rather that of the Atomic Energy Commission.

The US Air Force did not want the Soviets developing the idea if NASA was not going to do so; hence, the whole topic was classified—and dropped out of sight to the bulk of the ARS community. Only a few with security clearance would know of it. Worse, over time, the field of aerospace in the USA operated on the false assumption that the nearest extraterrestrial source of oxygen for propulsion was the moon. That was fine if you were going to go there and set up mining operations to support refueling in space, as soon as possible. However, the lack of investigation into a potential alternate source in LEO was very costly, if that was not a near term possibility. In fact, the result was a 40-50 year bottleneck holding up the development of cost effective on orbit refueling capability in the field of space logistics.

Through a series of happy accidents, a WPI graduate, Class of 1976, Paul Klinkman became convinced in about 2005 that there was enough oxygen in LEO to gather and started to independently investigate the matter. In preparing a paper (with Prof. Wilkes) to present at the Long Beach meetings of the AIAA in 2007, he was doing a literature review online and stumbled across a reference to PROFAC, really just an artist’s rendition picture generated by a space enthusiast with no source materials noted. Paul used the image with the title PROFAC in his talk, and someone in the audience knew Sterge Demetriades, still alive at the age of 78. However, that person did not give Paul a reference. This unknown person left after the LOXLEO paper was complete, not being interested in the other subjects on the agenda. Hence, he was not there after the session to talk. However, he soon contacted Sterge, who called Professor
Wilkes. Sterge Demetriades then provided the only open literature references to his work, strongly implying that there was much more if we could get it de-classified.

Paul was ambivalent about studying PROFAC, as he wanted credit for an independent insight with his LOX in LEO proposal. Sterge was suspicious of Paul and critical of aspects of his approach as well as leery of his lack of credentials in aerospace. Sterge noted that the lack of insider status was evident in the way he described his system. (Paul’s degrees are in computer science and political science, but he works as an independent inventor). Hence, they did not become collaborators, but Sterge and Professor Wilkes stayed in touch. The result was an independent effort by Paul to get an STTR (Small Business Technology Transfer) grant from NASA and a Delphi study of the reaction of the technical community in Aerospace as to the significance and likelihood of a breakthrough in this field as a WPI IQP advised by Wilkes.

Comparative reactions to descriptions of the concepts of Single Stage to Orbit Rocket, a Space Elevator, Space Tethers, a RAM Accelerator PROFAC and Paul’s concept dubbed “LOXLEO”, was undertaken by an IQP team (Fossett, Karasic, Lincoln, Moore and Roberts, 2008).¹ Half of these descriptions were taken from a prior Delphi study, so expert reaction to them was known already. Hence, the new panel could be assessed as more or less optimistic as the last panel on these items. The new items were PROFAC, LOX LEO and Space Tether, the latter included as a baseline for what an accepted but novel idea’s reception should look like. It was also of interest because it was a concept included in the LOXLEO design, so the two needed to be separated in the analysis.

Paul’s STTR received a split review and comments from one of two reviewers at NASA Glenn raised the same question that Sterge had raised, regarding his chosen altitude. Both
NASA Glenn reviewers offered a strong hint that he needed to recruit a partner with the right credentials to receive NASA funding. However, one was skeptical and dismissive of the whole idea that there was enough gas in LEO to gather. By contrast the other reviewer described the concept as “having large and far-reaching implications for NASA” if the claim proved justified. Clearly, he had never heard of PROFAC and considered this idea revolutionary. Paul did not cite Demetriades in this proposal, not thinking he would need justification for the general concept of gas gathering in LEO. He also wanted to avoid the possibility that the two approaches would be compared, since he believed NASA must have already carefully examined and rejected PROFAC on technical grounds. He did not want to give the impression that the idea had been tried and failed, but wanted it looked at as new and innovative.

Meanwhile, the IQP team was struggling to get expert respondents, especially from NASA people, who would be willing to comment on these related ideas in a Delphi study. At one level, it was near heresy to claim that one could do this, since it was enough out of the prevailing paradigm to seem impossible. Yet, the idea was presented as “in the literature” of the 1960’s due to the inclusion of PROFAC. There was a citation and this description drew heavily on Sterge’s own abstract in the British Journal. Further, the description noted that von Braun’s team had taken the idea seriously. It was not a maybe, but a clear claim of a technical finding.

Fossett et al. ended up with about 10 useable cases and the distribution of cases ran to both extremes, but the averages were typical of the prior Delphi study that had gotten about a 25% response rate compared to their 11%. Primarily, those who loved or hated the idea responded this time and about 89% of the sample remained silent. However, there was a
meeting of the National Space Society coming up in Washington DC, and the Advanced Space Technology Working Group (ATWG) was meeting the day before. Perhaps the Delphi panel could be augmented in a single day.

Klinkman and Wilkes got on the ATWG agenda at the last minute with the understanding that they would distribute the descriptions used in the study the first day of the conference, collect them the working of the second day and include the results provided by the audience in Paul’s talk the second afternoon. One of the questions asked people to self identify as “experts” in Aerospace technology or not and about half of the 12 respondents, (out of about 20 people present) considered themselves “expert”.

Interestingly, the experts were more optimistic about the idea than the non-experts were but in general, they were of the same opinion and that was that this idea was far more significant and likely to occur than the prior polarized panelists had thought. However, both groups rated it as about as likely to occur as a Space Elevator, though it could occur far sooner. The two groups of panelists had very different ideas of when a space elevator could be built and how likely that was to occur. They were not even fully agreed on the significance of such a development, but they agreed that if PROFAC or LOXLEO, which got similar ratings, worked it would be a big deal second only to a working Space Elevator or Space Tether system, which would even more radically alter the economics of space. Therefore, a total panel of 23 (with optimistic and pessimistic wings identifiable within it) was ready to put this idea on the aerospace table for another look based on a mere two-page description of the concept. While Wilkes considered these encouraging results, and a long step toward establishing the technical credibility of the idea, both Klinkman and Demetriades were critical of the Delphi
study. Klinkman found the results discouraging as he could not believe anyone would consider his concept as farfetched or as much of a long shot as a space elevator. He agreed that an elevator would be more revolutionary and significant, but the likelihood ratings were “crazy” making this a fringe idea when it was something we could do in 5-10 years not 50.

Demetriades was unhappy with the way PROFAC was described. He also objected to the description of his background in another part of the Fossett et al. report as having gotten some of the biographical facts wrong. Regarding the findings, however, the description in his abstract was supported by the whole article being right there to clarify the idea. This stand-alone description was written by WPI students who did not fully understand the idea, did not do the idea justice, as they were not aerospace majors and did not fully understand the concept due to limited physics background.

In his view, the ratings for PROFAC and LOX LEO should not have been the same and the non-experts had no right to an opinion; and they were probably dragging down the averages. The experts had indeed rated PROFAC a bit higher, but considered the ideas roughly comparable. Demetriades considered LOXLEO rough, crude, and vague compared to his precisely worked out rationale and detailed published conceptualization.

The students working with Klinkman also claimed that each time they spoke to Paul he had a new version, so LOXLEO was indeed a work in progress. Things changed so fast that Paul considered the description in the Delphi study obsolete (as was his proposal to NASA Glenn) by the time he got the Delphi study results. On the other hand, he claimed his design was more politically feasible since PROFAC required a nuclear reactor of considerable power orbiting at about 100km. Actually Demetriades had considered the use of other power sources, but not in
the articles to which Klinkman had access at the time. Klinkman decided that any system involving a nuclear reactor would be a hard sell to Congress, which had to fund all NASA projects. Paul had avoided this problem by moving LOXLEO to 300km, so that he could power it with an electro-dynamic tether. Hence, one concept had a controversial power source and the other one that was yet unproven, and which require the system to operate at an altitude where the gases available were very diffuse. In short, both conceptions had technical problems and neither inventor considered that Delphi study the last word on the subject and both wanted an impartial review by qualified experts based on better presentations of their ideas.

The current project picks up at this point. When I began work, Klinkman was finally ready to read the details of the PROFAC proposal and draw upon Demetriades’ greater technical legitimacy to make the case that gas gathering in LEO is conceptually possible. He then wanted to enter into a debate with Sterge about the specifics of an optimal design. He wanted a WPI Aerospace major to read all available reports on the subject of PROFAC and develop enough of a rapport with Demetriades that he could ask direct questions of the now 80-year-old man.

Hence, I was encouraged by Klinkman and Wilkes to focus on PROFAC and try putting this idea back in the literature for Sterge Demetriades, while he was still here to comment and answer the questions of those interested. Klinkman is ready to give credit to the master as a pioneer but still determined to operate at the highest possible altitude and to do without a nuclear reactor for a power supply. For his part, Demetriades does not think he needed Klinkman, and while acknowledging his role in the rediscovery of his ideas by the rank and file members of the AIAA, he had reservations about his involvement. For one thing, the way he
described things was not consistent with the conventions of the field of aerospace. He feared that Klinkman might undercut the credibility of gas gathering in LEO as a concept in that expert community.

For another thing, Demetriades disputed the idea that PROFAC was ever really “lost” and needed to be “found” again. In his view, the small group of people who really mattered had heard about the idea and would develop it when the time was right. He reported getting contact about once a decade, with questions about the concept from people who had heard of it from an old timer or had access to classified documents. He recalled a meeting in 1982 at Edwards with people working on SDI and another meeting in 1991 with people from NASA who wanted him to explain the concept again. However, he had to admit that nothing seems to have come from those meetings. Now that the idea was getting much broader attention due to its shock value to the rank and file at AIAA, he wanted to distance himself from the LOXLEO presentations and their author, but join into the general excitement about exploring this unexpected possibility. At the very least, he wanted to secure his claim to priority on the idea. With luck he might live to see the idea get some financial backing and start to be developed while, he could recruit, advise and consult on the early phases of the project. He wanted to see if there is finally enough interest in the PROFAC idea to launch one last entrepreneurial venture in his career. It is “unfinished business” from his first and second phases of career.

Since one clearly cannot work with both of them at this juncture, my job is to master the details of PROFAC and present on the subject before technical audiences to get their reaction to the concept based on a full presentation. Ideally, I wanted to get Demetriades to come to the East Coast himself and present at an AIAA New England Chapter meeting held at WPI or MIT.
AIAA was prepared to fund such a trip and designate him a “Distinguished lecturer” if I could get him to agree to come.

Failing that, I was to try to arrange a televised presentation at WPI, MIT or both with Sterge speaking from a studio at Cal Tech., which is near his home in California. He has refused to consider other sites as a stage since he wants his “colleagues” in Pasadena to hear the talk as well, and thinks it might be okay to videotape it as his final word on the subject, though he had not agreed to do that in advance of this project.

Since the September 2009 AIAA, annual meeting was to be held in Pasadena, Calif. It was also possible that I could get on the program and get my travel covered to that meeting. If so, we would get to meet. Prof Wilkes proposed a session on refueling in LEO as part of the space logistics track of the program to increase the odds of this meeting coming about. Paul Klinkman and I were to present back to back, me on the PROFAC concept and with him speaking about LOXLEO, with Sterge Demetriades invited to hear the session and help answer questions about PROFAC. Prof. Wilkes would chair the session and be present as well to “moderate” any technical debates that emerged out of the meeting.

Out of this meeting in Pasadena, a presentation by Sterge himself, open to the AIAA membership of New England was the desired outcome. I could then study the reaction of the aerospace technical community in New England to this daring “new idea” now nearly 50 years old. Should Demetriades decline to star in his own show, I would have to try to be the stand-in and put PROFAC back on the technical agenda myself. Someone else would have to do the assessment of how much my efforts had affected the technical credibility and perceived feasibility of the idea in the Aerospace community compared to the state of affairs when I
started. I considered the starting point to have been described by the Fossett et al. Delphi study. Hence, repeating something along those lines with an audience that had heard my talk would give one an idea of its impact on the credibility of the concept.

Step one was to master the concept myself, communicate with Demetriades, get his reaction to my efforts and try it out on one or two audiences. The first would be an audience of my peers at WPI, in particular those in the WPI chapter of the AIAA. The second would be open to the professional AIAA membership at either the national meeting in Pasadena, or a gathering of members from the New England Chapter of AIAA. I would have access to a membership list with 3 interests checked off to use in setting up an invitation list of about 100 likely experts out of the 1000 or so in the region. My goal was to produce something like the panel assembled at the ATWG meeting for the prior study. Ideally, I wanted Sterge to give an overview presentation, though I was willing to do it myself, if he had seen and approved the materials. I then wanted to entice 3-5 of those present to read Sterge’s ARS paper in its entirety and return to the next Chapter meeting to form a panel discussion group and offer their formal assessments in a Q and A format such that it could be videotaped and documented. Ideally, Demetriades would be able to listen in on this discussion and participate to the degree he wanted as well as answer direct questions from this knowledgeable audience.

So that was Plan A, B and C. In fact, there would have to be a Plan D for reasons I will explain later, but I am not unhappy with the idea of writing the oral presentation into a form suitable for publication and using that as my stimulus to the field that had lost sight of concept of gas gathering in LEO in general and had not heard of the PROFAC idea in particular. In some respects, the best way to put this idea back on the table for consideration in the open literature
is a formal article to which Sterge can formally add commentary and which has references back to his original published work. The only reason the oral presentation format seemed more appropriate in this case is that so little of the work he did on PROFAC ever got published. At this stage in life, nothing was going to stop him from talking about the “classified” part as well, if one could just get him in front of a video camera. He probably wants to lay intellectual claim to this important idea, this is his last chance, and I wanted to help.

Hopefully, someone will be motivated enough to go through his papers when he passes on, if the original classified reports are no longer in existence. Ideally the papers that were the background of the lost reports should be placed in the custody of a technical library at Cal Tech, MIT or WPI. It is my hope that a second WPI project team on the “organizational memory” issue in aerospace will be formed next year. Aerospace has a looming problem in which 25% of those currently active in the field will reach retirement age in the next 3-5 years. A mechanism to get those leaving and entering the field talking to one another about the promising ideas that never got developed for one reason or another is needed.

If such a team forms, I hope that it will pick up where I left off in helping Sterge Demetriades secure his claim to the PROFAC idea and recover as much documentation as possible that he might still have. The AIAA New England chapter has proposed such a project to WPI and at this time, one of the students interested in it for next year is an Aerospace/ Physics major from Southern California. Hence, there is a real chance that the PROFAC side of the organization memory project at WPI will continue.
Technical Introduction to the Problem

Analyses show that there are two distinct phases for space travel: the booster phase and the sustainer phase. The booster phase concentrates on the escape of Earth’s gravitational force. This requires substantial amount of thrust to break free. The sustainer phase requires minimal thrust or a high specific impulse provided for long periods. Solutions to this stage such as ion rockets, collage rockets, and plasma jets have been proposed and many have been put into production. These solutions have provided higher efficiency in completing missions; however, issues arise when means to run these systems require large quantities of propellant. With current technology, it takes a few hundred pounds of propellant and power plant to put one pound of mass into orbit.

A case can be made for an orbiting collection system and fuel depository if the mass of propulsive fluid required for spaceflight is eliminated from the gross lift off weight. Carrying just the energy source required to complete the first stage and then refuel will prove to be highly effective. An analogue to this is if one was preparing for a long distance road trip. He does not carry the total fuel required to complete the trip in a trailer behind the car. Currently, that is what NASA is doing; they are carrying all propellant necessary to complete a mission. This is not an efficient or a resource conserving way to proceed.

Boeing has made a proposal to NASA in hopes of solving this problem as well. Their plan is to station a fuel depot in Earth’s orbit in a plan that would require 10 missions. Then one would launch a chain of 20 more missions (each year) to maintain the supply of fuel in the depot for spacecrafts to use. The scale of their proposal was tied to the requirements of the Constellation program, which involved two trips to the moon each year for a decade. The
proposed depot could support 2 manned lunar missions before it needed to be refueled from Earth. This method would allow NASA to concentrate more on its primary mission objectives rather than be constricted and worry about fuel restrictions and would nearly triple the mass of equipment delivered to the moon to build a lunar base at the south pole given the same 20 missions to the moon with the same lift capacity. Unfortunately, Boeing’s proposal was not funded by NASA as it was deemed unnecessary, but NASA liked the idea enough to try to get Boeing to build it with corporate funds. Boeing declined, and there is a valid reason behind the decision of both parties not to fund this proposal. It was too expensive.2

The typical price of liquid oxygen (LOX) on earth is about $10/kg. It is a modest amount; but to transport a kilogram of mass to Lower Earth Orbit is about $10,000. This and along with the fact that it required 10 or more launches from Earth to fill the depot enough to support one lunar mission prevented Boeing from gaining support of NASA to build the depot. All Boeing got was a promise to use it if Boeing provided the up-front funds for construction and fuel delivery. It seems clear that a different approach is necessary.3

A fresh solution

As previously mentioned, Sterge T. Demetriades conducted several studies in the subject of harvesting gases in the low Earth orbit. At the time he wrote, efficiency was not a major concern. The United States was competing with the Soviet Union in the space race to match or better the other’s accomplishments in exploring outer space and particularly reaching the moon. Time was more important than money. The President of the US said we would do this in 8 years. There was no time to build a permanent infrastructure to support long-term lunar operations. PROFAC began to make sense as an investment when you were planning to
make the trip to the moon regularly. Sterge himself did not question this logic, as he estimated that the technology would take 20 years to develop and the Moon race would be over by then. It was not needed for Apollo but rather would be part of building the lunar base to follow and maintain the supply lines it would require in steady state.

Since Apollo 20 was to have been the start of lunar base construction, developing PROFAC should start with the planning for that mission. Having it by 1985 would have brought down costs and increased mass delivered to the moon quite substantially had the infrastructure investment been made. Von Braun was comfortable with a similar logic and was trying to make the case for a space station as a staging area for departures to the moon. PROFAC would have made as much sense as part of a big space station construction project in LEO as for a lunar base, and indeed von Braun considered them related projects.

Delay in working out the infrastructure to support cost effective space activity was costly since that is the kind of question that would have brought PROFAC back to the open literature while there were still a lot of people in the AIAA that had heard of it. Ideas are more likely to get lost if they are being deferred or brushed aside so long that their champions leave the field or move on to other things. In the case of gas gathering in LEO. It would be 2007 before the concept first proposed in 1960 was reinvented, and then it would appear in a much cruder form as the second inventor, Paul Klinkman, was not an expert in the field of aerospace.

Together Demetriades and Klinkman suggest a more effective way of space travel, a fresh solution. The essential feature to their concept is to lift only the energy source required to bypass Earth’s strong gravitational force. The basic procedure of a system that refuels spacecraft in LEO (Lower Earth Orbit) is as follows:
• Station an orbiting vehicle which collects gases (the harvester)
• Launch a vehicle from Earth with enough propellant to achieve the altitude of the harvester or a separate depot in a low but stable orbit to which the harvester offloads its fluids.
• Rendezvous and commence refueling
• Detach and undertake or resume mission

This system could dramatically reduce launch costs and upkeeps, increase the amount of payload, and enable one to run longer and more efficient missions. This is a very appealing feature for the designers of spacecrafts intended to complete long distance missions.

Satellites and other communication systems have a lifespan of about 5 to 10 years. A recent study estimated that about 22% of the satellites presently failed during that brief lifespan only because they were out of fuel. The lack of propellant turns functional systems into space junk that is a hazard to other satellites. A functioning satellite must be able to complete orbital maneuvers and stay on station. When in a decaying orbit a satellite that is operational in all other respects must be written off. If a system was created whereby satellites could be refueled using mostly in space resources, companies globally could save millions of dollars by extending the operational lives of these existing systems. In addition, the rate at which satellites will be considered obsolete and abandoned would be reduced since missions to de-orbit ‘junk’ will be possible when a ‘tug’ can show up to refuel, repair, or de-orbit a satellite. This kind of clean-up program would allow future missions to be conducted in greater safety.

The International Space Station (ISS), NASA space shuttles, and various crafts from different countries could also effectively utilize LOX from the harvester for this basic, yet vital re-boosting or station keeping maneuver. The design life of the ISS is much longer than a typical satellite because humans inhabit this major investment. Once again, this system is
currently refueled by launching oxidizer from Earth and this puts a larger burden on resupply missions to maintain its already hefty upkeep. The ISS could be another major consumer of the LOX from a harvester. It would only be necessary to boost the Hydrogen from Earth to go with the LOX gather in the upper atmosphere. Hydrogen is only, about 15% of the total mass of this kind of rocket fuel-oxidizer mix.

Payload is what mainly drives missions. Company and government projects finance missions to transport their payload to and through space. Increasing the payload capacity in turn means more funds are freed up for additional missions. If the harvester were to be used, the initial mass of propellant would be lower at launch; this allows missions to be able to transport a larger mass of payload. It will not be a one to one ratio between the extra mass of propellant and the payload because the overall mass of the propellant decreases as it is used up. The amount of surplus payload space freed up by not having to carry fuel will vary with various vehicles, but overall an increase in mass that can be lifted beyond LEO in the same number of launches will be evident.

It is hard to have both a long efficient mission and diminish costs. The gas harvester manages to attain both goals. It will cut costs by reducing the amount of fuel required during launch and raise efficiency depending on the number of times the craft refuels during its mission life and can stay in space rather than be subjected to the stresses of launch and reentry. If a wide scale application of such a system is applied, an interplanetary trade system could also be implemented. Therefore, if the spacecraft is LOX-Methane based and is performing missions on Mars, a planet with a high composition of carbon dioxide in the atmosphere, this system if implemented there could gather carbon dioxide in LMO. With a
supply chain from Earth and the Moon to provide LOX and hydrogen, the system will be sustainable. Variations of these systems are possible; this report will not go too deep into this idea, but it is worth looking into.

This report acknowledges Sterge Demetriades’s early design, Paul Klinkman’s third iteration, current design, and contains a proposal to test this concept and take a step closer to removing the uncertainty about whether gas gathering in orbit is possible. If it were possible, development of such systems would remove a constraint that holds humanity back from having much more efficient space programs and more ambitious missions, as well as more continuous space activity.
Technical Report

Spacecraft thrusters typically require two types of propellant: Fuel and Oxidizer as shown below in Figure 1. The upper atmosphere serves as a gigantic storage tank for a useful propulsive fluid – air/oxidizer.

![Figure 1: Thruster Schematic](image)

Figure 2 below shows the change in density as altitude rises. One method to use the gaseous mixture present at 100 km would be as a monopropellant; unfortunately, the atoms cannot be stored in a high-energy state and could only be used as propellant to maintain orbital speeds while collecting a balance of the air. Even so, calculations shown in “The Use of Planetary Atmospheres for Propulsion,” state that the energy of recombination alone is not sufficient to counteract the aerodynamic drag caused on the vehicle at orbital speeds. In addition, the atmosphere is far too light to provide practical lift at suborbital speeds.
The density may be low, but it is far from zero, a vehicle circling the Earth at orbital speeds would cut a ‘doughnut’ path containing a surprising weight of gaseous matter. Figure 3 illustrates this below.

At 100 km, approximately 400 kg of air can be collected in one day by a 1 m$^2$ scoop. Figure 4 below shows the dominant gases at various altitudes.
Table 1: Percent composition of gases at various altitudes

<table>
<thead>
<tr>
<th>km</th>
<th>Oxygen</th>
<th>Nitrogen</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>10.7%</td>
<td>89.3%</td>
<td>0.00%</td>
</tr>
<tr>
<td>150</td>
<td>21.5%</td>
<td>78.5%</td>
<td>0.00%</td>
</tr>
<tr>
<td>200</td>
<td>49.9%</td>
<td>50.1%</td>
<td>0.02%</td>
</tr>
<tr>
<td>250</td>
<td>59.5%</td>
<td>39.6%</td>
<td>0.05%</td>
</tr>
<tr>
<td>300</td>
<td>64.2%</td>
<td>35.8%</td>
<td>0.01%</td>
</tr>
</tbody>
</table>

Table 1 above magnifies the altitudes of interest and provides percent composition of gases. It is important to note that at 100km, Oxygen seems lower in percentage than what is expected; that could be because it is dissociated and therefore lighter. It could also be an error, but let us accept it as accurate since using a conservative number makes a stronger case for feasibility. The case would be even better if the proportion of oxygen available at 100 km is twice as great.

Assuming a harvester with an inlet of 1 m² is continuously scooping the atmosphere, the values stated on Table 2 below can be computed. It is important to note that even though it seems, that Oxygen, the gas of interest, is dominant at an altitude of 300 km, it does not mean
that the harvester will be collect a greater mass of it than it will at an altitude of 100 km. It is far more beneficial to collect gases at lower altitudes than higher ones, due to the density gradient.

Table 2: Masses of various gases capable of being collected per square meter at various altitudes per year

<table>
<thead>
<tr>
<th>km</th>
<th>Oxygen</th>
<th>Nitrogen</th>
<th>Other</th>
</tr>
</thead>
<tbody>
<tr>
<td>100</td>
<td>42,200</td>
<td>352,000</td>
<td>0.35</td>
</tr>
<tr>
<td>150</td>
<td>160</td>
<td>590</td>
<td>0.02</td>
</tr>
<tr>
<td>200</td>
<td>35</td>
<td>36</td>
<td>0.02</td>
</tr>
<tr>
<td>250</td>
<td>18</td>
<td>12.5</td>
<td>0.02</td>
</tr>
<tr>
<td>300</td>
<td>6.8</td>
<td>3.7</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Demetriades’s Conceptualization

During the late 1950s and early 1960s, Sterge T. Demetriades conducted several studies in the subject of harvesting gases in the lower earth orbit. As mentioned earlier, the essential feature in this concept is to lift only the energy source required to achieve the targeted orbit altitude, in this case: 100 km. At that point, begin collecting the propulsive fluid for continuing the journey into space. A Propulsive Fluid Accumulator or PROFAC accomplishes this.5

There are two ways to utilize the thin gases present in the upper atmosphere. The first would be to power an *Orbital Vehicle* in conjunction with a nuclear energy source. The idea behind this would be produce sufficient thrust to counteract the low aerodynamic drag encountered on its orbit. The vehicle would collect the air, accelerate it, and project it to the rear. The thrust required to remain in orbit is low; consequently, a low-powered nuclear drive would serve for a low-altitude satellite for almost indefinite life. This system would be maneuverable because it provides thrust.

The second way would be to use the air as a propulsive fluid for a *Space Vehicle*. In this case, the air will first be collected and stored. A second vehicle, the orbiting powered satellite,
would carry with it a PROFAC unit to collect and store air to be used for space travel by a second vehicle.

Initially, the *Space Vehicle*, PROFAC, and the *Orbital Vehicle* would be combined as a single package during the launching phase. Once sufficient air has been collected, the *Space Vehicle* will detach from PROFAC and the *Orbital Vehicle*. Eventually, PROFAC and the *Orbital Vehicle* would become permanent fixtures that will allow future *Space Vehicles* to make a refueling rendezvous with on their trip away from Earth.

Figure 5 below illustrates the great advantage that would result from such a system. To land one pound of payload on the Moon with a multistage chemical rocket, approximately 3,000 lb of takeoff mass is required. Likewise, a multistage nuclear rocket with hydrogen as a propulsive fluid would require approximately 600 lb. Both of these methods do not account for a return trip. The PROFAC design would only require 300 lb of takeoff mass for a round trip to the Moon and back. Once PROFAC units are left in orbit around the Earth, trips to the Moon and back would only require 150 lb of takeoff mass.
Figure 5: Relative mass ratios required to land one pound of payload on the Moon on equivalent basis (3).

PROFAC provides significant savings, especially with the collection equipment in orbit serving as an orbiting ‘gas’ station. The only expense in that case would be to lift the payload to an orbit near the system. In other words, the chemical rocket mass requirement for low altitude orbit is all the reaction mass that is required for subsequent travel in space be that a nearby space station, Geosynchronous Orbit or Mars. This reduces initial launch costs and mass significantly.

System Description

As mentioned earlier, the PROFAC system can be divided into three basic components.

Figure 6 below illustrates the Orbital Vehicle; it consists of a power source, guidance and
control equipment, an inlet for receiving, compressing and ionizing air, a driver section for accelerating the air, and a nozzle for ejecting the air back into the upper atmosphere.

![Figure 6: Schematic of Orbital Vehicle]

The second component is the PROFAC unit. This unit consists of an inlet, a compressor subsystem, a fixation unit, and a well-insulated storage tank. Figure 7 shows the schematic for such a unit; it will normally be powered by the Orbital Vehicle.

![Figure 7: Schematic of Propulsive Fluid Accumulator (PROFAC)]

The final component is the Space Vehicle as shown in Figure 8. This unit is a typical spacecraft and contains the instruments required to accomplish its mission.
Figure 9 below shows the conceptual design of all three components, the Orbital Vehicle, PROFAC, and the Space Vehicle grouped together. The actual system would be arranged such that drag is minimized.

**System Requirements**

For successful operation of a PROFAC system, the following design requirements must be met:

**Propulsion**

Enough thrust must be produced to overcome drag. Calculations allow one to estimate the exit velocity required to overcome the total drag. The required velocity increment is
relatively small because only small mass rates of flows are involved and the total power required to effect this acceleration will be in the order of 0.4 MW/m² of inlet area. The power can be reduced by an order of magnitude for every 15 km increase in operating altitude; however, the gas available to be gathered is falling off at a comparable rate. ⁶

Nuclear technology is to be utilized to provide sources of power of this magnitude. This type of energy source is especially beneficial because it has very long lifetime. A ramjet is to be the power plant of this system because it eliminates the need to carry a working or propulsive fluid. Additionally, the only major alternative to such a component is the rocket, where stagnation temperature must reach orders of 45,000 K or more to produce exhaust velocities of the order of 10⁶ cm/sec by expansion of heated air. On the other hand, a ramjet can achieve orbital speeds by increasing the stagnation temperature by only 10,000 K. ⁶

In order to increase the stagnation temperature to such a degree, simply heating it at these low densities and high temperatures is not sufficient. A method of accelerating low density, high velocity flows consists of an electrical discharge followed by magnetohydrodynamic (MHD) acceleration consisting of crossed applied electric and magnetic fields. ⁶

The basic principle of a MHD driver is when a high-voltage high-frequency alternating current is applied between a pair of parallel metal plates, the space between the plates exhibit a solid state, meaning it has attributes of mass, inertia, and momentum. ⁷ In other words, the transformed area is capable of undergoing mechanical forces. It is possible to produce thrust for a spacecraft using this technique. ⁸
In Figure 10 above, a box is constructed using two metal plates forming opposite planes and two insulated plates holding them in place and surrounding the area within. High frequency, high voltage alternating current is applied to the metal plates, creating an electrical field, $E$, acting between the plates as shown in black. A magnetic field, $B$, is generated due to the electrical field. It acts perpendicularly as shown in blue. These two fields produce a propulsive thrust, $F$, as shown in red. This propulsive force is not produced by ejecting any matter out of the box; instead, it is produced by a reaction against the solid-state condition of space-time caused by the high frequency electromagnetic pulsing of the area within the box.\(^8\)

To put this concept into perspective, if the amount of energy used to mechanically lift an object a distance of 1/100 of an inch off the ground, were used as an electromagnetic lifting force, then the amount of energy would lift the object more than $3.472 \times 10^{24}$ miles off the
ground. This Lorenz and Faraday type of drive used by a spacecraft would require small amount of input power to drive the ship at great speeds and over great distances.

The MHD drive is capable of overcoming the drag of the Orbital Vehicle and the PROFAC system and can produce positive accelerations of about $10^{-4}$ g for the entire duration of its flight. In addition, propulsive fluid stored in the craft can be ejected in large quantities for high power evasive or correction maneuvers.\(^7\)

**Collection and Storage of Upper Atmosphere Air**

Minimizing the PROFAC inlet and surface area relative to the Orbital Vehicle inlet, the thrust of the MHD drive from the Orbital Vehicle can be kept small to overcome drag. However, the PROFAC inlet must also be large enough to insure a reasonable collection rate. As mentioned earlier, a square meter of scoop area is capable of collecting about 400 kg of air per day. If the scoop expands to 100 m\(^2\) then about 4,000 kg is collected.

**Table 3: Power Levels and Requirements for Collection and Storage of Upper Atmospheric Air\(^6\)**

<table>
<thead>
<tr>
<th>Process</th>
<th>Power requirement, kW/m(^3)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Stagnation energy of air and recombination of O (^{\infty}) atoms</td>
<td>200</td>
</tr>
<tr>
<td>Compressor—power to compress from 0-001* to 1 atmosphere and 1000° K.</td>
<td>200</td>
</tr>
<tr>
<td>Cooling from 1000° K. to 90° K. followed by liquefaction of air at 1 atmosphere</td>
<td>10</td>
</tr>
<tr>
<td>Keeping 100 m(^3) of surface area (corresponding to 1 m(^2) of scoop area) cooled against sunlight</td>
<td>100</td>
</tr>
<tr>
<td>Losses, pumps, human needs and guidance equipment</td>
<td>490</td>
</tr>
<tr>
<td>Total power requirements for collection (6 g./sec. at 100 km.)</td>
<td>1000</td>
</tr>
</tbody>
</table>

* Ram compression accomplishes compression from $10^{-4}$ to $10^{-3}$ atmosphere.

Table 3 above estimates the thermal power requirements in the order of magnitude estimates. As mentioned earlier, they can be reduced an order of magnitude for a 15 km
increase in altitude until at around 150 km where the flux of solar energy alone is sufficient to provide power for thrust for the system. However, at altitudes above 130 km, it becomes uneconomical to collect. One megawatt of thermal energy can be radiated from a surface of 10 m$^2$ at 1000 °C; this thermal energy requirement is feasible to be produced.

Table 4: Estimated masses for Collection and Storage process

<table>
<thead>
<tr>
<th>Component</th>
<th>Mass</th>
</tr>
</thead>
<tbody>
<tr>
<td>Liquefaction Equipment</td>
<td>150 kg/m$^2$</td>
</tr>
<tr>
<td>Storage Tanks</td>
<td>5% of containing liquid</td>
</tr>
</tbody>
</table>

Once the air is collected, it will be stored as a liquid in an appropriate tank. Table 4 provides the estimated masses for each component for the collection and storage process. The storage tank mass includes the containing liquid, insulation and auxiliary equipment.

**Power Source Requirements**

As mentioned earlier, two types of power sources will be required. The first would require a source with a long life and a very high energy density; this can be accomplished by a nuclear power source. It is recognized that developing such sources is difficult; however, the task is simplified due to the low power requirements. Systems currently being designed are in the order of 10,000 MW, in this case, however, a typical power requirement is only about 0.26 MW/m$^2$ for practical plasmatization of the stream and 0.24 MW for the actual acceleration of the stream, for operation at about 100 km altitude.

Assuming that the Orbital Vehicle inlet is 10 m$^2$ and the PROFAC equipment has a scoop area of 1 m$^2$ the power requirements would be 5 MW and 1 MW respectively. For a total of 6 MW of required power, the power source auxiliaries and equipment would mass to about 2 tons; the PROFAC system in this case would accumulate about 40 tons in 100 days.
The second power plant used by the Space Vehicle would vary by mission. The power requirements for missions once in orbit are minimal.

**Primary Thrusters for the Space Vehicle**

The thrusters for the Space Vehicle can be a simple nuclear engine with powering to about 20 MW and a total mass of about 5 tons. This will heat the propulsive fluid through means of heat transfer and expand it through a nozzle. A more sophisticated plasma or ion thruster for longer-range interplanetary travel may also be used. In addition, solar energy can also be used. An alternative method would be to carry fuel (probably hydrogen) from Earth to burn with the collected oxygen. These choices will primarily be based on specific mission, but carrying hydrogen and collecting oxygen would suffice and any excess would be used to produce water, a stable way of storing propellant for long periods that is of value for its own sake. Easy and early conversion to water will help compensate for Hydrogen’s high boil off rate when stored for long periods, especially when subjected to direct sunlight. Some proposed designs for orbiting fuel tanks and depots include sunshades.

**Navigation and Guidance Requirements**

Successfully operating this system requires that a guidance and navigation system be in place. This is because these systems will undergo numerous rendezvous maneuvers and having a proper system in place will simplify the process.

**Paul’s Concept**

The overall concept of Mr. Klinkman’s design is similar in some respects to that of Mr. Demetriades; however, one way in which they dramatically differ is the way they plan to gather
the propulsive fluid. In other respects, Klinkman’s designs have converged with Demetriades as he became aware of constraints and problems that Demetriades knew about in advance.

In response to previous critiques by NASA reviewers, WPI students, and later Sterge Demetriades himself, Klinkman has set aside the ideas of operating at 300km, powering via an electrodynamic tether and trying not to use any of the collected product gas to produce the thrust to remain in orbit. He now thinks that 150-200km is the proper operating altitude, doubts that tether can be used that low, and is prepared for up to half the gathered gas in a fluidized form to be used to maintain station in orbit. He wants to operate the mechanics of the processing unit with solar power to avoid having a nuclear reactor on board and plans to separate the nitrogen and oxygen gathered on board and use primarily the nitrogen as the fuel to maintain orbit and maneuver the gatherer. The bulk of the oxygen gathered would be the product to sell as LOX. He is looking into how good a rocket fuel $\text{N}_2\text{O}_2$ would be and thinks it might be adequate for many purposes. Thus, one could sometimes avoid the need to lift Hydrogen to LEO to use with the LOX gathered in orbit.

**System Description and Requirements**

Over the last 4 years, Mr. Klinkman has had numerous designs; the basic concept underlying the current design is derived from the spalling effect that is recognized during spaceflight, especially in oxygen rich layers of the upper atmosphere. A solid-state collector of hyperthermic atoms, high velocity particles, will line the front. This nano-layer with a thickness of 50 nanometers would allow only hyperthermic atoms to pass. Aligned to this is a permeable stopping layer sizing about one micron thick through which stopped gases may permeate air
channels in the contained area. An impermeable back layer and a stiff layer support the entire component. Figure 11 below shows the schematic of such a part.

![Figure 11: Feather Magnified](image)

The impermeable and permeable layers need to be resistant to oxidation due to the fact that it is oxygen ions one is collecting. Gold does not react with oxygen and is impermeable; it can be used, however, it is delicate. Paper is another example of a permeable substance that can be used. Fiberglass will provide stiffness and air channels while resisting oxidation.

In theory, hyperthermic oxygen atoms penetrate the first layer, reach thermic velocities in the stopping layer, and combine with other oxygen atoms to form oxygen molecules. These molecules build up a minute pressure in the air channels. This pressure forces atoms down the embedded air channels, out of the feather’s exit, and down to a tube to a high vacuum pump. Figure 12 below illustrates this.
Feathers will experience severe damage if they collide with large particles in space. Fortunately, space dust particles at low altitudes are rare. These feathers are designed to be replaced if ever punctured or damaged. A robot set on a guide rail will replace these when necessary. A method for detecting gas leaks from a feather will be in place. Shown below in Figure 13 is another view of the system.
The steel central collector pipe will protect the central air tube and support the robot. The collector surface would have a mass of about two kilograms per square meter.

This gatherer is to be orbiting at an altitude of 200 km; each kilogram of deployed feather, including its central pipe, would absorb 300 kg in its ten-year lifetime. The mass of the collector becomes irrelevant compared to the mass of the solar panels needed to power the harvester’s ion propulsion engine or the LOX storage tanks.

**Feasibility**

*Economic Case*

A method for refueling in orbit is necessary; millions of additional dollars are spent each year for launching payload. As mentioned earlier, escaping earth’s gravitational pull cannot be avoided, fuel worth considerable money will be spent to overcome this force to deliver payloads to LEO. However, if one can refuel in LEO, it does not matter if one is going to the
space station at 350km, the Moon, and asteroid or Mars from there. You do not need to carry the fuel to move from LEO to GTO, Lunar orbit or even for the lunar lander. Even better, the shuttle could refuel and not have to return to Earth early. It would be a more efficient and a longer duration mission system that reduces the risks involved in take off and landing. It is also to be understood that the astronauts’ well being must also be taken into account. In most fuel systems, LOX is about 85% of the propellant mass. Hydrogen is light and in some cases, a Nitrogen oxide like N₂O₂ can be used. Hydrogen would have to come from Earth; keep in mind that even though it is light, the density is very low, and will require a much larger storage tank. Resources can be saved by reducing the initial wet mass. This can be accomplished by refueling in orbit using ‘in-situ’ resources the gas gathered described earlier. Anything that reduces the required propellant during launch will save money, as you are not using propellant to launch the propellant to be used later.

Assume a perfect system was created that was capable of harvesting all gas particles in its path at an altitude of 100 km; the following Table 5 will provide savings at various time scales.

<table>
<thead>
<tr>
<th>Period</th>
<th>kg</th>
<th>U.S Dollars</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 year</td>
<td>42200</td>
<td>$422,000,000</td>
</tr>
<tr>
<td>6 months</td>
<td>21100</td>
<td>$211,000,000</td>
</tr>
<tr>
<td>3 months</td>
<td>10550</td>
<td>$105,500,000</td>
</tr>
<tr>
<td>1 month</td>
<td>3517</td>
<td>$35,166,667</td>
</tr>
<tr>
<td>1 day</td>
<td>117</td>
<td>$1,172,222</td>
</tr>
</tbody>
</table>

It is important to note that the table does not take into account oxygen used by the harvester to operate itself and maintain a low orbit in the face of substantial drag. A note is to be made that in the case of PROFAC, Sterge plans to use all types of gases that are gathered to expel and
produce thrust whereas, LOXLEO plans to maintain its propulsion systems using mostly nitrogen and when necessary oxygen. Computations are based on the given figure of launching a kilogram of mass at $10,000 to LEO using the shuttle. Debate rages about how low this cost can be made using existing technology. The lowest figure I have seen mentioned using an ELA is about $4000, for a proposed private launch system, but that is not currently possible. Hence, this chart is based of prevailing NASA costs. If Nitrogen were to be used as propellant, savings would be nine times as much.

**Technical Feasibility**

The typical mission with refueling is not much different from today’s missions. Most of the technology is in its basic stages. The following shows the description for technology readiness levels. Figure 14 below shows a quick overview.

![Figure 14: TRL scale](image)

**Table 6: Technology Readiness Levels in the National Aeronautics and Space Administration (NASA)**

<table>
<thead>
<tr>
<th>Technology Readiness Level</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>1. Basic principles observed and reported</td>
<td>This is the lowest &quot;level&quot; of technology maturation. At this level, scientific research begins to be translated into applied research and development.</td>
</tr>
<tr>
<td>2. Technology concept and/or application formulated</td>
<td>Once basic physical principles are observed, then at the next level of maturation, practical applications of those characteristics can be 'invented' or identified. At this level, the application is still speculative: there is not experimental proof or detailed analysis to support the conjecture.</td>
</tr>
<tr>
<td>3. Analytical and experimental critical function and/or characteristic proof of concept</td>
<td>At this step in the maturation process, active research and development (R&amp;D) is initiated. This must include both analytical studies to set the technology into an appropriate context and laboratory-based studies to physically validate that the analytical predictions are correct. These studies and experiments should constitute &quot;proof-of-concept&quot; validation of the applications/concepts formulated at TRL 2.</td>
</tr>
<tr>
<td>4. Component and/or breadboard validation in laboratory environment</td>
<td>Following successful &quot;proof-of-concept&quot; work, basic technological elements must be integrated to establish that the &quot;pieces&quot; will work together to achieve concept-enabling levels of performance for a component and/or breadboard. This validation must be devised to support the concept that was formulated earlier, and should also be consistent with the requirements of potential system applications. The validation is &quot;low-fidelity&quot; compared to the eventual system: it could be composed of ad hoc discrete components in a laboratory.</td>
</tr>
<tr>
<td>5. Component and/or breadboard validation in relevant environment</td>
<td>At this level, the fidelity of the component and/or breadboard being tested has to increase significantly. The basic technological elements must be integrated with reasonably realistic supporting elements so that the total applications (component-level, sub-system level, or system-level) can be tested in a 'simulated' or somewhat realistic environment.</td>
</tr>
<tr>
<td>6. System/subsystem model or prototype demonstration in a relevant environment (ground or space)</td>
<td>A major step in the level of fidelity of the technology demonstration follows the completion of TRL 5. At TRL 6, a representative model or prototype system or system - which would go well beyond ad hoc, 'patch-cord' or discrete component level breadboarding - would be tested in a relevant environment. At this level, if the only 'relevant environment' is the environment of space, then the model/prototype must be demonstrated in space.</td>
</tr>
<tr>
<td>7. System prototype demonstration in a space environment</td>
<td>TRL 7 is a significant step beyond TRL 6, requiring an actual system prototype demonstration in a space environment. The prototype should be near or at the scale of the planned operational system and the demonstration must take place in space.</td>
</tr>
<tr>
<td>8. Actual system completed and 'flight qualified' through test and demonstration (ground or space)</td>
<td>In almost all cases, this level is the end of true 'system development' for most technology elements. This might include integration of new technology into an existing system.</td>
</tr>
</tbody>
</table>
According to Table 6 most of the primary components on these are of low TRL, because Sterge Demetriades’s research dropped out of sight and was not developed in secrecy by the few experts who knew of it. An opportunity was lost, since the rank and file of aerospace technologists were not thinking in these terms even to the extent of designing systems with refueling in mind as a future possibility. It is unfortunate that no one considered PROFAC as a way to make chemical rockets more capable when the popular nuclear power drive concepts of the 1950s and 60s ran into problems and were not developed as expected.

Additional study and research must be conducted to further affirm the feasibility of the gas gathered in LEO concept but this is not beyond the state of the art, and a determined program of development to hit TRL 7 would be possible in the 2010-2015 period. If successful, it would be a TRL 9 by 2020, in time to support the planned return to the Moon systems being designed as part of the Constellation program. By then, other lunar return systems would have to be finalized and modifications to take refueling into account incorporated into their designs.

What has to happen in the next five years would be:

- Research details regarding the composition of Upper Atmosphere at various altitudes
  - Probe can be sent
- Experiment land based harvester
  - In a vacuum chamber, test to see if particles can be collected when a high velocity stream of particles is sprayed on the collector
  - Test durability of the feather system in simulated launch conditions (LOXLEO)
- Test the ability for MHD to provide sufficient thrust
A simple test in a vacuum chamber on Earth to test the concept
Experiment in weightless conditions

- Test various low power nuclear power and alternative power sources for PROFAC Once these are completed, component prototypes can be created to be tested in simulated (test chamber) and then actual space launch missions.

**Schedule Feasibility**

Proving the concept is one thing. Committing to a design and putting it into production is quite another. The only candidate for early production is PROFAC. LOX LEO is not worked out in enough detail to be tested at present. By contrast, if PROFAC works it can be used as soon as it is in production and compatible with various spacecrafts, whether or not it proves to be the optimal design in the long run.

The controversial part of the PROFAC design seems to be the gas gathering intake system. When I presented the PROFAC system at the AIAA Regional student conference at Boston University on April 24, 2010, I was a student speaker, but also presenting as a special guest sponsored by the AIAA new England. Thus, while the other student presenters were in a contest and their presentations followed by questions from a panel of judges, mine was different. My presentation was followed by the comments of an invited expert discussant, Manuel Martinez-Sanchez, Professor of Aerospace from the Faculty of MIT. Professor Martinez-Sanchez commented that he hated to pour cold water over such an exciting idea, but he did not see how the intake system could contain the ionized oxygen and nitrogen molecules coming in at orbital speeds. They would bounce out, go off in all directions, penetrate the metal and in general, resist being dampened down and flowing into the capture system.
While some of the other problems were challenging, he did not see anything that could not be done if the gathering mechanism could be made to work, but he had no confidence in that. He was skeptical of my thesis that non-technical considerations explained why PROFAC was not developed in the period 1965-85. Its implications would have been so far reaching that the lunar program would not have been needed to justify the technology investment. It would have gone ahead whether or not the US was developing a lunar base. Thus, he concluded that there had to be some technical reason it was not developed and his hunch was that that was the problem that was so challenging as to have led people to give up on the idea.

My advisor John Wilkes rose in the final moments of the session and said that if Sterge were here today he would agree that that is indeed the make or break problem and to solve it he had had to develop a special pumping system to get the particle to flow into the capture system, that that was one of 4 key inventions that had been necessary to get the system to work. Unfortunately, Wilkes was basing this comment on a recent brief phone call and could not report any technical details of how it worked or at what technological readiness level it was. He could also say that Sterge was aware of the possible objection and claimed to have addressed it.

Professor Martinez-Sanchez responded that IF that problem were truly solved, he felt that such a system was indeed theoretically possible, and if possible, it was probably worth doing. He later commented in private that if such a cryo-pump exists he would want to invest in it himself. Its implications would go well beyond enabling PROFAC. He took with him a folder of Sterge Demetriades article in the original to examine more closely, but said that he remained a skeptic and there had to be a technical problem that was a show stopper to have
halted development of a system with these capabilities. I do not agree. Social and political factors shape technology just as much as technical constraints involving the state of the part or the laws of physics.

What we have here is a good illustration of how delays in technology development and the silencing of the champions of a technology erode the credibility of an idea in technical circles. Delay is taken as a bad sign even if no one has actually demonstrated that the system cannot be developed or is not worth developing. Nuclear fusion skeptics often comment that that breakthrough has been ten years away for the last 50 years. In this case I am willing to say that if PROFAC can be done the time to do it is concurrently with the Constellation Program. PROFAC was originally proposed and illustrated in the context of providing infrastructure for supporting a lunar base.

The technical research requirements mentioned earlier will need to be completed before a large-scale production of harvesters can be built. The quicker the concept is proven, the more economical launching spacecrafts will become.

**Operational Feasibility**

If the proposed solution, which I think will be a cross of the PROFAC concept with a few gathering and dampening idea borrowed from LOXLEO, is successful, launch costs for long duration missions in LEO and especially for missions beyond LEO will be reduced dramatically. Additional payload can replace the unneeded fuel. This will reduce the number launches required to complete missions. Each mission will vary by need; this system is capable of benefiting it.
The system can be launched from various launch vehicles; sizes can be modified and specified according to given volume measurements of the payload compartments. Upkeep requirements for these systems are minimal; guidance and navigation systems must be kept active with ground control to correct maneuvers and evade possible collisions. Issues with the system can be inspected while spacecraft rendezvous with the system or a depot supplied by the gathering system, to refuel.

**Discussion of Results**

PROFAC represents a concept that as a practical matter was lost for a generation. Yes it was still in the archival literature and those who remembered debates about it in the 1960’s had not all left the seen those most were at least retired. Granted, Sterge Demetriades was fielding a question about the concept about one a decade in the 1980 and 1990s. However, by 2005, the idea was so out of mainstream thinking that the visible literature discounted the possibility and reintroducing PROFAC in the 2009 AIAA meeting had shock value. This was not supposed to be possible and yet here is this knowledgeable expert in his 80’s claiming that it not only could be done, but that in the 1960’s there was a consensus among the best and brightest that it probably could be done, but was not yet warranted. How could something so important get suppressed and neglected to the point of being forgotten - especially since nuclear drives had not been developed in the interim?

So, how much of the original research and documentation can be recovered not and credited to the rightfully acknowledged original pioneer? I fear that most of the original reports are not just classified, but actually lost. Still, it would not be like starting from scratch to
reconstruct the system from what I have found and Sterge remembers. If developed, a PROFAC-based system could transform space activity by partly removing a major technical bottleneck to the economic feasibility of orbital refueling. It defies conventional wisdom (Jeff Foust 2008, so only a person marginal to the aerospace community would have been likely to seriously consider this possibility. However, at one time, the idea had the attention of the NASA rocket development team in Huntsville, Ala. assembled by Wernher von Braun, and they did not see any reason it could not be done - though they decided not to do it. Roth at Northrop was very keen on the idea and urged Sterge to make it a formal corporate project. I have examined the concept and agree with their concept feasibility assessment but disagree with the assessment of its significance and potential promise by Koelle. The success of PROFAC, LOXLEO or some combination of ideas from both of these systems would be transformative. The delphi team (Peter Moore et al., 2007) that looked into the concept, especially the group at ATWG, seems to have it right. This would not be as big a breakthrough as a space elevator, but it is a big deal and could be done much sooner.

I was very impressed by the papers by Demetriades et al. that I read about PROFAC, and was awed by the vision it represented and its economic and technological implications. I have conversed with Sterge Demetriades regarding this, mostly by phone, since he does not check his email too often. He prefers to be sent a formal letter as a fax and then he will generally call you back.

I prepared an oral presentation for the WPI AIAA Student Chapter and delivered it in February of 2009. The whole group of about 12 students was as impressed as I was, and no one could see any reason that it could not be done. My presentation stressed PROFAC since
LOXLEO is less well documented, and at that time, the LOXLEO concept was not written for a technical audience. However, Klinkman was present and he offered a variety of specific criticisms of design choices in the Demetriades proposal, focusing on the altitude of deployment and especially the use of a nuclear reactor. (At the time I did not know that Demetriades did not consider this an essential part of the system)

The tone of Klinkman’s critique was one of a discussion of means rather than feasibility. His criticisms were constructive. It was not that this version of the idea (PROFAC) cannot work, but rather -was that the best way to do it? He felt that the nuclear reactor component would no longer be politically acceptable. Klinkman, a Quaker and anti-nuclear in spirit, was determined to produce a system without a nuclear reactor and was convinced that it could be done. Demetriades would not disagree. He has worked on non-nuclear methods for meeting the power requirements of PROFAC and agrees that it could, but that it would be a much more complicated system, if for example solar power were used. He was prepared to defend the use of a nuclear reactor saying that it raised many fewer issues than a nuclear power naval vessel docking at a major port. Klinkman strongly disagreed. I do not think it matters, not at the level of conceptual credibility and technical feasibility. What I hear them both saying is that the nuclear system would work, but there are other ways to do it if there are insurmountable objections to that approach.

The upshot of the student AIAA WPI chapter meeting was a consensus that this seemed to be within the state of the art whether the specific proposal before us (PROFAC) worked in all details.
Later, in debrief I found my tone was at odds with my words. It was scary to be saying
sometimes we all ‘knew’ it was probably impossible, but actually, it was not impossible and
consequently, the field was wrong about this matter for the last two generations. I was trying
to hedge, and in this case, one really has to make ones best analysis, form a judgment, make a
claim and stand by it until proven otherwise. If I waffled, PROFAC might not get a technical
review by others and thus chance to be tested, and I was fully convinced that a ground based
feasibility test was warranted. Why was I so surprised that people doubted this could be done
if the idea had been purposely suppressed by the US government and hidden form the rank and
file at AIAA by removing it from the open literature? How could it be true if you consider
yourself an expert in your field and you never heard of it or thought of it yourself? Professor
Martinez-Sanchez’s reaction is to be expected, but even so he considered the idea exciting,
though a long shot. I got the impression that he wanted to see it tested, indeed starting with
what he considered the acid test. He did not want to see it ignored but rather demonstrated or
disproven, up or down in the next few years.

In a way, he and I have been in the same place, right after my first talk to the WPI AIAA
chapter I found that I had implied I had doubts without being able to articulate them or say
where they came from. Actually, that was not my job to decide whether to do this, but rather
to make a case for the idea and see if I could answer all reasonable objections. By the time I
spoke at BU, I think I hit the right tone, and was a true champion of the idea. We then let and
let the discussant do his job so that the audience got a balanced picture of what the most
challenging outstanding questions were.
It amuses me to think that I was not ready to do that in September when I agreed to improve the tone of the presentation to give a clear message reluctantly.

He agreed to consider repeating the talk at the National AIAA meeting in Pasadena. However, I decided that I could not go, so Prof. Wilkes credited me, and gave my PROFAC talk in Pasadena, with Sterge Demetriades present. Paul Klinkman gave his talk right after ‘mine’.

The first two talks by others made the case for why a refueling capability as needed and suggested that it might be worth creating, even if it meant 20 launches to fill a depot in LEO. Progress toward making such a system cost effective by bringing down the cost of launches was reported.

Then came ‘my’ talk. The 25-30 people present could clearly tell that this changed everything – and Professor Wilkes told me that the reaction was mostly thoughtful silence, with a few skeptical questions about how they could not have heard of such a thing before if it was really possible? Mr. Demetriades took the floor to correct a few details about who he was working for in his day job (Northrop) and who was working with him moonlighting on PROFAC, how far they got in testing and he corrected few technical details Prof. Wilkes got wrong, most of which I would not have gotten wrong.

In public briefly and in private in detail, Sterge Demetriades endorsed my presentation and said that I clearly understood what his proposal was claiming technically. He doubted that the prior WPI students (Moore et al.) who had worked on the Delphi project had so fully understood it. I could now advocate on his behalf, and he thanked Prof. Wilkes and I for
helping bring the PROFAC concept back into the attention of the aerospace community and giving him proper credit for his work nearly 50 years ago.

After Sterge spoke Paul Klinkman gave his talk, and Sterge left the scene in the middle of it muttering things that could not have been complimentary. He returned and made some sharp criticisms that amounted to saying that he did not understand the physics of space and was clearly a novice in Aerospace design. This was high theater as he ‘distanced’ himself from a person he implied did not know enough to be taken seriously. Sterge later claimed to have left the room to laugh at something he had said without being openly rude. Those present knew he was being openly dismissive and some claimed to have been shocked that he was so rude to someone who had referred to his prior work quite respectfully and conceded his priority, though disagreed about how best to de-energize and gather the incoming particles.

Paul Klinkman hopes for a truce and the possibility of future collaboration were dashed. Prof. Wilkes had been warned by an Manuel Martinez-Sanchez of MIT that Sterge Demetriades had a reputation for ‘not suffering fools lightly’ but this was an unexpectedly sharp attack. Though Wilkes met with Sterge for dinner, and they spoke by phone as well it was clear that Demetriades was trying to get Klinkman out of the picture and get the interest at WPI refocused on his proposed system, which I had to admit had greatly impressed me.

Sterge Demetriades confided that he did not want to ‘make up with Paul, but was impressed by the ‘Wilkes-Palooparambil’ presentation and wanted to explore the possibility of getting a next generation PROFAC design produced and into testing. He felt a graduate student team at Cal tech, WPI or both would be appropriate, but saw no place for Klinkman in such an
effort. He also wanted Wilkes to step back now and be the sociologist interested in the social implication of the technology leaving it to the experts to assess and develop it.

Wilkes had no problem with this and said he wanted to get back to doing the historical study and Society-Technology studies he saw evident in this case. They talked about the larger problem of organizational memory, politics shaping scientific and technical advance, and the kind of relationship a technical and nontechnical people should have in promoting a technology that is revolutionary and overcoming the inertia of precedent. Wilkes found himself wondering what other good ideas the people of Sterge’s generation had thought of, but didn’t see the light of day because they “weren’t needed” by NASA at the time.

Hence, this project concludes with an ethical dilemma. Wilkes did not rediscover PROFAC and Demetriades larger body or work, which I found so impressive. Klinkman found it and made a key contribution to its recovery by the larger AIAA community. However, this public showdown between Demetriades and Klinkman in Pasadena has reduced his chance of getting a fair hearing for his independent ideas at AIAA meetings. A fast track development of the concept should start from PROFAC noting Paul’s technical criticism, but moving beyond them.

What would be fair treatment of Paul Klinkman so that he could walk away now and let the professionals take over without ignoring this independent discovery of the Gas Gathering concept? Sure he would be play the role of Gray to Demetriades being Bell in the case of the discovery and rediscovery of the telephone, but this case is more like that of Mendel; since that work was lost nearly completely and Sterge Demetriades was working on other things before the WPI initiative on gas gathering in LEO started at Paul’s instigation.
Discussion between Klinkman and Wilkes revealed that Paul is an inventor, and it is much harder to cash in on an idea like LOXLEO than his Solar Greenhouse, which can be built in a garage. Hence, he would be willing to step back if his contribution was recognized financially. He would settle for a very small percentage of future profit or enough money to buy a modest house with room for an inventor’s shop, preferably a barn. This would be about $250,000, which he would pour into his first love, solar power technology suitable for heating and cooling a greenhouse in New England or southern Canada. As for space ideas, he has a number of them that would be applicable to developing a solar powered lunar base. He wants to work on ways to process lunar regolith to extract resources such as oxygen. In short, make him a homeowner for the first time in his life and he will walk away from the LOXLEO project with no regrets and turn to other pursuits.

Sterge has given the matter of a talk in New England for the AIAA chapter a bit of thought and declined. He does not want to prepare a formal talk. He would come if it were to talk to potential investor or to a professor with access to a suitable laboratory that wanted to do some testing. He is willing to meet with proposal teams, corporate managers or potential investors. Clearly, he would like to get something going at Cal Tech, as it is local but if efforts emerge at WPI or MIT first, he would go for it. He is now 80 and cannot wait around for 5 years if he wants to be part of the consultant team or board of directors overseeing the effort.

Therefore, my job was to talk about PROFAC, try the idea out on a suitable audience of experts, and set up a suitable channel for the exchange of ideas between Sterge Demetriades and interested experts currently active in the field. As a member of the next generation of technologists who knows of PROFAC, and understands it well enough to explain it to the
uninformed I have championed the idea to some extent, or at least made it more visible. This
idea is now something that the best graduate and undergraduate students in aerospace in this
region have been exposed. Through my talk at this AIAA Regional student conference the
concept has gone home with the students who were present to MIT, Drexel, Cornell, Syracuse
NJIT, West Point and other lesser known colleges and universities. His PROFAC is now
something I can discuss casually or about which I can supply a copy of one of Demetriades’
original papers on the subject to those more advance in Aerospace than I who want details.
Through my efforts written and oral I think I have reduced the chance that the gas gathering in
LEO concept will get lost again. I succeeded in my charge to put it back on the discussion table
where the average AIAA member can see it and think about how to do it and what the
implications of success would be.

I was also supposed to engage in an objective dialogue with Paul Klinkman and get him
to acknowledge, adopt and give proper credit to his ‘adversary’ where aspects of the PROFAC
design were superior to his ideas. I failed to get Sterge to come to New England or agree to a
telecast from Cal Tech. The jury is still out and whether I can get him to comment after a
presentation, I give on his behalf. I am ‘approved’ to put PROFAC back in the literature as long
as I correct the biographical error that Sterge objected to in the last IQP report dealing with
PROFAC. These corrections are made available in Appendix A. I want to thank Sterge for his
rapid response in getting the misconceptions that I had about how things happened and in
what order and why corrected in the last 48 hours before the submission deadline for this
report.
Conclusion

The significance of this case is as much to the management, technology policy and social organization communities as to the aerospace community. Serious organizational memory lapses like the suppression and neglect of PROFAC and the general concept that gas gathering in space is possible can and do happen. It was not my purpose here to prevent such memory lapses in the future, but just to document one well enough that it was clear how it happened and demonstrate that the consequences for my technical field of aerospace were serious. However, on a positive note, both the concept and some of the specific plans for PROFAC were recovered in time to acknowledge the innovator in his lifetime and advocate for the development of such a system while he is around to help plan the effort. PROFAC is still worth building if it is possible to do so. We have not yet returned to the moon to stay and that was the application Demetriades used as an illustration to make his economic case for PROFAC in 1962. However, it would still be worth doing it if the Constellation program is cancelled.

In this paper, I have offered a preliminary technical review and have not found any reason to believe that a system like this is not a possibility. Indeed, I have found evidence that the best experts 50 years ago that heard of it concluded that it would work. However, they were looking at the nuclear power part of the system with different eyes than we would use today. Still, there are other ways to meet the necessary power requirements with other technology available today, but I personally like the elegance of the system built around a nuclear reactor.

Further, a few recent Delphi studies that brought this general idea back to the attention of modern experts found that the idea was not dismissed out of hand. The ATWG group study
result was fairly optimistic about the possibility as soon as they heard about it and in a presentation that Sterge Demetriades considered woefully inadequate. My more complete presentation to the AIAA chapter at WPI was quite well received. The Preseantion at the Regional Conference at BU went even better. The next generation, at least, seems open to the possibility of looking further into this matter.

There seems to be a consensus in line with my position that the economics of space would be tremendously improved if this technology were successfully developed. Even the anonymous NASA reviewer from Klinkman’s SRTT proposal submitted to NASA Glenn came to this conclusion. As claimed earlier, it is hard to have both a long efficient mission and a decrease in expenses. The proposed gas harvester manages to attain both goals. It will cut costs by reducing the amount of fuel required during launch and raise efficiency depending on the number of times the craft refuels during its mission life. Given the broad consensus that this would remove a key technical bottleneck with large economic implications, this is a project worth attempting in the next decade. Demetriades estimated that it would take 20 years in 1962, but the state of the art then was quite different. We agree that it might be done in ten years today by a team that was determined and well funded.

I have laid out a schedule for the pace at which this technology demonstration would have to proceed if it was to influence the design of system scheduled for use on the moon in the period 2020-2025. More important is my list of the technical questions that have to be answered on the ground (in an applied research program) to prove the concept enough to justify the funding necessary to test a prototype in space.
Refueling in orbit using mostly in situ resources is a smart, simple solution to cut down launch expenses and gain more yield on investments in space systems. This concept will benefit various scientific, commercial and military applications. It will start to save millions of dollars as soon as it is deployed and operational. There should be no shortage of demand for its product. Two systems designed to accomplish this task have been proposed. Both independently state that this concept is feasible, and in combination, they are convincing. Further, with two approaches to explore the chances of ultimate success are increased.

The PROFAC system is more completely developed and easier to assess. It looks promising, but includes a few controversial design decisions. I conclude that it is possible to do something like this with accepted and mostly proven technologies and that there may be some useful idea in the LOXLEO system that should be assessed as well. It is probably within the state of the art to do this despite the reservations of Manual Martinez-Sanchez. Hence, it is certainly a concept that must be looked into and researched further. As of now, I consider the gas gathering in LEO concept to be feasible subject to the experiments that I have proposed concluding successfully, before a flight test is attempted.

On another note, I think there is a message to my generation not to judge too quickly the value of an idea based on the credibility of the first person to mention it to us. One should at least take the time to look back into the literature of ideas that were proposed in the past before judging the one before you. In this case, it was worth returning to the last time the space program was thinking about going to the moon and see if LOXLEO actually had some independent substantiation (PROFAC) before deciding whether it was worth looking into. There must be other such cases of dream ideas that was not developed at the time, but were
brilliant. Hence, there could be some more interesting treasures wasting away in the attic (out of sight out of mind) or possibly the technology lost and found.
Appendix A

A Corrected Biographical Description of Sterge Demetriades experiences during the critical period of 1955-65 in which he enters and leaves the Field of Aerospace and has the insights that become PROFAC. (This document supersedes the section of the 2008 IQP report by Roberts, Moore, Lincoln, Karasic and Fossett which was entitled “Innovation and credibility -- the LOXLEO startup” which is in substantial error regarding Sterge Demetriades’ history, background and motivations due to the fact that he was not given time to review the section before the report was submitted.) This section has been reviewed.

Sterge T. Demetriades was born and raised in Greece. In Athens, he attended a then small school named Athens College, a high school that taught English as a required course. After graduation, he attended Bowdoin College in Maine, where he received his BS in Physics, Math and Chemistry and then obtained his MS in Chemical Engineering from Massachusetts Institute of Technology. His thesis consisted of a study of the influence of chemical bonds on the specific impulses or rockets.

Things get a bit complicated at this point since he was increasingly interested in nuclear power and somehow got an a “watch” list resulting in a visit from people concerned with national security. One of them implied that to develop the technologies that interested him for a foreign government, including Greece, could result in penalties that might involve up to ten years in prison. The solution he was told was to become a US citizen and work for the US government. This he did, ending up at the Aberdeen proving ground, to the great distress of his father who had sent him off to the USA to train to represent Greece in the Olympics under a famous coach at Bowdoin. Now family members were warning him that the Greek military viewed him a draft dodger and he could not safely come home. If the plan of the US
government had been to keep him in the country, that plan had worked out even better than they could have imagined. He could not go home and started to make a new life in the USA.

He then applied to Cal Tech and was admitted to the doctoral program in Mechanical Engineering. After leaving Aberdeen, to attend Cal Tech as graduate student, he began to develop the concept of PROFAC (Propulsive Fluid Accumulator) on his own during that period. His work in that field was not part of his formal graduate work, which involved the flow of molecules in veins. He wanted to do something involving blood since it would not be classified research. Meanwhile he had many consulting contracts with aerospace companies dealing with rocket design. He also worked on the Atomic Oxygen Ramjet project at Aerojet.

His graduate thesis topic consisted of the orientation of colloidal particles and shear flow. This was useful in understanding capillary flow, though as it turned out he would not stay at Cal Tech long enough to complete the program and get his Ph.D. He left with a Masters M.E. Professional Engineer’s degree after 3 years of study. This is essentially a doctorate except for submitting a dissertation. He then published the research that would have been his dissertation over the objection of his thesis advisor, who did not consider it publishable yet, and at this point Demetriades essentially had the equivalent of a Ph.D.

He was eager to leave Cal Tech early due to a simmering problem. When he arrived at Cal Tech, there were disputes between the Turks and the Greeks over borders, and during the first week he was at Cal Tech. this tension resulted in a fellow student, a Turk, assaulting Sterge without provocation from behind, bloodying his ear in September of 1955. The incident was minimized by Sterge’s supervisors given the magnitude of the offense, but he persisted in
insisting that the Dean of Engineering find out from the Turkish student why he attacked Sterge
and whether his Greek classmates were safe from future attacks.

An unprovoked attack from behind (this one with several witnesses) was a serious
matter to Sterge Demetriades given his family’s history. His maternal grandfather, a winemaker
in Stenimanos (now called Ascenovgrad in Bulgaria), became concerned about the growing
inter-ethnic tensions in the Balkans and took his family to Athens. When he returned via his
winter home in Constantinople to sell his business, a Bulgarian shot him from behind and killed
him in 1927. Therefore, to Sterge, ethnic tensions with a Turk were to be taken seriously. He
was also about to be married (March of 1956), and had to protect his fiancé as well as himself.
He wanted assurances and the other student put on warning.

Every month or so Sterge would see the Dean again and be given assurances that he
would look into the matter. By March, the Dean had had enough and told him to drop the
matter or he would be expelled. Sterge ended up leaving Cal Tech without an official doctorate
in large part due to the attitude the administration was taking in this matter. He was the victim
and just wanted to know if he was still a target for violence. The Turk was never called to
account for his actions, stayed at Cal Tech., graduated and became an academic at a school in
California. By contrast, Sterge’s career had taken a turn. Though he interviewed for a few
academic posts at Rice, Duke and the University of Arizona he found that he had no desire to be
an academic, and thus getting a doctorate was not so important to him anymore.

Leaving Caltech, Demetriades took a full time job at Aerojet, where he had been a
consultant. He was there, working on rocket engines and expecting to be laid off in December
of 1957 when Sputnik changed everything in the field and there were suddenly many new
opportunities. He took a job at Northrop working on plasma thrusters and magneto gas
dynamics. Given the new situation in the field, he was able to negotiate a deal in which he
could keep all his old consulting contracts and take this new job. Sterge became the head of
Space Propulsion and Power Laboratories at Northrop. Yet, he and a few colleagues continued
to develop PROFAC, but they did so on their own time. He refused to make this a formal
funding proposal to Northrop despite the interest of Ludwig Roth, one of his managers, in
having it handled that way. Roth was a close associate of Wernher von Braun and he is
probably the one that brought PROFAC to the attention of the NASA team in Huntsville.

In the end, the research of the small group assisting him in looking into this concept
filled 2000 pages of research reports, which involved several separate but necessary inventions.
Sterge was ready to start presenting them at conferences and publishing on the concept by
1958-9, which was just before he was employed at Northrop. However, the team supporting
this effort was finally assembled in one place when he could hire them at Northrop.

There would be another in that journal in 1961-62. Also in March of 1962 he was scheduled to
give the first of 4 papers on this research at the Berkley meeting of the American Rocket Society
“ The use of atmospheric and extraterrestrial resources in space propulsion system, part I.” by
Demetriades, Hamilton, Ziemer and Young (This paper is ARC#1250057 in the Forth Worth
National Archives) The second, third and fourth papers in the series were also accepted for
presentation at later conferences- but would never be presented. The whole body of work was
classified by the US authorities as soon as the first paper was presented. Hence, only the first
paper made it into the open literature.
Why did the US government move so rapidly to suppress the details of PROFAC? The State Dept had been watching this matter for two years at that point, given that Sterge was invited by Russian aerospace expert Leonid Sedov, to give a paper at the International Astronautics Federation Meeting in Stockholm Sweden in 1960. Sterge needed a passport to go to the event and that was denied until the very last minute when international pressures led the US State Dept. to relent on the matter and allow the presentation and the meeting with Sedov. It raised their suspicions that Sterge was publishing and speaking in Europe where the Russians would have easy access to materials before the USA had decided whether or not to develop PROFAC technology.

However, there are articles on related subjects in this period that mention a PROFAC engine that appear in this period, for example “Plasma Propulsion”, appeared in Astronautics (ARS) March 1962 and he had an article on the “Propulsive Fluid Accumulator Engine” included in the 1963 McGraw-Hill Yearbook on Science and Technology.

The next time one sees mention of PROFAC in the American aerospace literature is when it is mentioned by Heinz H Koelle in his chapter 5 “Evolution of Earth-Lunar Transportation Systems” in an edited book called Astronautical Engineering and Science (Published in 1963), edited by Dr. Ernst Stuhlinger (Associate Director of Science at NASA Marshall). Koelle was at the time head of the future projects office at the Marshall Space Flight Center in Huntsville, Alabama, technically the “Chief of the Preliminary Design Section “in Huntsville which he took over in 1954. Hence, his article can be taken as the assessment of Stuhlinger and the von Braun team influential in NASA policy at the time.
In effect, Koelle et al. concluded that it would work, but we do not need it. He seems to have felt it would be made obsolete by the development of a nuclear rocket before the level of traffic between the Earth and the Moon would justify its development. “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” p 92. Demetriades found that amusing when he read it recently, since the concept was very clearly NOT limited in application to chemical rockets. He was working on plasma thrusters too.

Therefore, we know that NASA was aware of the concept and did not start to develop it at the time of the Apollo Program. Once that decision was made, it was probably the Air Force that asked that the material be classified so that the Russians could not develop it before the USA did. They probably had no idea that the concept would drop out of sight and out of mind to the degree that it did. This decision by NASA not to actively pursue PROFAC in the 1960’s does not seem to have surprised Demetriades, since he felt that at the time it would have taken 20 years to develop the technology (today it would still take ten) and the mission of Apollo was to get to the moon “before the end of the decade”, which was code for “before the Russians”. It might make sense as an investment later. He had 3 versions in mind, one as a stationary device located on a planet or asteroid, one for use in orbit and one which was part of a single mission in which the system would orbit until it had fueled itself and then depart from Earth orbit taking the system with it to another planet, preferably but not necessarily one with an atmosphere.

When and if the USA was ready to construct a lunar base it would certainly make sense to develop PROFAC and he used the cost savings on a lunar mission as an illustration in his first
article. Building a lunar base was scheduled for the Apollo 20 through 30 missions to take place in the 1970’s if the program was continuously funded after the initial lunar landings in 1969-70. In fact, funding was not continued and Apollo 17 was the final mission. The Saturn 5 construction facilities in Huntsville were then closed down.

My interpretation is that Demetriades’ idea was not accepted for immediate development because it was not seen as essential to NASA’s manned moon landing space goal – reaching the moon and getting back safely. Secondarily, there seems to have been great optimism in the group around von Braun that chemical rockets were going to be made obsolete by nuclear drives in the next 20 years, certainly by 1985. The concept of cost efficient space missions, especially paying extra to build a space infrastructure was not a pressing issue 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 the focus of research. On top of this, in the space race between the United States and the Soviet Union, no one cared how cheaply we got to the moon, as long as we got there first. Setting up an infrastructure for more affordable space travel, such as PROFAC would do, was not an R&D priority at the time.

In addition to the cold war concerns, PROFAC as originally presented, used a nuclear reactor as a power source. In a later article, he refers to other possible sources of energy, that would be sufficient but the main article had a nuclear reactor on board. Shippingport, the world’s first commercial nuclear power plant, had gone critical for the first time only three years earlier. Practical nuclear power application was still an experimental and immature technology. Technologists were more focused on the question of whether a nuclear rocket was
possible, than they were on how they could use one to refuel chemical rockets. The manner in which Demetriades intended to use it, which was in a ramjet configuration, was quite unconventional thinking.

Demetriades’ reaction to the Koelle review was that what was not said was as important as what was said. Stuhlinger and Koelle did not say would not work. He also noted that he did not provide materials on the PROFAC concept to Koelle or anyone else on the Huntsville team, nor was he asked by them. They would have had access only to the published work prior to his ARS paper. He recalls that Koelle presented the first version of that chapter at the same conference in which he presented the first paper on the subject of PROFAC with attention to the details of how it would work. This timing could be taken as evidence that the Huntsville group was opposed to developing the idea. He later had the opportunity to discuss the attitude of the Redstone Arsenal people (Huntsville) with James Gehwig a staffer working for a Senator on the Senate committee dealing with science and space, at that time.

Gehrig confided in him that the nuclear electric propulsion system development area was a battle ground in which the Atomic Energy Commission wanted control of the project, as did the propulsion experts working with von Braun at Redstone Arsenal. The AEC won the political battle. Hence, any system involving a nuclear reactor would not have been under the control of Redstone Arsenal. PROFAC, if it had been developed, would have drawn the AEC into the post-Apollo Program activities of NASA in a substantial role. That was a development that the group around von Braun wanted to forestall, despite their great interest in nuclear drives. Thus, the negative reviews at the time make political sense when placed in the context of the
bureaucratic turf wars of the Federal government at a time when both nuclear power and space activity under NASA were heavily funded.

PROFAC was “withheld” during the democratic administration of Kennedy-Johnson, but it was officially classified a state secret by the Republican Administration under Nixon. While the United States was not interested in the immediate development and application of the device, it did not want the Russians developing it first.

Sterge left Northrop suddenly after a disagreement with a manager who was basically insisting that everyone that reported to him buy US bonds. By now, he was tired of government restrictions due to his interests in nuclear power and space propulsion being relevant to national security. He left the aerospace field looking for a place an immigrant could operate without security restrictions. His research attention turned to Energy Self Sufficiency for the USA. His next application of plasma physics would be to the efficient burning of coal.

Starting in the mid 1960's he became an independent entrepreneur and been the founder, president and chief financial officer of three very profitable small corporations, one of which flourished by selling computer system and software systems integration systems that his company developed for its own use and for a friend in the pharmaceutical industry. Druggists using this system could write 2-3 times as many prescriptions in a day, so the innovation done for the friend got a lot of attention in this market niche.

However, a 1980 ad placed in Computer World brought his software system to the attention of IBM and one of their lawyers contacted him. Unfortunately, though he probably had priority due to evidence of his using the systems in question in the 1969-75 time frame, his own lawyer died in the middle of the affair. When his partners in the law firm did not handle
the transition smoothly, Sterge gave up the legal battle and moved on to another area of technical interest.

Renewable energy sources to deal with the inevitable energy crisis, was a continuing interest of his and he worked closely with people interested in using seaweed as a source of biomass for alternative fuels after the oil era ends. So it was that by the mid 1960’s the field of Aerospace lost one of the most promising innovators of his generation, and also the main champion for the idea of extra terrestrial gas gathering for the purpose of refueling spacecraft. As this idea dropped out of sight, many influential people in the field concluded that it was an impossibly, and a moment of opportunity for the field of Aerospace in general to examine the possibility in the open literature was lost. However, there were people who knew of PROFAC or had access to the classified literature. Hence, in the 1980’s and 1990’s the idea would reappear periodically, and Demetriades would be contacted to explain the concept. Hence, Sterge says he worked on aspects of the PROFAC system off and on during the 1980’s and was asked to brief some DOD people mostly from the Air Force assigned to the SDI program on the concept in March of 1982 and some NASA people in 1991.

However, by 2005, the open literature was so completely out of this loop that the literature was including comments that implied gas gathering in LEO was not possible. Indeed, the head of NASA, Mike Griffin, strongly implied in a speech that the closest supply of LOX was the moon. Jeff Foust editor of Space Review (in 2008) and others made even stronger statements to the effect that a refueling capability was needed, but that the only way to do it was to lift fuels from Earth, find a mostly ice asteroid to exploit or mine LOX out of Lunar regolith.
As a practical matter, for 90% of the field of aerospace the concept of gas harvesting in LEO was lost and its reintroduction in 2005-2007 by a total outsider not privy to any of closed debate about PROFAC had shock value for most of the people at a typical AIAA meeting. PROFAC would be recovered to serve, as supporting documentation for Paul Klinkman’s talk on “Harvesting LOX in LEO” at the 2007 AIAA meeting in Long Beach, California and the cat was finally out of the bag in the open literature. PROFAC had been “rediscovered” if indeed it had ever been lost. Sterge himself contacted WPI to prevent the people just starting to work the problem there from needing to reinvent the wheel. He coached them on how to find all the materials that had not been classified. Sterge was contacted about PROFAC far more often than once a decade in the period after 2007. In Sept. of 2009 he would get to address an AIAA session assembled to talk about the refueling in space problem and publicly lay claim to the idea for the first time in nearly 50 years and answer questions from those just hearing about the idea for the first time to clarify the record.
References


