PROFAC and PHARO:
Changing Perceptions of an Idea in Aerospace

An Interactive Qualifying Project submitted
to the faculty of
WORCESTER POLYTECHNIC INSTITUTE
in partial fulfillment of the requirements for the
degree of Bachelor of Science

by
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Submitted to:

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Abstract

Despite continuing advances in space technology, the cost of lifting payload to orbit remains prohibitively high due to the exponential relationship between propellant mass and payload. Therefore, one of the primary goals in the design of spacecraft is to reduce required take-off mass. A continuation of the effort to resurface the concept of a technology that gathers gases in LEO to be used as propellant, thus significantly reducing required take-off mass in many cases, has made significant progress. The team has deeply researched and compared two such concepts, known as PROFAC and PHARO, and attempted to inform peers within the aerospace community about them. A distinguished lecture by Dr. Alan Wilhite, the lead professor behind PHARO, at WPI and a presentation delivered by the team at an AIAA YPSE Conference were met with an overwhelmingly positive response, demonstrating interest in the concept and its possible implications. Due to the impact that development of an infrastructure based on a PROFAC-like concept would have on the approach to and economy of human activity in space, it is important to seriously consider these technologies. The incoming generation of aerospace professionals, if they are so inspired, could see the realization of such a capability, and so the team proposes a student contest to further inform and inspire our own and future generations.

Acknowledgments

Our team would like to gratefully acknowledge the contributions to and support for our project from the following individuals:

Mr. Sterge T. Demetriades, for his guidance, feedback, time, and patience throughout our project. His involvement has undoubtedly shaped and refined it, and we are very lucky to have had his input and assistance.

Dr. Alan Wilhite, for his cooperation, expertise, and frank and open perspective. We would also like to thank him again for visiting and presenting at WPI; our team learned much from the experience.

Of course, our project would not have been possible without the guidance, assistance, and input of our advisor, Professor John M. Wilkes. His ever-present energy and excitement, as well as his gracious flexibility and support, have continually made this project more than we expected or imagined.

Table of Contents

working on making it operational. This would be a technological "fish that got away" story. The risk is not serious and public embarrassment would not be caused by the study but only if one goes on to be a public figure in the debate by choice,.

Benefits to research participants and others: As PROFAC was lost to the open literature for close to 60 years, it is only an idea on paper right now. But if it was able to be built and put into use, it could revolutionize the space industry, cutting cost of space travel and opening multiple doors to further exploration and space colonization. Because PROFAC has chance to change the economics of space travel, it has the potential to generate a lot of money.

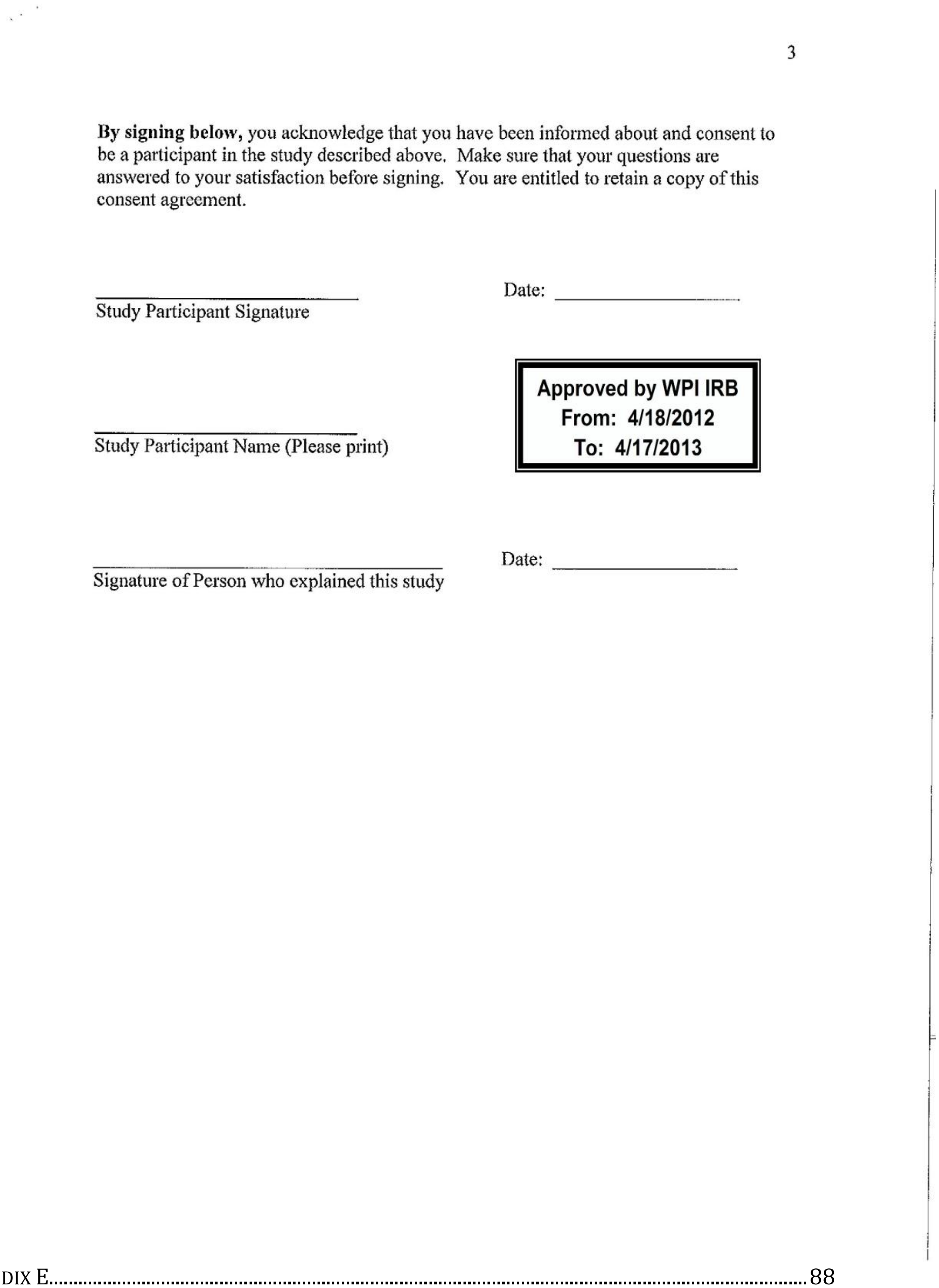
Subjects that interview and are interested in the idea and would like to see it moved on to the next step of creation may be offered to join a special team Sterge Demtriades is forming. If this team is able to move PROFAC into later stages of creation and end up putting it into implementation in future years, there is a big potential payoff for those subjects. Subjects that just interview and give us their feedback would not receive any benefits from our study. There is only a small possibility to those that would accept being part of a team to help bring the PROFAC idea to fruition, and earn rewards through the actual accomplishment of turning the idea into a reality.

Record keeping and confidentiality: Paper forms, computer files and audio tapes will be left with our advisor professor Wilkes. John Wilkes will have full access and Sterge Demetriades will have partial and controlled access to those records. Information from an individual the study will only be reported to Sterge Demetriades at the request of the respondent. He will have access to the distribution of responses. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or it's designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

Compensation or treatment in the event of injury: There is no expected injury. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: John Wilkes, Email: jmwilkes@wpi.edu, Blair Capriotti, Email: bcapriotti@wpi.edu, Derek Montalvan, Email: derekanthonym@wpi.edu, IRB Chair (Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu) and the University Compliance Officer (Michael J. Curley, Tel. 508-831-6919, Email: mjcurley@wpi.edu).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.



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By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

______________________ Date: ______________
Study Participant Signature

____
Study Participant Name (Please print)

Approved by WPI IRB
From: 4/18/2012
To: 4/17/2013

______________________________ Date: ______________
Signature of Person who explained this study

Table of Figures

Introduction

The amount of propellant required for a spacecraft to reach earth orbit increases exponentially with the amount of mass that must make it there. In most cases, the vast majority of the gross lift-off weight (GLOW) of a spacecraft is propellant, both for reaching orbit and any maneuvers the craft must perform thereafter. In turn, the required amount of propellant directly drives the size, complexity, and thus cost of any spacecraft in use today. This relationship can be most easily understood through what is typically called the *rocket equation*.

In its simplest form the rocket equation is capable of demonstrating the differences for required takeoff masses based on the initial weight of the spacecraft and whatever it might be carrying (known as *payload*). Using the following equation:

$$m_o = m_f e^{\frac{\Delta u}{c}}$$

Where m_o is the initial take off mass, including propellant, required to change the velocity of a spacecraft of final mass m_f by Δu, using a propulsion system with an equivalent exhaust velocity (i.e. how fast the propellant leaves the rocket) of c. So as the final mass increases, as it does if the mission is to involve further propelled space travel, or to carry large scientific instruments, so does the total initial mass required. Moreover, if the spacecraft is going to continue to travel, say to the moon or Mars, then the amount that the velocity of the spacecraft must change, Δu, will also increase; this causes the initial mass (or GLOW) to rise exponentially. Since all spacecraft currently need to carry all of the resources they will need for their entire useful lifetime with them from Earth's surface, travel beyond Earth orbit is enormously complicated and costly.

If it became possible to reduce the mass that must be lifted into orbit, then the amount of propellant required would be decreased. Chemical rockets currently account for all propulsion systems used to launch things into space and almost all propulsion systems used in space (Wertz and Larson). Most launch vehicles utilize a *bipropellant* system, which functions by combining a fuel (such as hydrogen) and an oxidizer (such as oxygen) and then inducing the chemical reaction of combustion. The energy produced by that combustion is used to accelerate the propellant mixture, usually through a rocket nozzle, and the force of the propellant leaving the nozzle is what propels the rocket. For the two most commonly used oxidizers and fuels, the amount of oxidizer required is more than double the mass of the fuel required (Wertz and Larson). So if any required resources (for instance, the oxidizer) can be collected *in situ*, or where it is going to be used, then the amount of mass that must be lifted into orbit is greatly reduced, and according to the rocket equation the spacecraft launch vehicle can then operate with a reduced amount of propellant (and be much smaller, and thus less costly). In situ resource utilization has always been a major part of visions for moon and Mars bases, and more recently NASA has been discussing Earth-orbiting fuel depots to achieve the same effect (Committee).

A concept first published in the late 50's by Mr. Sterge Demetriades included a device for the collection of oxidizer in LEO (Low Earth Orbit) in the form of O_2. This concept he called PROFAC, for the Propulsive Fluid ACcumulator system; the full system could utilize at least three technologies and architectures, with oxygen collection in LEO being just one (S. Demetriades). A simplified explanation of the device is that it worked by scooping up the thin but still significant atmosphere in very low Earth orbit (around 100-150 km altitude), collecting and compressing the incoming oxygen, and accelerating the nitrogen and other gases in order to overcome the atmospheric drag it induced and maintain its orbit. The use of this system would allow spacecraft on their way to higher orbits to enter a temporary parking orbit to replenish the required oxidizer and then continue to higher orbits or interplanetary trajectories. The ability to reduce the required take off mass would have great implications for things like the reusability of spacecraft, feasibility and ease of repeated trips to and from our moon (recall that at this time the United States and Soviet Union were blatantly engaged in a Space Race, with the moon as the primary objective), and in the future more distant space travel by greatly reducing the cost of a single launch.

From the perspective of the current state-of-the-art, many additional benefits may be possible from such a system. For instance, there is no reason to limit its application to chemical propulsion; the collected gases can be used as the primary propellant in electric propulsion systems of various types. Satellites might be refueled instead of destroyed when they use up their initial store of propellant for attitude and orbital control. It may even be seen as having a positive environmental effect, since both the amount of fuel being burned within the atmosphere and the amount of oxidizer that must be gathered, handled and transported using existing resources is reduced by the reduction in necessary initial take-off mass.

The potential impact of this concept on the economics and possibilities of space travel are fairly clear; however, the technology was never fully pursued, due to a range or combination of possible reasons from political pressures, available resources, necessary technological advancements, and perceived need to personal professional prestige. The reasons for PROFAC's slip into obscurity, to the point that, more than 50 years later, the professional aerospace community is almost entirely unaware of its ever having been proposed, are discussed in detail elsewhere (Palooparambil) (Anderson, Andrews and McKenzie). In this project and report our team explores the awareness of, perception of, and possible development of the concept after its unexpected resurfacing.

Chapter 1: Before Our Project

This project is the fourth of a series of Worcester Polytechnic Institute society-technology projects (IQPs) to look into some aspect of the case of the Propulsive Fluid Accumulator System (known as PROFAC).

The technology was first brought to the attention of Dr. John Wilkes, the advisor of these projects, by a WPI alumnus named Paul Klinkman (Fossett, Karasic and Lincoln). Mr. Klinkman is an avid inventor, and had come up with an idea for a device that would gather liquid oxygen in low earth orbit from the residual atmosphere. He and Professor Wilkes decided to work together, and they jointly presented the idea at a 2007 AIAA conference (Wilkes and Klinkman). In the presentation, Klinkman made brief reference to PROFAC, which he had seen online in the form of a concept drawing, which had with it just the name of the device and the date. During the next school year, a team of students was assembled and began an IQP to further develop and examine the feasibility of the idea, which they called LOXLEO (Liquid Oxygen in Low Earth Orbit). Part way through this project, news of PROFAC's mention at the presentation reached Sterge Demetriades, the inventor of the PROFAC system, and he subsequently contacted WPI. This started a dialogue in which, bit by bit, the details of the PROFAC system and the history of its invention and transition to obscurity were revealed. Demetriades guided this first team to some of the published materials on his work, in his words to try and keep the team Klinkman and Wilkes had assembled from needing to "reinvent the wheel" (Palooparambil). The team ended up conducting a Delphi study on the aerospace community's assessment of the feasibility of LOXLEO and PROFAC as compared to other potential space technologies. The feedback was largely positive, as professionals seemed to think that the idea was both plausible and realizable, though not necessarily in the near future (Fossett, Karasic and Lincoln).

The second project, an IQP by Ashish Palooparambil, focused on exploring how PROFAC "dropped out of sight and whether a case can now be made for trying again to develop such a system" (Palooparambil). Although Demetriades' first publication on PROFAC was in 1959, for a variety of reasons (including the sociopolitical climate, the Cold War and the seemingly imminent creation of a reliable nuclear rocket drive) the idea was almost classified and definitely "obscured", and remained unknown to the bulk of the aerospace community for the rest of the century. A more detailed account, along with relevant biographical information on Mr. Demetriades, can be found in Appendix A. [*Note on biographical information: This section is in direct response to completely warranted criticisms of Ashish's presentation of Mr. Demetriades' family history. The requested changes to Ashish's report were approved by Ashish, who expected his report to be revised and resubmitted. However, having graduated and no longer in the area, making the changes have proved logistically difficult. Hence, we will make them on his behalf as part of this next submission in the series. He wishes to apologize to Sterge Demetriades for not getting the facts right the first time, and needing to be corrected.*] This project, along with the evolving understanding of the history of the PROFAC concept, inspired yet another IQP, this time on organizational memory within the American Institute of Aeronautics and Astronautics (AIAA).

The goal of the organizational memory project was to determine whether there were other cases similar to that of PROFAC within the aerospace industry, and if so to give ideas that were not fully realized (for whatever reason) a chance to be heard and passed on to the next generation of aerospace professionals (Anderson, Andrews and McKenzie). The research was conducted by contacting AIAA members above the age of fifty and asking them to recall their good ideas that never came to fruition. While there were a number of stories to be told, many of the ideas under discussion were classified or no longer of significant interest to the members. There was hope that other significant cases could be uncovered, but the results of the research and difficulties the team encountered suggest that Demetriades and PROFAC were atypical. The potential of PROFAC to change the industry around space exploration and use, though, was still very apparent. It was the possible implications of the implementation of this idea that inspired our project. The team believed that it was possible and important get the concept of gas gathering in low earth orbit, and specifically PROFAC as a way to accomplish that, back into the open (and hopefully more widely known) literature. Additionally, we hoped to inform aerospace professionals of our generation about it, and to see if we could generate some interest. In a way, it is an experiment in reintroducing a technical idea to a field in a totally different political, social and economic climate.

Chapter 2: Our Project Begins

Original Goals and Methodology

The original goal of this Interactive Qualifying Project was to rekindle interest in the aerospace community in a specific technology, PROFAC, which had been obscured in the literature. The project started with high hopes of getting funded by NIAC (NASA Innovative Advanced Concepts). Were this the case, we planned to fly out to California and learn from the inventor, Sterge Demetriades, face to face about his invention. Hopefully, we could then assist him in the concrete steps of making it a reality. However, we were instead informed that the project would not be funded this year, and it was time to go back to the drawing board for a new direction.

Our team brainstormed multiple ideas on how to rekindle this interest and came to the conclusion that, because the idea was never fully realized, the best place to start would be a Delphi study to assess the feasibility of the technology in the present day. The study would use a panel of experts in the aerospace engineering and physics communities to review current technical viability of the PROFAC system. With the feedback and information given from the experts it would then be possible to assess, based on direct information from the people in the industry, whether or not they thought this technology could be realized in our coming generation.

The Delphi study would be run in two phases; first using a short abstract and then, if significant interest could be shown, a longer 12-page paper. The study would have two rounds of literature review, with each round followed by questions about the opinion of the expert on the feasibility of the different aspects of the system. For the first round, participants would be asked to read an abstract to be used as the stimulus in a cursory overview study of general reaction to the concept. For round two our team wanted to be able to provide a concise paper for the experts to read that would have more detail about the system, and include calculations that Mr. Demetriades had done as well as subsystem-level descriptions of PROFAC; the paper should inform the experts on exactly how PROFAC was designed to work. This at first seemed like a formidable task, since there were a very limited number of papers published on the concept and no work had been done on it in over 60 years. Luckily, our team was already in direct contact with Mr. Demetriades, giving us the unique opportunity to read over some unpublished articles as well as receive guidance to locate the published ones. With the information so spread out, and much of it difficult if not impossible to obtain, we decided that the easiest way to provide all the information to the experts was to take the most important parts of the papers and compile them into one paper on PROFAC, edited by a member of our team. This way we could give the experts a paper they would be able to read in one sitting that contained enough information for them to develop informed opinions and comment on the system.

In the end a 12-page detailed paper drawn from the best four sources, published and unpublished, on the subject was created (Appendix B). If participants were interested in the topic and wanted to learn more, they would be asked to join a more detailed study and be provided with this paper. Then they would be asked to participate in a 30-50 minute interview (preferably in person) in which they could offer a more specific and nuanced reaction, going through the four key system components one at a time and then providing an overall feasibility assessment.

The plan was then to take all the feedback from the experts and try to determine if it was truly going to be possible to start designing, manufacturing, and testing a PROFAC-like system. With positive feedback and comments from the experts, it would be clear that the system was ready to be pushed into the next stages of development within the industry. If the feedback from the experts were negative, our team would try to assess the cause of the negative response. In particular, we were curious to see if the experts found one bottleneck in the design or had an array of concerns about the feasibility of the system. If the experts were all pointing to one thing they saw as a crucial fallacy in the workings of the PROFAC system, it was our hope that we could relay that concern to Mr. Demetriades himself and see if we could work around the problem.

Once the Delphi study had been completed, our next step was to try to create a student contest based around PROFAC, which would bring the idea to the people who are just about to start their careers. In creating the contest, we considered a number of variables that would change its dynamic. These included selection of judges, availability of prize money, the type of contest, and the scope of the contest, among others. The ultimate goal was to create a contest, hopefully sponsored by the AIAA, which students could compete in while learning about PROFAC, possibly even earning credit from their respective college. The subject of the contest went through several iterations. For instance, one idea was to have the teams attempt to design a way to power the orbital vehicle and PROFAC that doesn’t use nuclear power. As we brainstormed, we decided that some of the tasks would be too advanced or involved for undergraduate students, and so considered separating the competition into graduate and undergraduate divisions. Each would have an appropriate prompt, and the submissions would be considered and awarded prizes separately. This kind of setup, however, would require far more complicated logistics on the part of the contest organizers and probably more resources, etc. Through much discussion and revision, we eventually refined the contest to its current form, in which participants assume the existence of a PROFAC-like architecture and design missions that take advantage of the benefits it would impart (discussed in detail in Chapter 3).

PHARO

We were well into implementing the Delphi study, having gone as far as having a formal proposal approved by WPI's Institutional Review Board (Appendix D), when we were contacted by Mr. Demetriades with some interesting information. Word had gotten to him that an idea very similar to that of PROFAC, known as PHARO (Propellant Harvesting of Atmospheric Resources in Orbit), had been proposed as part of a student Revolutionary Aerospace Systems Concepts – Academic Linkage (RASC-AL) competition and had won second place. The two systems were so close in concept and design that Mr. Demetriades was shocked to find no mention of PROFAC in the paper. He found it hard to believe that the team had come up with it completely independently, and was upset at not having been given any credit for his ideas. To complicate matters further, the faculty advisor to the project, a professor at the Georgia Institute of Technology named Alan Wilhite, had published a PHARO paper in his own name with a few of the same grad students that did mention PROFAC. Our team was subsequently enlisted to look into the matter further; if the PHARO team did know about PROFAC, we wanted to know how, and if they did not, then the independent emergence of a strikingly similar technology was interesting in and of itself.

It was thus that our team got in touch with Dr. Wilhite, and devised a plan to hopefully achieve two of our goals at once. We invited Dr. Wilhite to come to WPI as an AIAA-sponsored distinguished lecturer to give an open presentation on PHARO to the entire WPI community. We would set up a video link so that Mr. Demetriades would also be able to watch the presentation and engage by asking questions. Afterwards, we would sit down and interview Dr. Wilhite as one of our experts for the Delphi study; he was undoubtedly qualified and very interested, as he had been the lead researcher on a technology so similar to PROFAC.

He did in fact come to WPI and give an approximately 20 minute presentation, which Mr. Demetriades was able to digitally attend and even engage in a short debate. The presentation proved to be very controversial, filled with conflicting data of two different times and backed by calculations done by each. Sterge listened closely to the approach and direction of PHARO while also posing many of the same questions he had answered in his papers on PROFAC. It was not until Professor Wilkes, as moderator, was able to step in that the discussion was brought to a close.

Our team was able to secure some time with Dr. Wilhite before the presentation to conduct a 45-minute interview, from which a good deal of insight was gathered on PHARO and Wilhite’s knowledge of PROFAC. He had a hold of a couple of papers that the team hadn’t seen yet on PROFAC that he told us he had obtained from Sterge. He went on to talk to us about the importance of certain technologies that needed to be developed in order for a concept such as PROFAC or PHARO to even be possible. His insight on the inner workings and politics of the introduction of a new technology such as this one helped us understand the setbacks it may experience. Backers of competing technologies that have been in development for years and that have been heavily invested in essentially prevent these new concepts from surfacing in order to preserve their interests. Incumbent technologies can maintain their status by quieting new, innovative ideas through bribe, threat or other leverage. He also answered questions on what he felt were the major issues with PROFAC and whether or not he believed it was a plausible idea. He believed it was feasible, but more money needed to be allocated to its research and development for it ever to be possible. This feedback carries particular weight coming as it does from a respected and well-informed source. Dr. Wilhite also pointed out that science and theory aren't the only things that make ideas inventions; there are also practicality and manufacturability. His opinion, essentially, supports the plausibility of a gas gathering orbiter as long as certain external conditions can be met.

As far as when he and his team found out about PROFAC, we believe the timeline of events went something like this:

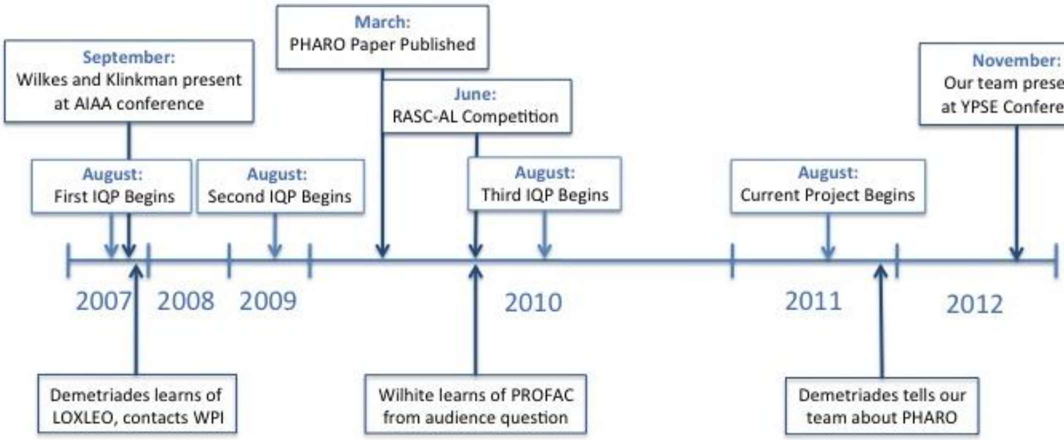


Figure 1: Timeline showing the predecessors of this IQP.

The paper in Wilhite's own name was presented at the March 2010 IEEE Aerospace Conference (henceforth the "IEEE paper"), and briefly mentions Demetriades and PROFAC in its introduction (Jones, Masse and Glass). The RASC-AL contest in which his graduate students participated was in June; their paper has no mention of PROFAC, despite using the same image that Paul Klinkman had found on the Internet several years earlier. According to Dr. Wilhite, he found out about PROFAC from a question asked by a WPI student after the team's presentation; it appears that he then managed to revise the proceedings version of the IEEE paper, giving credit to Demetriades and PROFAC with the few pieces of information he could find at the time (specifically the JBIS and Northrop papers, references (S. Demetriades) and (S. T. Demetriades, Design and Applications of Propulsive Fluid Accumulator Systems)). Our team believes that Wilhite didn't know about PROFAC before he began work on

PHARO, though he informed us that he was asked to look into the idea of gas gathering in LEO by the chief technologist at NASA, who may have known of it.

During this time the team was also working on presenting the findings from the Delphi study at the AIAA Pasadena Conference along with a comparison of the two technologies and a proposal for a student contest in order to bring young new minds to the table. This Delphi study would also be a means of gathering a panel of judges for the competition since those being interviewed would be experts in the fields required for this concept to surface. The abstract was constructed and submitted with some technical issues but after a couple of weeks it was accepted for a poster session.

A Minor Setback

After having written the abstract for the AIAA Conference in Pasedina, California and submitted it we were changed from a presentation to a poster session with a table in which to present from. The issue was that the paper used a portion of Sterge's work that he had submitted in another proposal, specifically the NIAC Proposal, and didn't want public in this abstract. The abstract was subsequently submitted causing a loss in faith in the team from Sterge. This loss of support and guidance slowed the production of the team and coupled with the summer break halted progress till the next term.

Starting anew with new goals and another conference to attend helped the team focus on project and clearly define the necessary steps toward completion. The abstract sent to the conference in Pasadena is in Appendix E.

Refocusing Our Project

After researching PHARO and contacting Dr. Wilhite, our team decided that the original Delphi study idea had become a moot point; by publishing their recent work, Wilhite and the PHARO team had successfully reintroduced the idea of gathering propulsive fluid in LEO and were professionals convinced of the feasibility of the concept. We therefore needed to refocus our project.

Our new goals became:

1. To more thoroughly re-introduce PROFAC to the literature, with better and more comprehensive references than the PHARO team had had access to (and thus cited).
    a. Our hope with this was that more people in aerospace could be exposed to the idea, and if they were interested in learning more, our paper could provide a path to finding the materials that we only found with the guidance of their original author.
2. Attempt to find the best way(s) to implement a PROFAC-like device, by systematically comparing the two proposed technologies (PROFAC and PHARO) and synthesizing their strongest aspects.
    a. This is meant to be a more technically basic comparison that actually examines the similarities and differences of the two. By taking from each concepts aspects which we found appealing or most plausible, we hoped to inspire others to take a serious look and improve on the design.

3. To introduce the idea of resource gathering in LEO to our generation and increase awareness of it generally, since its implementation would have far-reaching implications for the cost and design of missions and spacecraft (and subsequently influence policy and industry).

It was these goals that we worked towards for the remainder of our project.

Revised Methodology

To achieve these goals, or at least move as far as we could toward their achievement, we decided to pursue several courses of action.

First, we sought to compile the most complete list of available original sources related to PROFAC that we could, since no such list currently exists. We recognize that, through maintaining a direct correspondence with the inventor of the technology, we were granted a unique opportunity to access and assess the significance of such sources. Therefore, our team sought to compile a reference list including all of the materials around PROFAC that we have ever reviewed. Further, we sought to present ourselves as a source for this information, should anyone be interested in pursuing it.

Second, the team decided to review the materials available to us on both the PROFAC and PHARO concepts and perform a direct comparison, complete with recommendations for the best ways to synthesize the strong points of the technologies into a single vision for a possible gas-gathering infrastructure in LEO. This would, we felt, provide the most compelling argument that such an infrastructure could exist in the not-too-distant future, outline the current challenges to its development, and perhaps inspire some aerospace professionals and future aerospace professionals to give it serious consideration.

Finally, in order to inform members of the aerospace community of the existence of this idea, especially members of our own generation who may soon be entering the field, our team set out to present the significant results of our comparison of PROFAC and PHARO to an appropriate audience. This would also allow us the chance to connect anyone who showed a greater interest in the technologies with the information and references we have compiled. Additionally, a student contest of the type we had previously considered was still an appealing way to pursue these goals, and a public or semi-public presentation could be the perfect opportunity to announce that intention and gauge interest in it, as well as explore possible sponsors.

Chapter 3: Results and Discussion

PROFAC vs. PHARO

It is important to remember that the PROFAC and PHARO concepts were developed in different eras, with different reference goals in mind, and so their comparison cannot be direct in all aspects. The PROFAC concept, first published in 1959, bases most of its figures of merit on travel to and from the moon, though Demetriades did envision and discuss wider applications (S. Demetriades). PHARO was initially proposed in the 2010 RASC-AL competition to address a “technology enabled human mars mission”, and as such compares itself throughout the initial paper to NASA’s mars mission Design Reference Architecture (DRA 5) (Jones, Kelley and Masse). Despite this basic difference, both concepts have the potential to be useful to many activities in space, from Earth-orbiting satellites to deep space exploration.

The orbiting vehicle configuration of PROFAC and PHARO are remarkably similar, as can be seen in figure 2 and 3. Both use a scoop or nozzle inlet to collect gas in the upper atmosphere, then store a portion of it and use the rest to maintain the orbit and perform maneuvers. They then pass this gathered gas to another vehicle, where it can be stored or used for propulsion. Even the on-board propulsion system is the same. The reason for the similarities, despite completely independent development, stems directly from design constraints, such as minimizing drag and maintaining orbit with what they gather. The major differences are the storage mechanisms, power systems and overall mission architecture.

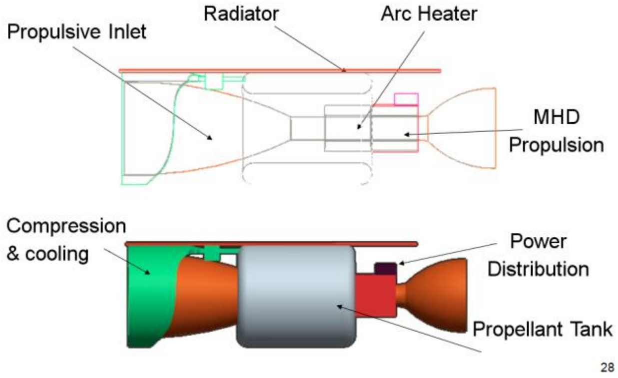


Figure 2: Picture of PHARO's collection and propulsion system.

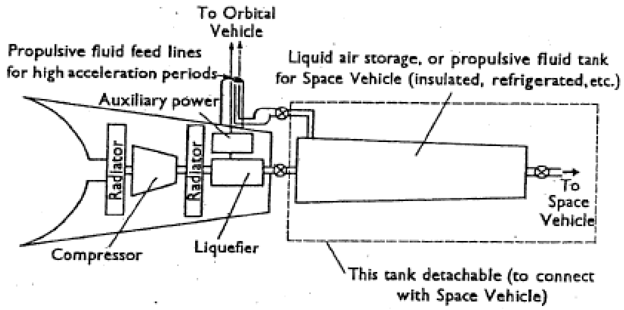


FIG. 5. Schematic of Propulsive Fluid Accumulator (PROFAC).

Figure 3: Schematic of Propulsive Fluid Accumulator.

Both PROFAC and PHARO utilize inlets configured as a modified truncated cone (S. T. Demetriades, Design and Applications of Propulsive Fluid Accumulator Systems) (Jones, Masse and Glass). The PHARO team designed an inlet with a “dual cone compressor”, which allowed for improved compression and cooling as the gas entered the collector (Jones, Masse and Glass). They mistakenly believed that PROFAC had used a simple truncated cone, and compared their design to that; in fact, Demetriades had considered a number of inlet geometries and eventually settled on what he refers to as a “dissipative inlet”, which is extremely close to the dual cone design (Evening Tribune). Both designs are pictured in their first published version in figure 4 and 5. Both were proven by their authors to slow the collected air to a workable speed and temperature, meaning that gas gathering in LEO is completely feasible without overly complicated inlet design (Evening Tribune) (Jones, Masse and Glass).

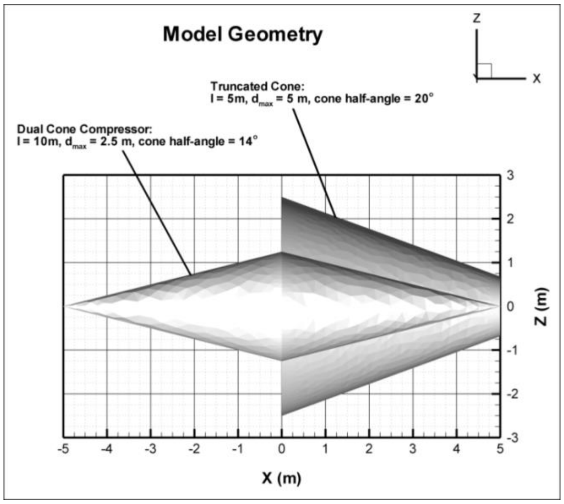


Figure 4: The Diamond shaped inlet surface used in PHARO.

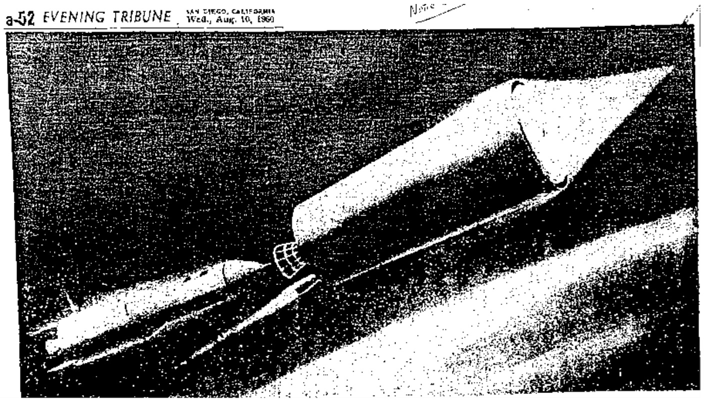


Figure 5: A demonstration of the dissipative inlet utilized by PROFAC.

Another difference is in the processing and storage of the collected gas. In the PROFAC system, air is gathered and the oxygen is separated from the nitrogen and other gases. It is then cooled, compressed, and stored in liquid form in an on-board tank, while the nitrogen diverted through the ramjet and used for propulsion (S. Demetriades).

PHARO, on the other hand, uses air as its working fluid, and stores it without separation. The team estimated that 30% of the air gathered by the PHARO collector would be used for propulsion (Jones, Kelley and Masse). It is unclear which configuration is most advantageous for a wide variety of missions. For the refueling of chemical rockets, it would seem more advantageous to divide the gas either on-board the collector or within a fuel depot, since the main idea is to supply oxidizer. Converting it to liquid form would require more complicated systems and cryopump technology, but would enable the collector to gather more oxygen at a time. For longer missions with different forms of propulsion, though, using air as the working fluid is not out of the question; the PHARO team determined that augmenting the nuclear thermal rocket (NTR) propulsion system of the DRA 5 Mars transfer vehicles with magnetohydrodynamic (MHD) systems would make air just as viable as helium for the mission (Jones, Kelley and Masse). The collector design is thus simpler, and since their concept utilizes multiple collection vehicles, the collection rate would not be severely impacted. A more in-depth cost-benefit analysis could be conducted to determine which configuration is overall more desirable.

Although PROFAC and PHARO were developed more than 50 years apart, both systems utilize a magnetohydrodynamic (MHD) ramjet to maintain the collector orbit (S. Demetriades) (Jones, Kelley and Masse). It is similar to an air-breathing ramjet, but uses the Lorentz force to accelerate the working fluid (in plasma form) as it passes through the jet instead of combustion (Landrum) (S. T. Demetriades, Design and Applications of Propulsive Fluid Accumulator Systems). Of currently developed propulsive technologies, it is the option that best takes advantage of the low orbit altitude, requires no carried fuel, and can achieve orbital speeds. However, to maintain the magnetic field will require a large amount of fairly continuous power; the amount calculated per orbiter by the PHARO team is 175kW, and Demetriades determined it to be 0.4 MW/m^2 of inlet area (although his model also included the maintenance of a larger orbital vehicle) (Jones, Kelley and Masse) (S. Demetriades). In the PHARO case, 99% of the power requirement for the collector is for propulsion (Jones, Kelley and Masse).

One of the main remaining technical difficulties in realizing a PROFAC-like system is the generation of enough power without overweighting the system. While Demetriades considered several viable power sources, he decided that nuclear energy was the most “elegant” solution, though “if operation above 150 km proves desirable, solar energy can be used” (S. Demetriades). At the time, the nuclear power was popular, the nuclear rocket drive was under development, and it was expected that technology would meet this need within the next 10 years (S. Demetriades). The PHARO team was concerned with the safety issues surrounding nuclear power, and determined many other possible solutions “too heavy”; thus they conceived of a network of power-beaming satellites to enable the use of solar energy (Jones, Kelley and Masse). This network would consist of 14 satellites at a higher orbit, with large solar panels continually gathering energy. The power would then be beamed directly to the collectors, allowing them to maintain their orbit and transfer to a rendezvous with a Mars transfer vehicle or fuel depot. Figure 6 shows the configuration (Jones, Kelley and Masse).

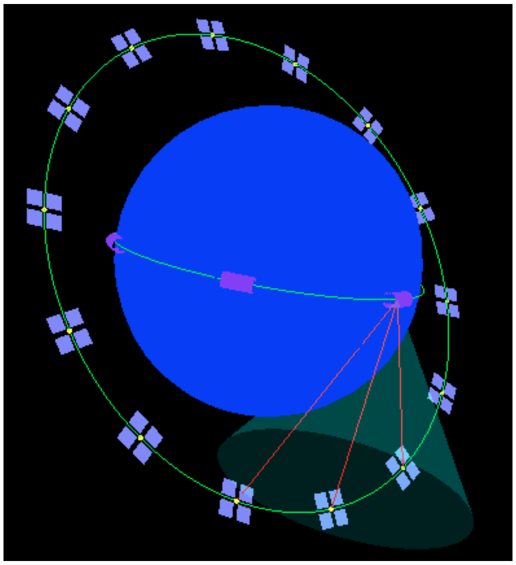


Figure 6: Satellite system required to power the PHARO orbiters.

While nuclear power does present significant safety issues, it is a great way to produce large amounts of energy with relatively little weight. Solar panels cannot be directly attached to a collector, as they would either be destroyed by the trace atmosphere or radically increase drag on the collector at such low orbit altitudes (the operating altitude for PROFAC is about 100 km, and for PHARO 123 km). The power-beaming satellite network idea does produce the energy in a desirable way and without significant added weight to the collector, but the design is cumbersome and would require full deployment of a new infrastructure before the collectors could be operational. There may be other solutions, and power generation technology is currently being developed at a rapid pace, but as of yet it is a definite barrier to the implementation of gas-gathering technology in LEO.

For both PROFAC and PHARO, the advantages over traditional spacecraft and mission design are clear. Demetriades calculated that with PROFAC in place, for a mission to the moon and back, the amount of takeoff mass per pound of payload would be only 150 lbs, as compared to roughly 3000 lbs one-way with a standard multi-stage chemical rocket (S. Demetriades). In the case of PHARO, after the infrastructure is in place, the Mars missions would require 90% less mass than the DRA 5; even with the initial costs and infrastructure deployment, this would mean that the mission cost would break even with the DRA 5 model after two missions, and allow significant savings thereafter (Jones, Kelley and Masse).

To conclude, we summarize what we have learned from the cases of PROFAC and PHARO. First and foremost, gas gathering in LEO for propulsive fluid is viable and could significantly impact the future of spacecraft and mission design. Overall, the PROFAC system has more technical detail – Demetriades had worked out the subsystems and components and even the necessary development steps to make his idea a reality. The PHARO concept was better integrated with current mission architecture schemes and had a more complete mission timeline since it was designed to enable more specific missions. An ideal system would probably be a combination of these two, taking aspects of each. A simpler, initially cheaper craft is desirable; this could more of a PROFAC-like collection vehicle, perhaps with air as its working fluid. It would utilize a conical inlet with a dissipater or compressor. The orbit would be maintained and the craft made maneuverable by an MHD ramjet propulsion system. When its tanks were full, the collector would change orbits and deposit its payload on an orbiting fuel depot, which could separate and store the gas; satellites and spacecraft could then rendezvous with the depot to refuel. The power system of choice is still unclear. Demetriades maintains that the PROFAC collector could be powered with on-board solar energy, which would be simpler and cheaper than the satellite network of PHARO. There would be reasonable initial cost for development, production, and implementation of the system, but it would quickly repay the investment. The cost of individual missions of many types could be greatly reduced, making the space industry more accessible and opening up a whole new regime of possible missions and discoveries. In a private communication, Demetriades estimated that with current technology, a PROFAC-like system could be in place in 10-15 years, or certainly by 2035.

Presentation

The way the project eventually led us was towards a comparison of the two technologies and a summary of its best aspects. These included a partial comparison of certain components of each concept such as the inlet design, the power source, infrastructure, whether or not the air should be separated into oxygen and nitrogen onboard the orbiter, and higher orbit fuel depots. This comparison was presented at an AIAA Region I Young Professional, Student, and Education Conference at the Johns Hopkins Applied Physics Laboratory on November 2nd 2012 and received an Honorable Mention. The presentation was done using an online tool called Prezi that allowed us to organize a more image-oriented discussion on the two concepts. Data from Sterge's and Wilhite's papers were used as well as concepts from our major classes which aided us in understanding the advantages of different technologies over others in certain situations and altitudes. This led to a very successful presentation on the importance and advantage low Earth orbit refueling gave to deep space exploration and the economics of space travel.

One of the technologies onboard PROFAC and PHARO that were compared as well were the power sources used for each and the heavy 14 satellite infrastructure needed for solar power beaming. As described in the PROFAC concept for altitudes below 120 km solar energy just didn’t provide enough power to overcome the force of drag. A nuclear reactor however, would supply more than enough power to the MHD ramjet at this altitude and more to propel itself through the thin atmosphere. So for these reasons a nuclear power source is more elegantly implemented than a large infrastructure of solar beaming satellites.

Another interesting comparison between the two concepts was the inlet design. PHARO used a large scoop with a truncated cone in order to increase the density of the atmosphere at the inlet for easier compression where it only collected the gasses around the rim of the inlet and used an MHD augmented ramjet for the rest of the gasses. This design did not call for separation of gases onboard the orbiter but instead would compress and liquefy the air, which would later be brought up to a higher orbit where it would be deposited into a fuel depot for other craft to use. Onboard the fuel depot is where the gasses would be separated since the separation process would use more energy than solar power beaming could supply to the orbiter while also running the MHD ramjet. PROFAC had a similar design that predated the PHARO design of a cone at the inlet scoop. Demetriades coined this term the dissipative inlet since he used the thin boundary layer on the side of the cone to slow the flow and increase the density of the air just like the PHARO team did. The PROFAC design with the nuclear power source as the one that was studied in further depth showed how it could compress and liquefy the incoming air and also separate the oxygen from the mixture while accelerating the rest as propulsive fluid for its MHD plasma propulsion.

The inlet difference and oxygen separation became an important difference since these were driving factors to the cost of maintenance for each concept. The PHARO concept requires much more maintenance since it would require many orbit changes to continue refueling its orbit depot as well as the power beaming satellite infrastructure's maintenance. PROFAC came up with a way to do it all in one however, had the issue of requiring an orbit transfer to a higher orbit in order to refuel a spacecraft. Since rendezvous in orbit is difficult as it is doing so in an irregular atmosphere at an altitude of 120 km will be hazardous for both the craft and the orbiter. Therefore it is important to increase altitude for the safety of both systems.

All these differences stem from the power source choice since there are limitations in altitudes and ability with solar energy usage. Therefore the presentation came to an agreement on a couple of aspects from each concept such as the nuclear power source and the use of fuel depots when at or under 120 km and nuclear-solar hybrid for anything higher in order to reduce the amount of nuclear power used and increase efficiency.

We went on to discuss a new kind of student contest that would be either unlikely or impossible to carry out without the ability to refuel in orbit. This would be an undergraduate contest hopefully to be carried out by the AIAA Region I. The contest idea seemed to take a backseat since they were all so new to these two concepts. They seemed to be more interested in getting this idea out which still was the important part of this project.

After the presentation it was surprising to note that these concepts seemed new to all of the judges. They asked questions about the inlet design and the power source as well as on where we had found this information and who had come up with it. We were pleased to find that one of the judges actually attended CalTech where she had heard of Sterge and enjoyed his enthusiasm. The question and answer session proceeded flawlessly since it was part of all of our majors and we had been studying this for more than a year. The Q&A went on after the presentation session was over where we were able to network with many of the judges and other teams that had even come up to us to congratulate us on our presentation. It seems that most if not all of them hadn't heard of either of these concepts and were impressed by the importance and reduced cost this has to deep space travel.

The presentation was well received and definitely got these ideas back out into the minds of young engineers who will pass it on to the next generation. The importance this paper has is to document the source of the ideas in order to give credit to their inventors while also reintroducing the concepts in a manner that encourages advances in the field. Hence, the contest idea in order to really get these minds thinking about the new lengths deep space travel can achieve with such a technology.

Student Contest

Our team would like to propose a student-based contest, to be sponsored by the AIAA New England chapter, which would be focused around this idea of an orbiting fuel depot. The participants of the contest would be undergraduate students interested in the aerospace field and eager to study an invention that could change the economics of space for their coming generation. The contestants would be given the task of planning a mission specifically around a PROFAC-like system. It would assume that some sort of refueling depot has already been built and functional in space. The contest part would then be to design a mission that would only be possible or economically doable with this refueling system. The contestants could explore a wide range of ideas as PROFAC was designed to not just be limited to just Earth but other plants, like Mars, as well. The students would be able to look at the range of applications a fuel depot like this could have, and the possibilities that could arise from this sort of technology.

The missions would be judge by a panel of experts in the aerospace community and hopefully the inventor of PROFAC himself, Sterge Demetriades. The judges would look at who fully utilized the system for their mission and showed that there would be no other way for the mission to be completed without the PROFAC-like device. We then hope that there would be a cash prize could be awarded for the top three contestants.

The idea of this contest is to really get the next wave of students coming into the aerospace community to start thinking about a new type of infrastructure that would change the whole workings of their field. The contest would show the advantages of PROFAC and the limitations the field faces without it, in hopes that people in the field can see just how important successfully developing this technology would be. Seeing what PROFAC could lead to would also make it more likely to be a funding priority over the next 10-15 years, and more likely to be in place by 2035. A contest would also bring PROFAC back into the current literature, making it more accessible for the next generation to learn from and help progress the industry.

Chapter 4: Conclusion and Recommendations

The goal of this project was to reintroduce an obscured technology back into the current literature and get the next generation of aerospace engineers informed and excited about a promising outer-space refueling depot, PROFAC. The project went in many different directions during the course of its completion, but in the end we were successfully able to expand the accessible information on PROFAC, through presentations and a compiled 12-page paper on the system.

We were also fortunate enough to bring the lead developer of a similar system, PHARO, to WPI to share his knowledge and give an open presentation to anyone interested in the topic. We were then able to give our own presentation on all the information we gathered at a student-based conference. This was a golden opportunity as it allowed us to share our project with the coming generation of aerospace workers, which was one of our main goals. In our presentation we gave a detailed explanation of the refueling concept, then compared PROFAC and PHARO, and finished by explaining our idea for a student contest based around a PROFAC like system. Our presentation at the Young Professional, Student, and Education Conference went over very well, as our team won third place honors.

We recommend that another IQP team be assembled for next year to carry on the idea of a student-based contest formed around a PROFAC like device. This team could continue to develop the parameters of the contest and begin marketing it to the AIAA to be a sponsor. They would also need to find suitable judges, prize money, and the location of the contest. We believe a contest along these lines is the best way to get students interested and knowledgeable about this obscured technology. It would allow students not only to be introduced to the idea, but to see its real life applications and begin developing possible missions as well.

As for getting the system into the next stages of realizations, we believe the best thing would be to create a research and development timeline with all key steps highlighted to show what needs to be done next. This would involve doing more in-depth research on the system and updating some of Mr. Demetriades equations and ideas to match modern day technology. It would then be possible to point out any bottlenecks stopping the technology or show that a system like PROFAC or PHARO is ready to be pushed into the next stages of development and move one step closer to realization.

References

Anderson, Alessandra, et al. *Organizational Memory: An AIAA Investigation*. Interactive Qualifying Project Report. Worcester, MA: Worcester Polytechnic Institute, 2011.

Demetriades, Sterge. "A Novel System for Space Flight Using a Propulsive Fluid Accumulator." *Journal of the British Interplanetary Society* 17 (1959-60): 114-119.

Demetriades, Sterge T. and Carl Kretschmer. *The Use of Planetary Atmospheres for Propulsion*. Azusa, CA: Aerojet-General Corporation, 1958.

Demetriades, Sterge T. *Design and Applications of Propulsive Fluid Accumulator Systems*. Astro Systems and Research Laboratories. Hawthorne, California: Northrop Corporation, 1960.

"Evening Tribune." *Cheap Vehicle for Travel to Moon Revealed* 10 August 1960: a-52.

Fossett, Ryan, et al. *Innovation & Credibility: The LOXLEO Startup*. Interactive Qualifying Project Report. Worcester, MA: Worcester Polytechnic Institute, 2008.

Jones, Christopher, et al. "PHARO: Propellant Harvesting of Atmospheric Resources in Orbit." 2010.

—. *PHARO-Propellant Harvesting of Atmospheric Resources in Orbit*. Big Sky, MT: IEEE, 2010.

Landrum, Brian D. *Dynamic Model of the Magnetohydrodynamic Bypass Ramjet Engine*. Extended Abstract. Huntsville, AL: AIAA, 2002. AIAA 2000-2135.

Palooparambil, Ashish. *Harvesting Gases in Lower Earth Orbit to Propel Spacecraft*. Interactive Qualifying Project Report. Worcester: Worcester Polytechnic Institute, 2010.

Sterge T. Demetriades, Richard W. Ziemer. *Energy Transfer to Plasmas by Continuous Lorentz Forces*. Evanston, Illinois: American Rocket Society, 1961.

Wertz, James R. and Wiley J. Larson. *Space Mission Analysis and Design*. New York: Springer, 1999.

Wilkes, John and Paul Klinkman. "Harvesting LOX in LEO: Toward a Hunter-Gatherer Space Economy." 2007. AIAA SPACE 2007 Conference.

Appendices

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.)

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 of rockets.

Things get a bit complicated at this point since he was increasingly interested in nuclear matters and somehow got on 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 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 Ballistic Research Labs, to the great distress of his father who had sent him off to the USA to train to represent Greece in the 1948 Olympics under a famous coach at Bowdoin. Now family members were warning him that the Greek military viewed him as 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 a 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 initiated the Atomic Oxygen Ramjet project at Aerojet, sponsored by AirForce Office Scientific Research (AFOSR).

His CalTech thesis topic consisted of the orientation of colloidal particles in 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 mechanical engineering 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. The article was peer reviewed and accepted for publication. At this point Demetriades essentially had the equivalent of a Ph.D, but not a degree from Cal Tech which would have been a problem if he had wanted to teach at the college level, but he did not.

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 in Turkey, and during the first week he was at Cal Tech. In September of 1955, this tension resulted in a fellow student, a Turk, assaulting Sterge without provocation from behind, bloodying his ear. The incident was minimized by CalTech authorities given the magnitude of the offense, but he persisted in insisting that the Dean of the graduate school find out from the Turkish student why he attacked Sterge and whether he and 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 to sell his business, a Bulgarian shot him from behind and killed him in 1927. His brother was beaten to death by Turks near Adana (Turkey). 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 the Dean 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 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. Earlier when He was there working on rocket engines and expecting to be laid off in December of 1957, Sputnik changed everything in the field and there were suddenly many new opportunities. Later, he joined Aerojet full-time but left to take 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 mostly 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, Alabama.

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 innovations. 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.

The first paper appeared in 1959 in the Journal of the British Interplanetary Society. 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 Fort 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. Publication of the whole body of this work was frowned upon 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 government 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 is speculated that this 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 and April 1962 (two issues) 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. Demetraides 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.

So, we know that NASA was aware of the concept and did not start to develop it at the time of the Apollo Program. It is speculation again but, once that decision was made it was probably the Air Force that asked that the material be obscured 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 or more years to develop the technology (today it would still take ten or more) 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 (i.e. Mars).

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, assuming that 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 rocket 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, though promising and popular, 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, was quite unconventional thinking.

Demetriades' reaction the Koelle review was that what was not said was as important as what was said. Stuhlinger and Koelle did not say it 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 a staffer “insider G” (who shall remain unnamed at Sterge’s request) working for a Senator on the Senate committee dealing with science and space at that time.

“Insider G” 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 Aerospace Experts 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.

Apparently, PROFAC was “withheld” during the democratic administration of Kennedy-Johnson and not noticed 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 in the open literature for fear of the Russians developing it first.

Sterge left Northrop suddenly after a disagreement with a manager who was basically insisting that everyone that reported him not buying US bonds. The penalty for not buying by withholding part of salary at Northrop was dismissed. By now he was tired of government interference and 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 frightening security restrictions. Sterge’s 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 has 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 and software in question, he did not prevail. 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 mass 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 impossibility, 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 via the oral tradition 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 disconnected from the inside classified information pool that the literature influencing most AIAA members 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 as an independent discovery by a total outsider not privy to any of the 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 in the Pasadena meetings assembled to talk about the refueling in space problem. Here he publicly lay claim to the idea for the first time in nearly 50 years and answered questions from those just hearing about the idea for the first time to clarify the record.

Appendix B

PROPULSIVE FLUID ACCUMULATOR SYSTEM

Table of Contents

List of figures

Abstract

A system that harvests gasses in LEO, in order to propel itself through the thin atmospheric drag, using a power source to do so, while collecting surplus gasses to be used by itself or other spacecraft, can significantly lower required take off masses. The fundamental morphological study which revealed the advantages of the Propulsive Fluid Accumulator system over conventional rockets is summarized and a comparison of launch mass, energy and power requirements for various missions where PROFAC is used with various missions where other conventional nuclear, chemical or hybrid systems are used is presented.

INTRODUCTION

Although it has been recognized for some time that great economies can be effected in space travel by splitting the problem into two distinct phases, the booster phase (concerned mainly with escape from the Earth's gravitational field) and the sustainer phase (concerned with providing low thrust at very high specific impulse for long periods of time), the devices proposed for solving the second phase of the problem (ion rockets, colloid rockets, plasma jets, etc., deriving energy from a nuclear reactor) still suffer from the disadvantage that the greater part of the weight of the space vehicle must be made up of propulsive fluid. Since with present techniques it takes scores of kilograms of propellant and power plant to put one kilogram into orbit, even greater economies can result if the mass of the propulsive fluid required for spaceflight can be eliminated from the total take-off mass.

The essential feature of the scheme is to lift only the energy source into orbit at approximately 100 km, and at that point to collect the propulsive fluid for continuing the journey into space. This is accomplished by a Propulsive Fluid Accumulator, or PROFAC, and some figures presented here (Figure 1, 2, 3) reveal the startling reduction in take-off mass made possible by this approach. Without going into too much detail it will suffice to point out that the energy required to scoop, liquefy and store one kilogram of air at orbital speeds is ten to one hundred times less than the energy required to lift one kilogram of mass into orbit with present techniques.

The principles involved in the operation of the Propulsive Fluid Accumulator are not different from those involved in a two-phase wind tunnel, at least one of which is now operating.

The development of the PROFAC device is the logical extension of the work the author has been doing in upper planetary atmosphere power plants.[1] The success of this device would have such immediate and beneficial impact on the economics and potentialities of space travel that we may refer to it as the PROFAC system for spaceflight, even though we recognize that the PROFAC is only a component part of the system. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

Since most of the size requirements of space vehicles spring from the propellant needs of the reaction motor, elimination of the reaction mass from the list of internal constituents either by continuous or by intermittent supply from the surroundings (refueling), is bound to decrease the size of space vehicles drastically without recourse to an increase in exhaust velocity.[1-5] (Demetriades, Preliminary Study of Propulsive Fluid Accumulator Systems, 1961)

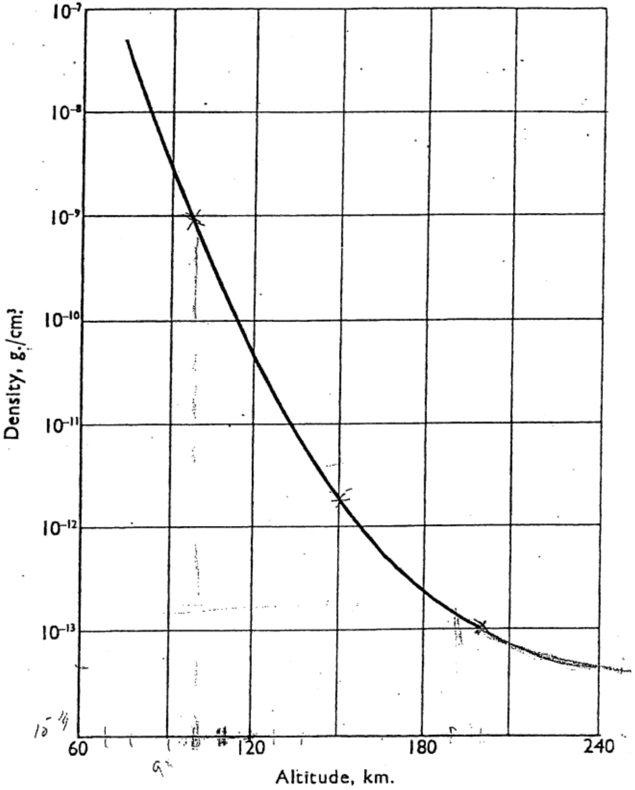


Figure 7: Density of upper atmosphere, ardc model, 1956.

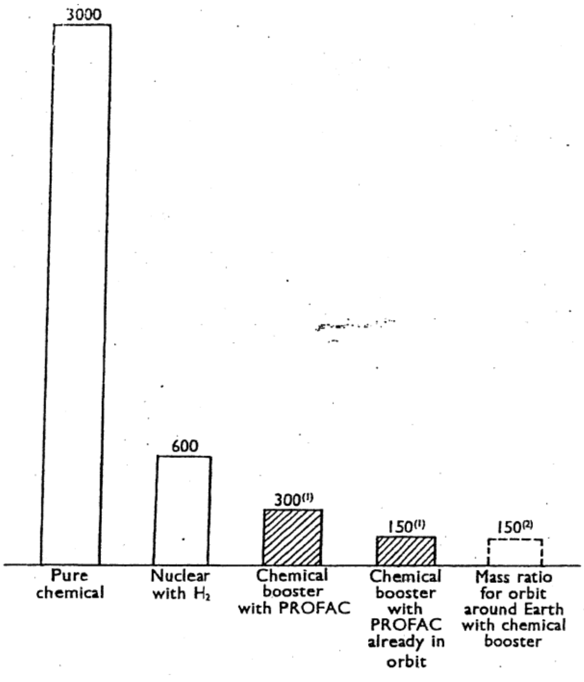


Figure 8: Relative mass ratios required to land one pound of payload on the moon on equivalent basis.

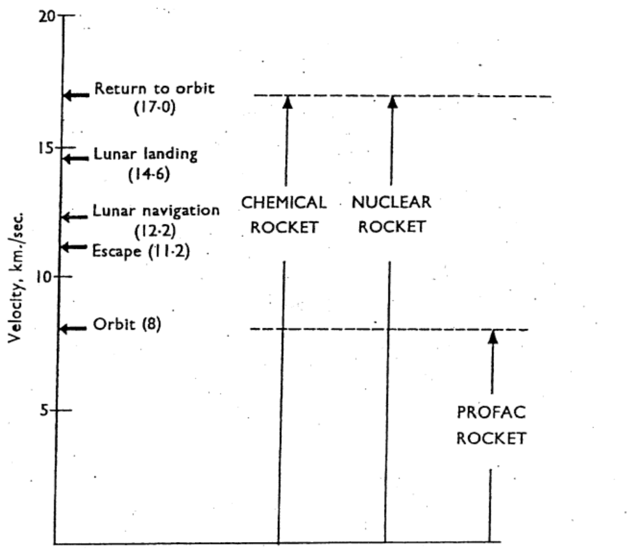


Figure 9: Relative velcoities that must be achieved with take-off mass for different systems in order to land on moon and return.

the upper atmosphere as a source of propulsive fluid

The upper atmosphere serves as a gigantic storage tank for a useful propulsive fluid, air. At 100 km of altitude the density of the atmosphere is approximately 7.1×10^{-10} kg/m^3 (Figure 1), and it consists of a mixture of oxygen atoms and oxygen and nitrogen molecules.

One possible way of using this gaseous mixture would be as a monopropellant. At that altitude the dissociated oxygen atoms can supply approximately 2 Pascals by recombination. But the atoms cannot be stored in a high-energy state, and could be used as a propellant only to maintain orbital speeds while collecting the balance of the air. Even in this case, calculations have shown[1,2] that the energy of recombination is not alone sufficient to counteract the aerodynamic drag on the vehicle at orbital speeds (at the same time, the air is too thin to provide useful lift at suborbital speeds).

The gas mixture has great value, however, as a propulsive fluid. The density may be low, but it is far from zero, and any vehicle circling the Earth at orbital speeds would cut a "doughnut" path containing a surprising weight of gaseous matter. At 100 km approximately 400 kg of air can be collected in one day by a 1 m^2 scoop. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

USING THE GASSES COLLECTED

There are two basic ways in which the thin gases of the upper atmosphere could be put to work. The first would be to power an Orbital Vehicle in conjunction with a nuclear energy source. The objective would be to provide sufficient thrust to counteract the low aerodynamic drag encountered at this altitude. In this case, the vehicle would consist simply of a method to collect the air, accelerate it and project it to the rear, i.e., an orbital ramjet.

Since only a slight thrust would be needed, a low-power nuclear reactor would serve as a suitable power plant for a low-altitude satellite of almost indefinite life. Since the vehicle would be developing thrust, it would also be maneuverable, and this, in itself, would be of sufficient advantage to warrant interest.

The second, and most important use of the air, would be as a propulsive fluid for a true Space Vehicle. Before the air could be used in this fashion, it would have to be collected and stored, and the principal role of the powered satellite would be as a fluid collector. The orbiting powered satellite or excraft* would carry with it a PROFAC unit to collect and store air to be used for space travel by a second vehicle. Here the stored air would be used as a reaction mass (in the form of molecules, atoms or ions or a plasma) to propel the space vehicle on its mission.

In early experiments, the Space Vehicle, PROFAC, and Orbital Vehicle would probably be combined into a single package during the launching phase. The Orbital Vehicle and PROFAC would be detached after sufficient air had been collected. In later versions, however, the Orbital Vehicle and PROFAC unit would be a permanent “fueling station” in the sky, with which space vehicles would make rendezvous on their trip away from Earth. Similar powered stations could be established in other planets or their satellites. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

REDUCED FUEL TO PAYLOAD RATIO

A simple comparison will illustrate the great advantages that would result from this scheme. To land a one kilogram payload on the Moon with a multistage chemical rocket requires approximately 3,000 kg of take-off mass (assuming no return to orbit around the Earth.) A multistage nuclear rocket with hydrogen as a propulsive fluid (if one could be developed) would require approximately 600 kg of take-off mass to accomplish the same objective.

The PROFAC scheme, on the other hand, would require only 300 kg of take-off mass per kilogram of payload for the entire trip to the moon and return. And this would apply to only the first trip. If the PROFAC equipment were left in orbit around the Earth, subsequent trips to the Moon and back would require only 150 kg of take-off mass (Fig. 2 and 3).

The important saving in subsequent trips is of extreme significance. With PROFAC equipment in orbit, the only expense of putting pay-loads into lunar or interplanetary trajectories is that involved in lifting them the first few score miles and into orbit. In other words, the chemical-rocket mass requirement for low-altitude orbit is all the reaction mass that is required for a subsequent ravel in space.

At the same time, an orbiting, powered PROFAC fueling station would be a device of great potential military significance. In effect, the PROFAC scheme offers a practical solution to both the Orbital-Strategic and Lunar-Strategic vehicle problems. By establishing similar systems around other planets (notably Mars) the economics and feasibility of interplanetary flight could be greatly enhanced. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

SYSTEM COMPONENTS

THREE SYSTEMS

There are three basic types of PROFAC Systems:

(a) PROFAC-A; accelerating or suborbital PROFAC. An Aerospace Plane, with the LACE (Liquid Air Cycle Engine), an air-breathing rocket engine which manufactures its own oxidizer by liquefying atmospheric air and uses hydrogen as fuel (Demetriades, Propulsive-Fluid Accumulator Engine, 1963), engine, is a system of this type. Hydrogen or other chemical fuel reacts with the atmospheric gasses to furnish the power required to accelerate the vehicle, overcome drag and accumulate atmospheric gasses for further missions. Although, if sufficiently optimistic assumptions are made concerning wing structure, lift, etc., there is not much doubt concerning the feasibility of this vehicle, additional work is required to prove its economic advantages, if any. In particular, it remains to be proven that the mass of atmospheric gasses collected per unit mass of fuel expended and the collection rate are lucrative from the economic point of view (a hydrogen-burning PROFAC-A using the liquid hydrogen fuel as a heat sink would collect approximately 4 kg of air per kg of hydrogen consumed and would require a collection and liquefaction rate of the order of 227 kg/s, making it necessary the use of a huge heat exchanger which severely decreases the payload). However, PROFAC-A may possess sufficient operational advantages (recoverability or ability to return to base, ability to maneuver, to control the injection-to-orbit parameters, etc.) to make its role as a vehicle for boosting to orbit quite promising.

(b) PROFAC-S; stationary PROFAC. This system is an automatic propellant or expellant accumulator on the surface of a satellite or planet.

(c) PROFAC-C; constant velocity or Orbital PROFAC. The essential feature of this scheme is to lift only the energy source into circular orbit at approximately 100 km and at that point to collect the propulsive fluid (air) for continuing the journey into space or for satellite/excraft maneuvers. This system consists of two vehicles. The Orbital Vehicle, which contains PROFAC apparatus, is one, and the Space Vehicle, which is the maneuverable satellite, lunar or interplanetary vehicle, is the other. The feasibility and economic advantages of PROFAC-C for certain missions are quite definite. Note that the PROFAC-C collection rate is of the order of .0453 kg/s. perhaps the problems encountered in a recoverable booster of the PROFAC-A type can be eased by refueling PROFAC-A from PROFAC-C on the way to orbit as well as in orbit. Thus the two systems are complementary rather than competitive.

Since all the accumulator gasses (which are collected and stored, as opposed to the propulsion gasses which are used for propulsion) have to be stopped with respect to the vehicle, there are two main variants of the propulsion cycle for PROFAC. The first variant involves completely stopping all the propulsion air with respect to the vehicle, in addition to the accumulator air, and is known as the interrupted flow PROFAC engine. The second involves a partial stopping or slowing of either all or part of the propulsion air with respect to the vehicle, known as the uninterrupted flow PROFAC engine. The power requirements for these engines were given elsewhere.[3, 5, 8, 11] A hydrogen-burning PROFAC-A with an interrupted flow engine cannot possibly accumulate significant amounts of air at speeds in excess of 2042 m/s. (Demetriades, Preliminary Study of Propulsive Fluid Accumulator Systems, 1961)

The remainder of this paper will be more closely oriented to, but not limited to the orbital or constant velocity PROFAC.

The PROFAC system can be divided into three basic components.

The first component (Fig. 4) is the Orbital Vehicle. It consists of a power source, guidance and control equipment, an appropriate intake for receiving, compressing and ionizing air, a driver section for accelerating the air and a nozzle for ejecting the air back into the atmosphere.

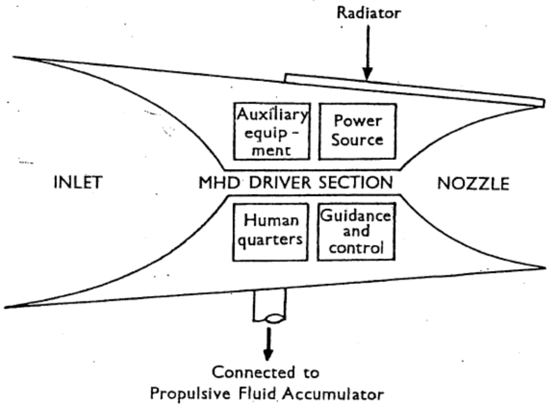


Figure 10: Schematic of Orbital vechile.

The second component (Fig. 5) is the Propulsive Fluid Accumulator, (PROFAC). It consists of an inlet, a compressor subsystem, a fixation unit (which may be a liquefaction, chemical, adsorption or absorption plant) and finally an appropriately constructed and insulated storage tank. Power for the PROFAC component will normally come from the Orbital Vehicle power source.

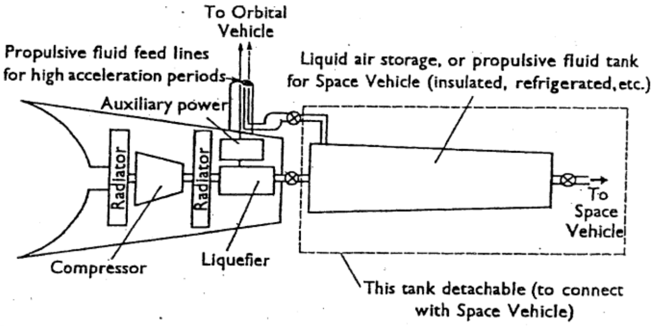


Figure 11: schematic of propulsive fluid accumulator.

The third component is the Space Vehicle (Fig. 6). This contains guidance and control equipment for space navigation and a number of power plants or stages appropriate to its mission.

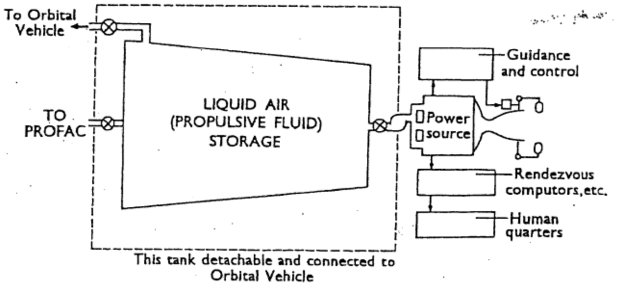


Figure 12: schematic of space vehicle (one stage shown only, many can be connected).

Fig. 7 is a conceptual design showing the orbital Vehicle, PROFAC and Space Vehicle in rendezvous. The drawing is a schematic; the actual arrangement of components would be parallel, concentric, or in some other compact form with minimum drag. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

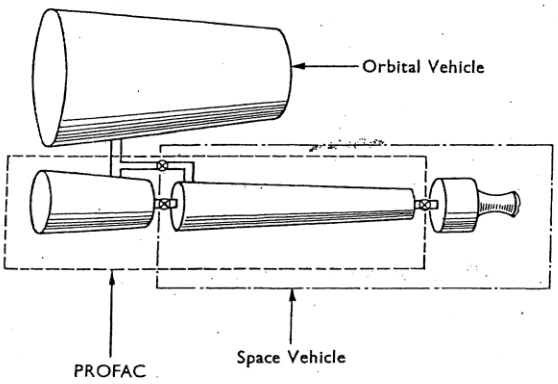


Figure 13: schematic of orbital vehicle, profac and space vehicle in orbit rendezvous.

System Requirements

The design requirements for the successful operation of a PROFAC system would consist of:

(1) A means to counteract the aerodynamic drag of the Orbital Vehicle and PROFAC plant while collecting air.

(2) A means for collecting and storing air at 100 km and orbital speeds.
(3) Power sources having high energy content per unit weight, long life and moderate power output.
(4) A means for producing thrust for Space Vehicle propulsion.
(5) Guidance and navigation equipment required to rendezvous the orbital and Space Vehicles and to execute various missions.

Producing thrust for propulsion of the orbital vehicle

The first requirement for a permanent, powered satellite at an altitude between 85 and 120 km is a method of producing enough thrust to overcome drag.

The maximum drag of a vehicle flying at orbital speeds at 100 km is of the order of 6 dynes/cm^2 of skin surface. For a vehicle with an inlet of 1 m^2 and 5 m long, the skin friction drag is less than 1.2×10^6 dynes. If all the air through the inlet is stopped relative to this orbiting vehicle, the additional drag is 4.5×10^6 dynes. Extreme care must be exercised in handling the hypersonic (Mach No. $\cong$ 25) low-density air stream.

If, however, only one-fiftieth of the entering air is stopped and collected, the drag due to collection will be approximately 0.1×10^6 dynes. Since the Orbital Vehicle can be designed so that the cross-sectional area of the inlet is equal to the frontal area of the vehicle and the PROFAC scoop can be designed so that its area is a fraction, say one-fiftieth, of the Orbital Vehicle, including PROFAC equipment, will be less than 1.3×10^6 dynes (wave drag is negligible at this altitude and PROFAC skin-friction drag can be neglected since the PROFAC surface area can be made negligible compared to the Orbital Vehicle surface area).

Since the mass rate of flow through 1 m^2 is about 6 g/sec, the exhaust velocity, V_4, required will be given by $V_4= (1.3\times10^6)/6 + V_1=2.2\times10^5 + V_1$ cm/sec. With the orbital speed, $V_1=8\times10^5$ cm/sec, it follows that $V_4\cong1.28V_1$. Actually, it may be shown that this is a high estimate for the drag and that by appropriately shaping the external walls (i.e., converging them towards the rear) the total drag, including wave drag and diffuser losses, may be halved, so that for the ratio length/diameter = 5, the exit velocity required to overcome the total drag is $V_4>1.15V_1$.

It is significant that the required velocity increment is relatively small. Since only small mass rates of flow (10 g sec^{-1} m^{-1}) are involved, the total power required to effect this acceleration will be of the order of 0.4 MW/m^2 of inlet area. Nuclear technology can be relied upon to provide sources of power of this magnitude and with total weights of the order of 10^3 to 10^4 kg and very long lifetimes. The most useful type of power plant would be the ramjet, because it eliminates the need to carry a working or propulsive fluid and its only serious competitor, the rocket, would require stagnation temperatures of the order of 45,000^o K. to produce exhaust velocities of the order of 10^6 cm/sec by the expansion of heated air. In a ramjet at orbital speeds, on the other hand, exhaust velocities of approximately 9.5×10^5

cm/sec can be reached by an increase of the stagnation temperature by $\Delta T_o \cong 10{,}000^o$ K.

The major problem is how to increase the stagnation temperature of the gas. Simple heating at these low densities and high temperatures can be ruled out. One method for acceleration low-density, high-speed flows (other alternative methods are also under consideration) consists of an electrical discharge, with or without electrodes, followed by magnetohydrodynamic (MHD) acceleration consisting of crossed applied electric and magnetic fields.

The theory of simple, constant-area MHD acceleration of supersonic flows of partially ionized gases is relatively well understood. Theoretical computations indicate that if the conductivity of the inlet air is raised to 10 mhos/cm., the ratio $V_4/V_1 = 1.50$ may be obtained with a magnetic field of 100 gauss, and an electric field of 2.7 volts/com. Acting across a channel of 100 cm.^{2} Cross section (since the inlet area is 10^4 cm.^{2}, this implies an area ratio of 100 and a pressure rise by a factor of 1000). The direction of flow is normal to the plane of the mutually perpendicular electric and magnetic fields. The mass flow rate used in this computation was 10g./sec., the ratio of the specific heats was $\gamma=1.4$, and the initial Mach number (at the entrance of the driver section) was $M_o=10$. The required length of the MHD driver for $V_4/V_1 = 1.5$ is of the order of 550 cm. For $V_4/V_1 = 1.5$, the length required is only 165cm.

It has been verified that there is no electrical breakdown of air under these fields and conditions (i.e., $\rho = 10^{-4}\rho_o$ where ρ_o is the standard atmospheric density and $P = 10^{-3}P_o$ where P_o is the standard atmospheric pressure). The conductivity of the air can be increased to 10 mhos/cm. by introducing a virile radioactive coating on the walls of the diffuse followed by an electrodeless (microwave) discharge or a glow discharge upstream of the MHD driver. This discharge will “shake up” the atoms and molecules of the gas and create ion pairs (0.1-1% is sufficient) in much the same way an electrodeless discharge dissociates oxygen and nitrogen. Ion recombination at these densities is sufficiently slow and flow velocity is sufficiently high to permit these ions to survive for several metres downstream of the discharge and throughout the length of the MHD driver. The thermal energy of the stream within the driver is increased only slightly if recombination does not occur.

The MHD drive described here can overcome the drag of the Orbital Vehicle and the PROFAC apparatus and in addition, it can provide positive accelerations of about 10^{-4} g for the entire duration of its flight (many months of years). For short periods of high acceleration (up to 5 g) the propulsive fluid stored in the PROFAC device or elsewhere in the system, can be ejected in large quantities. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

Power Source

Two types of power sources will be required, one for the Orbital Vehicle and one for the Space Vehicle. Because long life and very high energy content per unit weight are required, nuclear power sources are indicated, although if operation above 150 km proves desirable, solar energy can be used.

The difficulty of developing such sources has long been recognized. In this case, however, the task is simplified by the lower power output required. Thus a typical Orbital Vehicle power sources will require only about 0.26 MW per m^2 of inlet area for the 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 this imposes a requirement of 5 MW, the attached PROFAC equipment with scoop area of 1 m^2 will require 1 MW. Thus, a total of 6 MW will be required. Such a power source with auxiliary equipment would weight about 11 metric tons with the present state of the art and perhaps as low as 2 metric tons with the expected development of nuclear power sources in 10 years (using the same dimensions, the PROFAC equipment will accumulate 430 kg of liquid air per day or 43 metric tons in 100 days).

The second type of power plant would be specified by the mission required of the Space Vehicle. Assume that its mission is to land 10 metric tons of payload on the Moon and that the propulsive fluid can be accelerated to about 3×10^5 cm/sec (by simple heating to about 3000 K). then, since the acceleration due to gravity at the surface of the Moon is 163 cm/sec^2, we obtain a required mass flow rate of $\dot{m}$ from the equation:

$$(10^7 g) \times \left(163\,\frac{cm}{sec^2}\right) = (m\ g/\mathrm{sec}) \times (3\dot{}\times 10^5\ cm/\mathrm{sec})$$

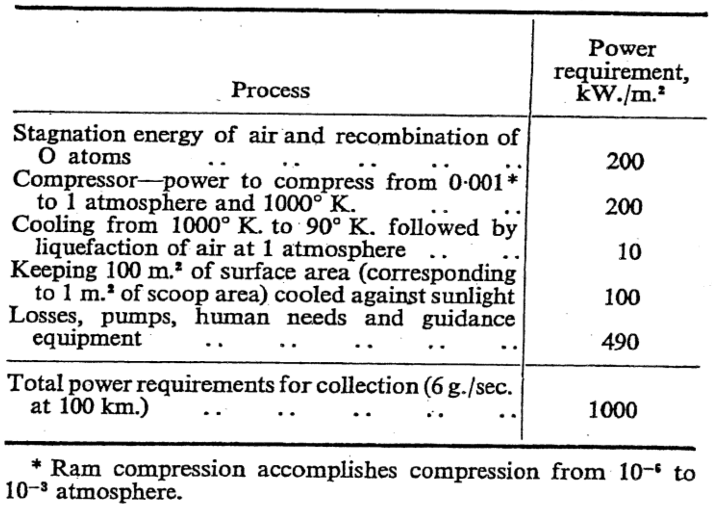
or $\dot{m} \cong 500$ g/sec then the power required is approximately $(5\times10^3)(9\times10^{10})/2 = 2.3\times10^{14}$ ergs/sec = 2.3×10^7 watts = 23 MW.

It is clear that the power sources required are small compared to the nuclear rocket power plants now being planned (most are of the order of 10,000 MW). Consequently the problems should be easier to solve. It must be emphasized that even these power source requirements can be decreased by operating at higher altitudes or using solar energy. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

Collection and Storage of Upper atmosphere air

By making the PROFAC inlet and surface area small compared to the Orbital Vehicle inlet, the drag of the PROFAC device will be kept small compared to the thrust of the MHD drive of the Orbital Vehicle. At the same time, the PROFAC inlet will be large enough to insure a reasonable collection rate. Thus, at 100 km the collection rate will be about 430 kg of air per day per square meter of scoop area. In one day 43,000 kg can be collected with a scoop of 100 m^2 or 4300 kg with a scoop 10 m^2.

Approximate power requirements per $m.^2$ of scoop area or for a collection rate of 6 g/sec are given in Table 1.



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

* Ram compression accomplishes compression from 10^{-6} to 10^{-3} atmosphere.

Table 1: power levels and requirements for collection and storage of upper atmosphere air.

These thermal power requirements are order-of-magnitude estimates. They can be reduced by an order of magnitude of a 15 km increase in altitude, until at about 150 km the flux of solar energy alone is sufficient to provide power for the Orbital Vehicle thrust engine and for the PROFAC equipment. The attendant decrease in collection rate, however, makes operation at altitudes above 130 km. rather uneconomical from the point of view of time required for collection. It should be noted that 1 MW of thermal energy can be radiated from a surface of 10 m^2 at 1000^{o} C.

Once the air is collected and frozen or liquefied, it will be stored as a liquid in an appropriate tank. The estimated weight of the liquefaction equipment is 150 kg/m^2 of scoop area. The estimated weight of the storage tanks is 5% of the liquid it contains, including insulation and auxiliary equipment.

Low pressure at the end of the inlet will be maintained by liquefaction of the inlet stream, using the same principle as a two-phase wind tunnel. Other methods might be used for the fixation and storage of the inlet stream (e.g., chemical reaction, absorption and adsorption) to decrease further the power requirements. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

POWER sOURCE rEQUIREMENTS

Two types of power sources will be required, one for the Orbital Vehicle and one for the Space Vehicle. Because long life and a very high energy content per unit weight are required, nuclear power sources are indicated, although if operation above 150 km proves desirable, solar energy can be used.

The difficulty of developing such sources has long been recognized. In this case, however, the task is simplified by the lower power output required. Thus a typical Orbital Vehicle power source will require only about 0.26 MW per m^2 of inlet area for the 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 this imposes a requirement of 5 MW. The attached PROFAC equipment with scoop area of 1 m^2 will require 1 MW. Thus, a total of 6 MW will be required. Such a power source with auxiliary equipment would weigh about 11 tons *with the present state of the art* and perhaps as low as 2 tons *with the expected development of nuclear power sources in 10 years* (using the same dimensions, the PROFAC equipment will accumulate 430 kg of liquid air per day or 43 tons in 100 days).

The second type of power plant would be specified by the mission required of the Space Vehicle. Assume that its mission is to land 10 tons of payload on the Moon and that the propulsive fluid can be accelerated to about 3×10^5 cm/sec (by simple heating to about 3000 K). Then, since the acceleration due to gravity at the surface of the Moon is 163 cm/sec^2, we obtain a required mass flow rate of $\dot{m}$ from the equation:

$$(10^7\ g) \times (163\ cm/sec^2)$$
$$=(\dot{m}\ g/sec) \times (3\times10^5\ cm/sec)$$

or $\dot{m}\cong500$ g/sec. Then the power required is approximately $(5\times10^3)(9\times10^{10})/2 = 2.3\times10^{14}$ ergs/sec = 2.3×10^7 watts = 23 MW.

It is clear that the power sources required are small compared to the nuclear rocket power plants now being planned (most are of the order of 10,000 MW). Consequently the problems should be easier to solve. It must be emphasized that even these power source requirements can be decreased by operating at higher altitudes or using solar energy. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

Thrust Engine for Space Vehicle

The thrust engine for the Space Vehicle can be a simple boiler-type nuclear engine of about 20 MW and total mass of about 5 tons, which heats the propulsive fluid by heat transfer and expands it through a nozzle into space for short range (lunar) trips or a more sophisticated plasma or ion-rocket (using N^+ or O^+) for longer range (Mars) interplanetary travel. The problems of both types are well understood and the construction of at least the boiler-type engine presents no new problems since the mass rates of flow are small (5 kg/sec). Solar energy can be used as the source of the power for the space vehicle also. The alternative scheme of carrying the fuel (e.g., hydrogen) to burn with the collected oxygen also deserves attention. (Demetriades, A Novel System for Space Flight Using a Propulsive Fluid Accumulator, 1959)

Plasma Propulsion

Plasma propulsion deserves special attention to the academic, scientific, engineering, and managerial communities for two reasons: (1) There are missions where, at this time, plasma propulsion promises significant advantages over other electrical propulsion systems, for instance, in orbital airbreathing electrical propulsion; and (2) there are many vital national programs whose success depends on the solution of a few critical problems, most of which are identical with those encountered in plasma propulsion. (Demetriades, Plasma Propulsion Part 1, 1962)

PROFAC

Additional non-published papers exist however, only one of the four was allowed to be submitted due to administrative decisions by the American Rocket society and the Government. More information may be found in the following source whose abstract is as follows:

Requirements for various missions where use is made of Propulsive Fluid Accumulator (PROFAC) systems are compared with the requirements of conventional nuclear, chemical, or hybrid systems. These requirements include power, total energy and launch mass. Continuous or intermittent refueling with propulsive fluid collected while a vehicle is accelerating to orbit, in low altitude orbit and/or on the surface of satellites or planets offers several practical advantages over a mere increase of specific impulse. Problem areas and requirements of PROFAC systems are defined and discussed. Methods for computing the performance of dissipative inlets and cryopumps for orbital air collection are presented and specific design results are given. Propulsion and power requirements of various types of PROFAC vehicles are discussed, and experimental results are presented of a promising electromagnetic engine for orbital air collection. This engine consists of a continuous Lorentz or J × B accelerator using an arc jet plasma source. Argon, nitrogen or air are used as expellants. At flow rates of 0.003 lbm/sec directly measured thrusts of up to 3.6 lbf, exclusive of the arc jet, were obtained with acceleration efficiencies as high as 54%. These engines can be used with a wide variety of expellants over a specific impulse range of 1000 to5000 seconds for a number of orbital, lunar or interplanetary missions. Atmospheric and extraterrestrial resources can also be used in chemical or nuclear propulsion systems to cover the specific impulse range below 1000 seconds at high accelerations. (Demetriades, The Use of Atmospheric and Estraterrestrial Resources in Space Propulsion Systems Part 1, 1962)

Works Cited

Demetriades, S. T. (1959). A Novel System for Space Flight Using a Propulsive Fluid Accumulator. *Journal of the British Interplanetary Society, 17*, 114-119.

Demetriades, S. T. (1961). Preliminary Study of Propulsive Fluid Accumulator Systems. *Journal of the British Interplanetary Society, 18*, 392-402.

Demetriades, S. T. (1962, March). Plasma Propulsion Part 1. *Astronautics*, 20-21,40-41.

Demetriades, S. T. (1962). The Use of Atmospheric and Estraterrestrial Resources in Space Propulsion Systems Part 1. *Electric Propulsion Conference* (pp. 1-56). Hawthorne: American Rocket Society.

Demetriades, S. T. (1963). Propulsive-Fluid Accumulator Engine. In McGraw-Hill, *McGraw-Hill Yearbook Science and Technology.* McGraw-Hill Book Company.

Appendix C

Propellant Harvester of Atmospheric Resources in Orbit (PHARO)

Dr. Alan Wilhite
Professor of Advanced System Architectures
School of Aerospace Engineering
Georgia Institute of Technology
at
National Institute of Aerospace

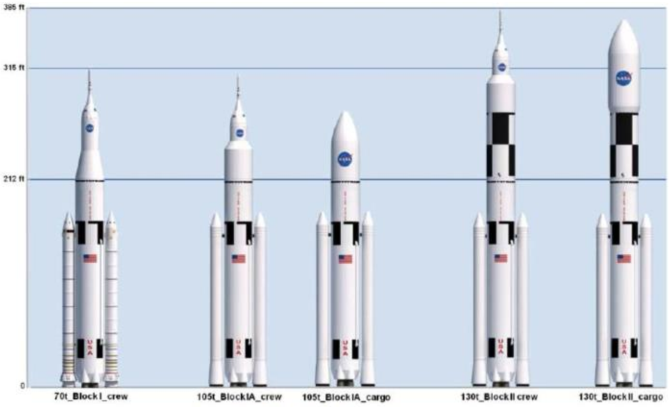
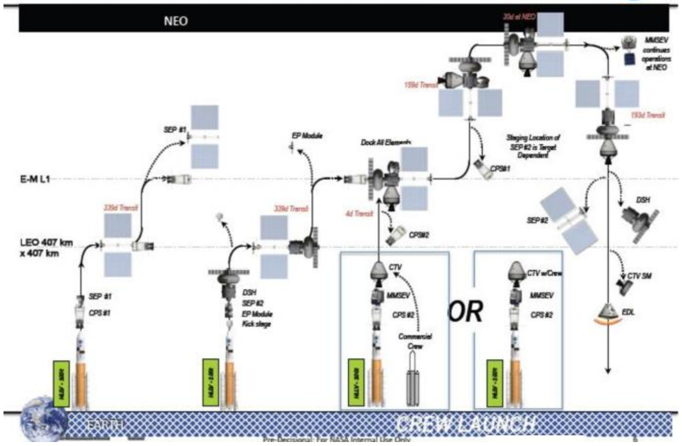
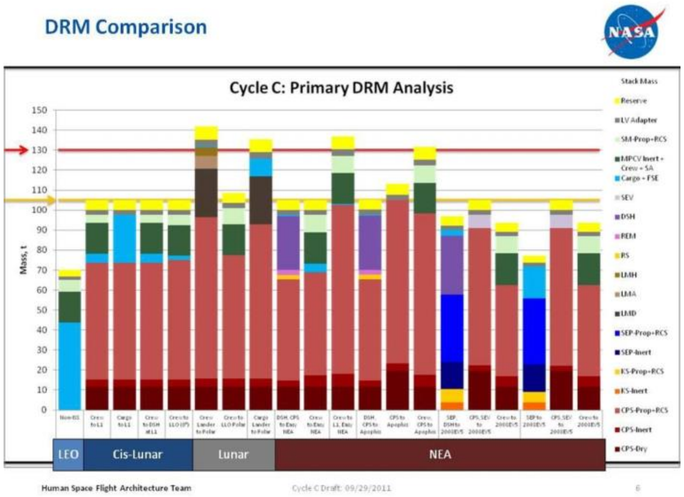


Figure 1. SLS Vehicle Configurations

Concept of Operations (NEO Crewed Missions, 100 t HLLV)



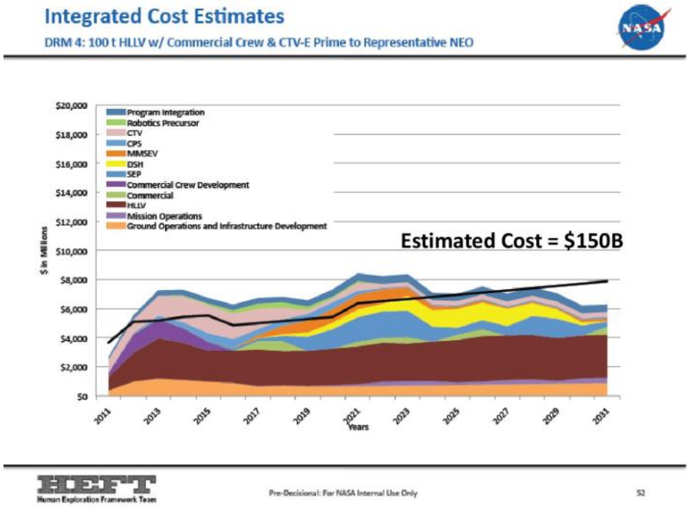


DRM Comparison

Human Space Flight Architecture Team

Cycle C Draft: 09/29/2011

6



Integrated Cost Estimates

DRM 4: 100 t HLLV w/ Commercial Crew & CTV-E Prime to Representative NEO

HEFT
Human Exploration Framework Team

Pre-Decisional: For NASA Internal Use Only

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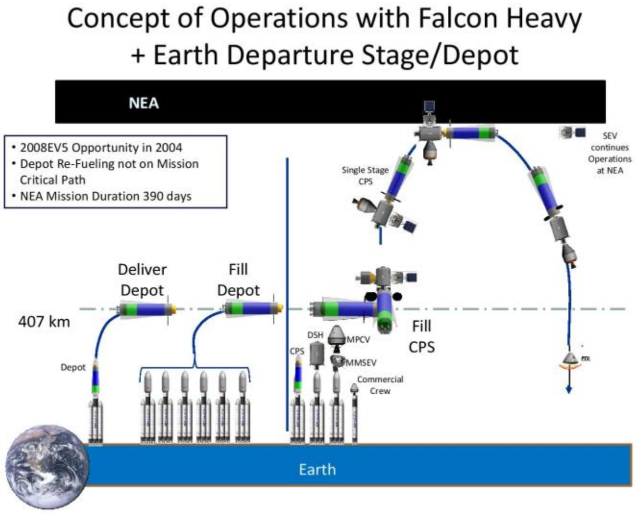


Concept of Operations with Falcon Heavy + Earth Departure Stage/Depot

- 2008EV5 Opportunity in 2004
- Depot Re-Fueling not on Mission Critical Path
- NEA Mission Duration 390 days

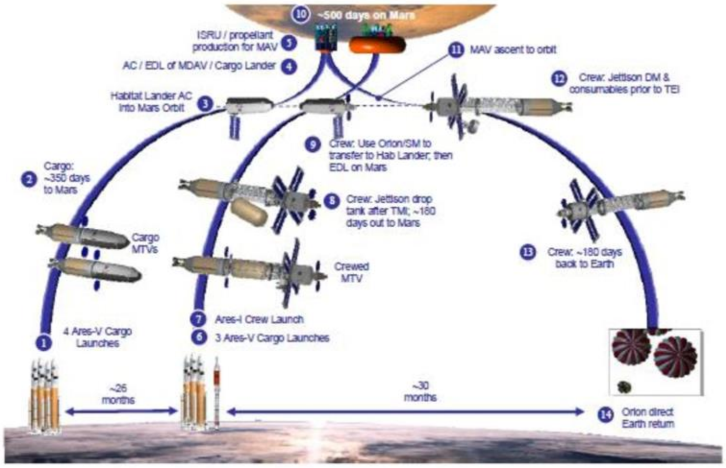
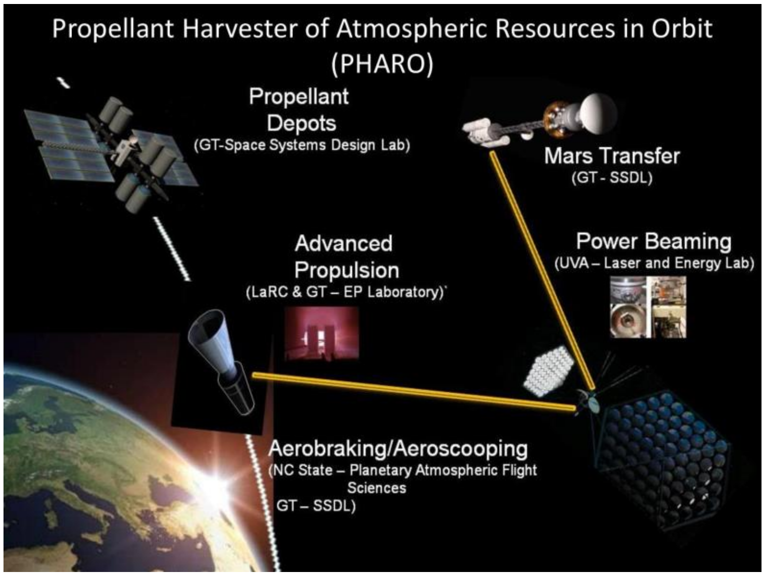


Figure 2-2. Mars Design Reference Architecture 5.0 mission sequence summary (NTR reference).



Propellant Harvester of Atmospheric Resources in Orbit (PHARO)

Propellant Depots
(GT-Space Systems Design Lab)

Mars Transfer
(GT - SSDL)

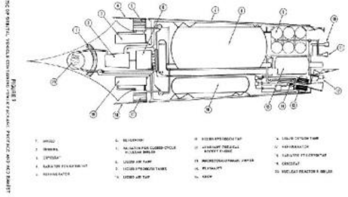
Advanced Propulsion
(LaRC & GT – EP Laboratory)`

Power Beaming
(UVA – Laser and Energy Lab)

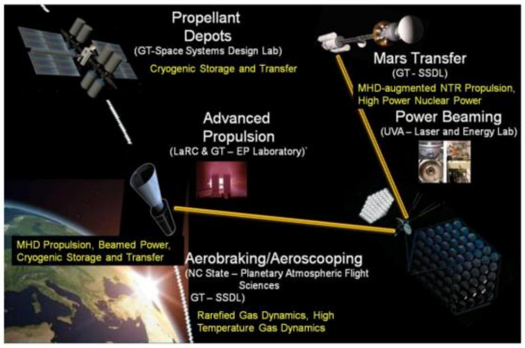
Aerobraking/Aeroscooping
(NC State – Planetary Atmospheric Flight Sciences
GT – SSDL)

History

- PROFAC
  - Sterge Demetriades, Northrop, 1959
  - Monolithic collection vehicle to collect and store atmospheric gases
  - Used nuclear-powered MHD acceleration (magnetohydrodynamic) propulsion system to maintain orbit
  - Transferred collected propellant to future exploration vehicle



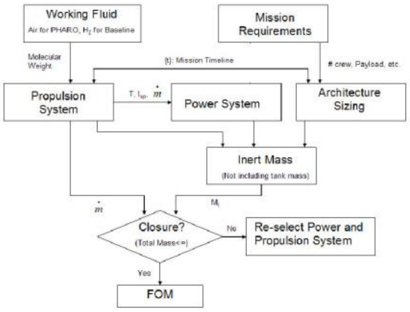
PHARO



- Our concept utilizes propellant collection and related technologies to significantly reduce launched mass as well as the overall campaign cost

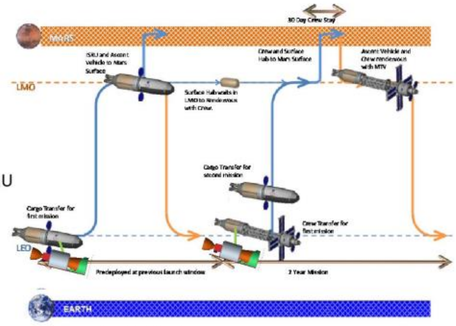
Mars Transfer Vehicle Design Process

- Begin with mission requirements from DRA 5/RASC-AL
- Flowthrough for selection of propulsion and power systems
- Once system closes, evaluate using Figures of Merit
  - Life Cycle Cost
  - Number of Launches
  - Reliability



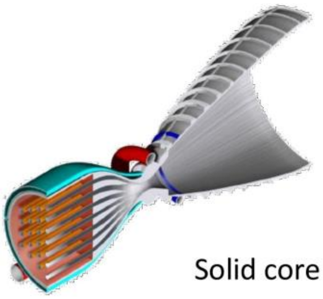
PHARO Mars Architecture

- Mission
  - Less than two years for crewed mission
  - Thirty day stay
  - Crew of four
- Architecture
  - Reusable Cargo MTV: Predeploys MAV and ISRU systems, returns for refueling
  - Reusable Crew MTV: Transports crew to and from Mars, refuels after Earth return
  - PHARO refuels MTVs



Propulsion Fluid: Air
Propulsion System: Magnetohydrodynamic augmented NTR

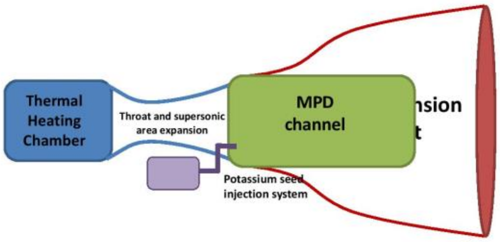
Thermal Rockets



Solid core

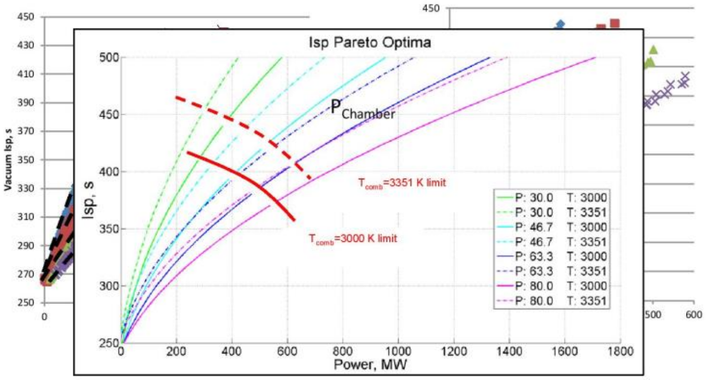
Source: John Martin, SACD/VAB Briefing

Proposed MATR Design



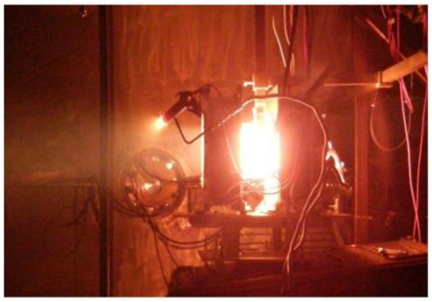
Magnetoplasmadynamic Augmented Thermal Rocket (MATR)

Pareto Optimization



GaTech - N_2 Thruster Experiment

500 W, 11.9 MHz, 20 G, 1.5 mg/s nitrogen, 1.8×10^{-5} Torr.



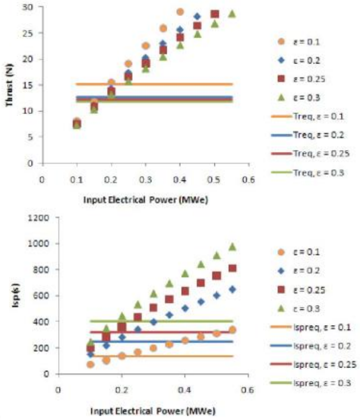
Gridded Helicon Ion Thruster

Performance

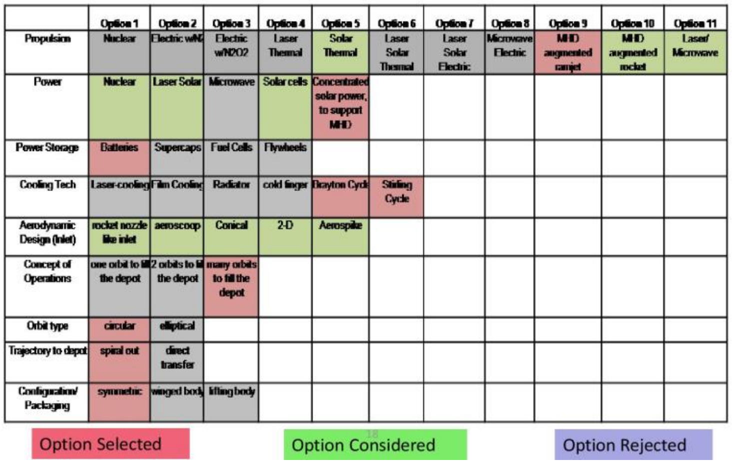
- Thrust/Power ~ 1 mN/500W
- Helicon can be optimized to increase thrust

Collector Design Process

- Mission Requirements
  - Mass
  - Time to collect
- Spacecraft Parameters
  - Inlet drag coefficient $C_{D,geom}$
  - Storage fraction ε
  - Inlet Reference area A
  - Inlet efficiency α
- Orbit Parameters
  - Atmospheric density ρ
  - Velocity V
- Spacecraft Requirements
  - Thrust
  - Specific Impulse



Collector Morph Matrix



	Option 1	Option 2	Option 3	Option 4	Option 5	Option 6	Option 7	Option 8	Option 9	Option 10	Option 11
Propulsion	Nuclear	Electric w/N	Electric w/N2O2	Laser Thermal	Solar Thermal	Laser Solar Thermal	Laser Solar Electric	Microwave Electric	MHD augmented ramjet	MHD augmented rocket	Laser/ Microwave
Power	Nuclear	Laser Solar	Microwave	Solar cells	Concentrated solar power, to support MHD						
Power Storage	Batteries	Supercaps	Fuel Cells	Flywheels							
Cooling Tech	Laser-cooling	Film Cooling	Radiator	cold finger	Brayton Cycl	Stirling Cycle					
Aerodynamic Design (Inlet)	rocket nozzle like inlet	aeroscoop	Conical	2-D	Aerospike						
Concept of Operations	one orbit to fi the depot	2 orbits to fi the depot	many orbits to fill the depot								
Orbit type	circular	elliptical									
Trajectory to depot	spiral out	direct transfer									
Configuration/ Packaging	symmetric	winged body	lifting body								

Option Selected

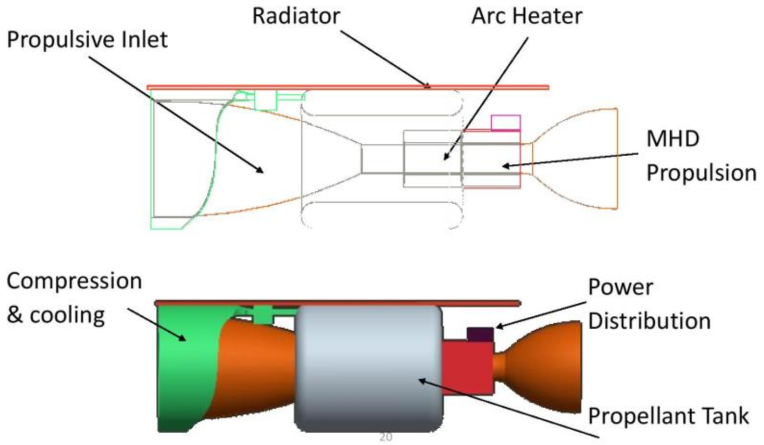
Option Considered

Option Rejected

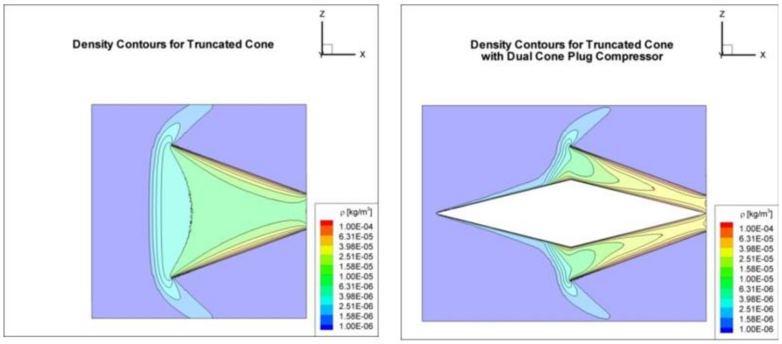
Collector Trade Studies

- Power: selected solar beamed power
  - Nuclear rejected due to safety issues
  - Onboard power too massive → drag penalty
  - Stored power not viable for long term use
- Propulsion: selected MHD ramjet
  - Thermal approaches have insufficient Isp
  - Chemical propulsion depletes fuel
  - Other electric propulsion requires too much power for required thrust level

PHARO Collector



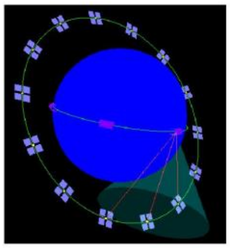
Inlet Analysis



Density at end of inlet improves by a factor of 3 with the introduction of the compressor

PHARO Collectors and Power Satellites

- Collector Mass: 17.5 T
- Propellant Stored: 98 T
- Power Required: 175 kW
- Collector Thrust: 15 N
- Stores 30% margin
  - 20% for transfer burns
  - 10% for ullage
- Two trips per collector per Mars mission



- Seven Collectors (one spare)
- Fourteen satellites

MTV Comparison

	DRA 5 Derived	PHARO
Transfer Type	Direct	Spiral
Propellant	Hydrogen	Air
Propulsion	NTR	MHD Augmented NTR
Specific Impulse	950 s	5000 s
Payload Mass (Crew)	62 T	56 T
Dry Mass (Crew)	272 T	140 T
Prop Mass (Crew)	481 T (Round trip)	450 T (Round trip)
Payload Mass (Cargo)	56 T	45 T
Dry Mass (Cargo)	150 T	140 T
Prop Mass (Cargo)	120 T (One way)	450 T (Round Trip)
Launch Mass (Initial)	0 T	279 T
Launch Mass (Per Mission)	1032 T	101 T

- PHARO architecture has 90% less mass on each subsequent Mars mission relative to baseline architecture
- PHARO architecture requires 80% fewer launches per mission (ten Ares V vs two)

NPV Cost Analysis

- DRA 5 Derived Architecture
  - DDT&E Cost: $13.8B
  - TFU Cost: $2.4B
  - Yearly Operations: $1.2B

- PHARO Architecture - Breaks even before 4 missions (~30 years)
  - DDT&E Cost: $3.5B (Collector); $1.2B (Power Sat); $10.2B (MTV)
  - TFU Cost: $165M (Collector); $209M (Power Sat); $1.9B (MTV)
  - Yearly Operations: $120M (Collector); $125M (Power Sat); $635M (MTV)

Critical Technologies

- Cryogenic fluid storage and transfer (TRL 4)
- MHD propulsion with air (TRL 3)
- MHD-augmented nuclear thermal propulsion (TRL 2)
- High power space nuclear power (TRL 2)
- Rarefied, high temperature gas handling (TRL 2)
- Lightweight radiators (TRL 3)
- Concentrated solar power beaming (TRL 3)

Conclusions

- Propellant harvesting can have dramatic impact on humans-to-Mars mission
  - 90% reduction in recurring mass
  - Net present value approach shows life cycle cost savings after four missions
- This approach requires significant investment in several key technologies:
  - Beamed solar power
  - Magnetohydrodynamic augmented propulsion
  - Cryogenic fluid storage and transport
  - Space nuclear power and related systems
- For a humans-to-Mars campaign over multiple missions, application of new technologies can lead to improved architecture

References

- Axdahl,E., Chai, P., Gaebler, J., Grimes, M., Long, M., Lugo, R., Rowland, R., and Wilhite, A. "Reusable Lunar Transportation Architecture Utilizing Orbital Propellant Depots." Space 2009.
- Brown, D., Beal, B., and Haas, J. "Air Force Research Laboratory High Power Electric Propulsion Technology Development." IEEE Aerospace Conference, Big Sky, MT. 2010.
- Chang Diaz, F., Squire, J., Bering, E., George, J., Ilin, A., Petro, A., and Cassady, L. "The VASIMR Engine Approach to Solar System Exploration." AIAA 2001-0960.
- Demetriades, S. "A Novel System for Space Flight Using a Propulsive Fluid Accumulator." Journal of the British Interplanetary Society, Jan. 1959.
- Humble, R., Henry, G., and Larson, W. *Space Propulsion: Analysis and Design*, Revised ed. The McGraw-Hill Companies, Inc., 1995.
- Jones, C., Masse, D., Glass, C., Wilhite, A., and Walker, M. "PHARO—Propellant Harvesting of Atmospheric Resources in Orbit." IEEE Aerospace Conference, Big Sky, MT. 2010.
- Larson, W. and Pranke, L. *Human Spaceflight Mission Analysis and Design,* The McGraw-Hill Companies Inc., New York: 1999.

References

- Litchford, R., Cole, J., and Bityurin, V. "Thermodynamic Cycle Analysis of Magnetohydrodynamic–Bypass Hypersonic Airbreathing Engines." NASA TP-2000-210387.
- "Power to Overall Weight Ratio of the 2013 Hyperion Power Nuclear Reactor." http://nextbigfuture.com/2008/10/power-to-overall-weight-ratio-aspect-of.html
- RASC-AL 2010 Guidelines, http://www.nianet.org/rascal/
- Satellite Signals, "Internet VSAT Access via Satellite: Costs." http://www.satsig.net/ivsatcos.htm
- SpaceX Falcon Data Sheet. http://www.spacelaunchreport.com/falcon9.html
- Wilhite, A. Notes from Spacecraft and Launch Vehicle Design I. 2009.

Collector Design Process

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  - Mass
  - Time to collect
- Spacecraft Parameters
  - Inlet drag coefficient $C_{D,geom}$
  - Storage fraction ε
  - Inlet Reference area A
  - Inlet efficiency α
- Orbit Parameters
  - Atmospheric density ρ
  - Velocity V
- Spacecraft Requirements
  - Thrust
  - Specific Impulse

$$\dot{m}_{\text{storage}} = \frac{m_{\text{total}}}{t_{\text{total}}}$$

$$\dot{m}_{\text{overall}} = \frac{\dot{m}_{\text{storage}}}{\varepsilon}$$

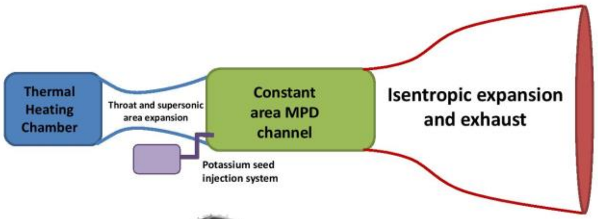
$$\dot{m}_{\text{overall}} = \alpha \rho A V$$

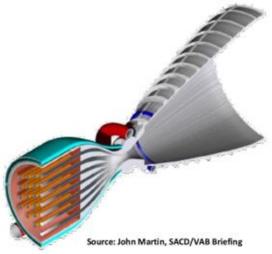
$$\dot{m}_{\text{propulsion}} = (1-\varepsilon)\alpha \rho A V$$

$$T_{\text{required}} = \frac{1}{2}\rho A V^2 C_{D,\text{geom}} + \alpha \varepsilon \rho A V^2$$

ΔT depends on transfer to MTVs

$$Isp_{\text{required}} = \frac{(\varepsilon + \frac{C_{D,\text{geom}}}{2\alpha})V}{g_0(1-\varepsilon)} + \frac{\Delta T}{g_0(1-\varepsilon)\alpha \rho A V}$$

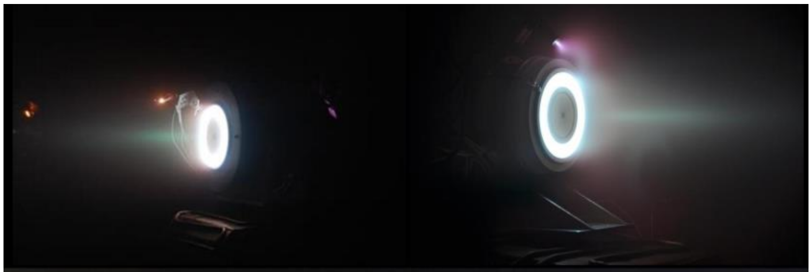


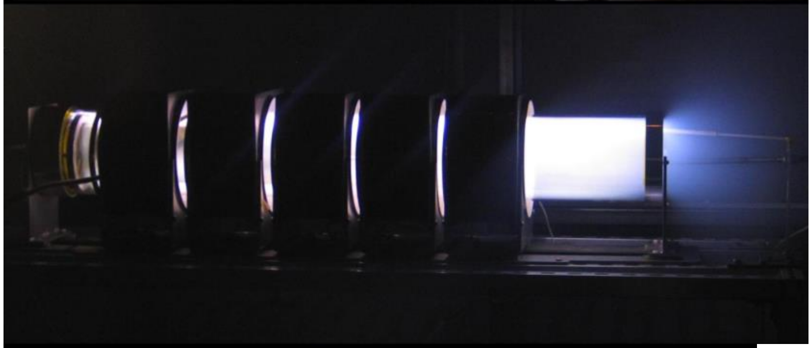


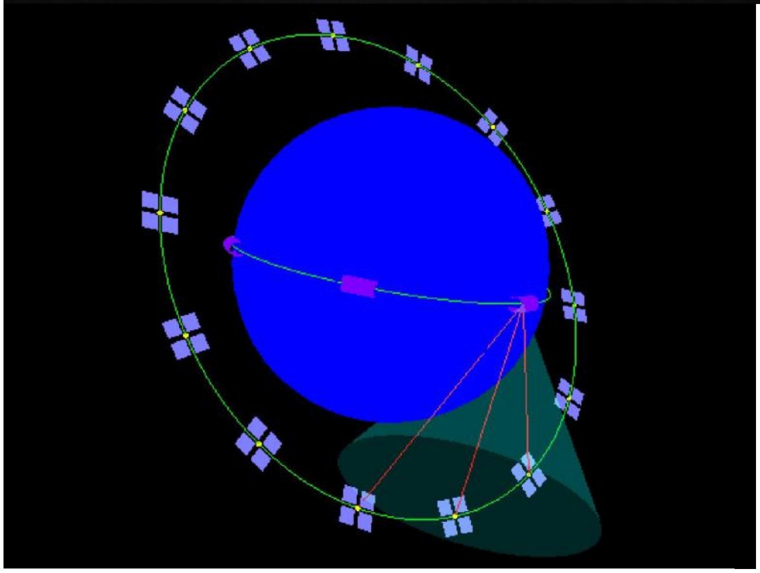
Source: John Martin, SACD/VAB Briefing

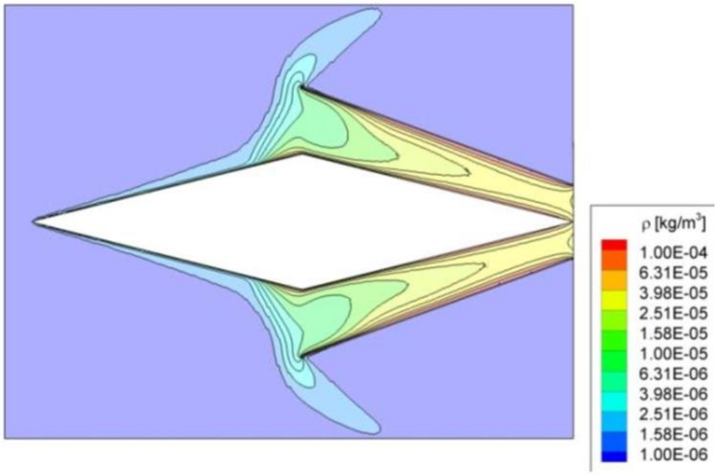
Chamber Parameter	Units	Min	Max
Pressure	bar	30	80
Temperature	K	2750	3351

Accelerator Parameter	Units	Min	Max
Area	m^2	1.01 A^*	2.0 A^*
Length	m	0	1
Magnetic field	T	0.5	8.0
Seed	%	0.5	1.5
Load	-	1.0	4.0








ρ [kg/m³]
1.00E-04
6.31E-05
3.98E-05
2.51E-05
1.58E-05
1.00E-05
6.31E-06
3.98E-06
2.51E-06
1.58E-06
1.00E-06

PHARO

Propellant Harvesting of Atmospheric Resources in Orbit

Christopher Jones, David Masse,
Alan Wilhite, Mitchell Walker
Georgia Institute of Technology
Christopher Glass
NASA LaRC

Outline

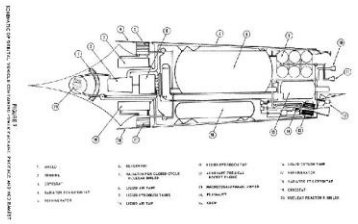
- Motivation and History
- Objectives
- Concept of Operations
- Trade Study Definition
- Trade Study Results
- Inlet Analysis
- Continuing Work
- Summary

Motivation

- Propellant represents a large fraction of the mass lifted into orbit for exploration systems (Moon, Mars, etc.)
- Technologies that can reduce the amount of mass launched from Earth to orbit have the potential to dramatically reduce mission cost
- One such technology is on-orbit collection of propellant

History

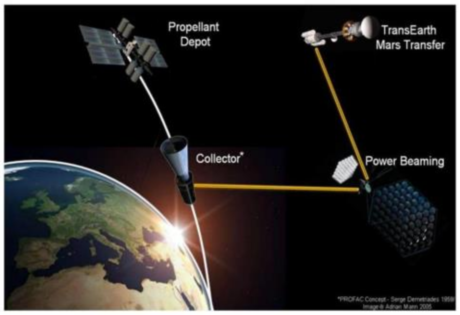
- PROFAC
  - Sterge Demetriades, Northrop, 1959
  - Monolithic collection vehicle to collect and store atmospheric gases
  - Used nuclear-powered MHD acceleration (magnetohydrodynamic) propulsion system to maintain orbit
  - Transferred collected propellant to future exploration vehicle



Objectives

- Establish ranges for relevant parameters for a nominal mission
- Determine thrust and Isp requirements for the collector propulsion system
- Begin studying inlet geometries in the continuum/free molecular flow transition regime

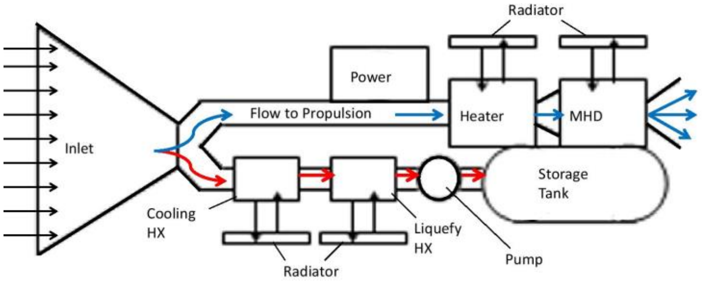
Concept of Operations



*PROFAC Concept - Serge Demetriades 1959
Image © Adrian Mann 2005

- Collector in circular orbit
- Ingests gases; some liquefied and stored, others used for propulsion
- When full, transfers to depot to unload
- When depot is full, propellant transferred to exploration system
- Collector energized by power beaming

Collector Schematic



Relevant Parameters

- Mission Requirements
  - Mass
  - Time to collect
- Spacecraft Parameters
  - Inlet drag coefficient $C_{D,geom}$
  - Storage fraction ε
  - Inlet Reference area A
  - Inlet efficiency α
- Orbit Parameters
  - Atmospheric density ρ
  - Velocity V
- Spacecraft Requirements
  - Thrust
  - Specific Impulse

$$\dot{m}_{storage} = \frac{m_{total}}{t_{total}}$$

$$\dot{m}_{overall} = \frac{\dot{m}_{storage}}{\varepsilon}$$

$$\dot{m}_{overall} = \alpha\rho A V$$

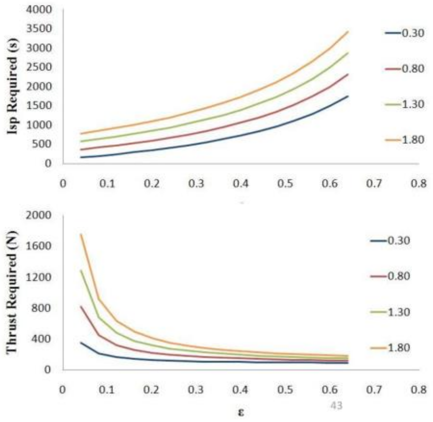
$$T_{required} = \frac{1}{2}\rho A V^2 C_{D,geom} + \alpha\varepsilon\rho A V^2$$

$$Isp_{required} = \frac{(\varepsilon + \frac{C_{D,geom}}{2\alpha})V}{g_0(1-\varepsilon)}$$

Nominal Mission

- Mission Requirements
  - Mass: 300 MT of propellant
  - Time: 1 year
- Spacecraft Parameters
  - $C_{D,geom}$: between 0.3 and 1.8
  - ε: between 0.04 and 0.64
  - A: 19.6 m^2 (based on shroud geometries)
  - α: 1 (for this study; ongoing work in inlet analysis)
- Orbit Parameters
  - Determined by above values
- Spacecraft Requirements
  - Plotted as functions of $C_{D,geom}$ and ε

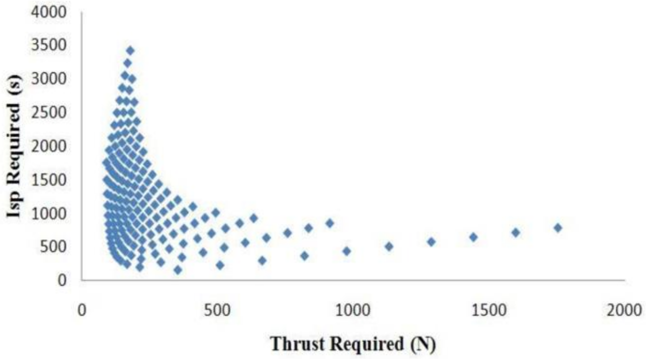
Spacecraft Requirements



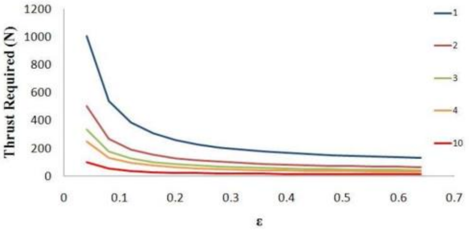
- •Isp requirements increases as ε increases
- •Lower amount of propellant increases performance requirement

- •Thrust requirement decreases as ε increases
- •Greater ε yields lower total mass flow rate, thus higher altitude and lower density

Requirements and Performance



Collector Performance

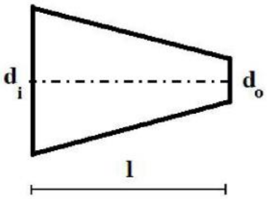


- •One way to reduce thrust requirement is to increase the number of collectors
- •Significant gains at low values of ε
- •Most improvement seen going from 1 → 2 collectors
- •High numbers of collectors provide little additional gain while raising cost and complexity
- •No variation in Isp requirement due to changes in number of collectors

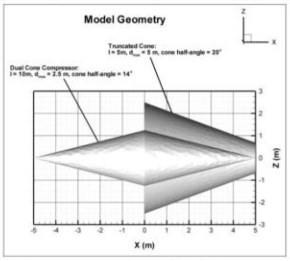
Inlet Analysis

Nominal Altitude: 100 km
Nominal Velocity: 8 km/s

Element	O	O_2	N	N_2
#/m³	3.995E+11	2.025E+12	2.020E+5	8.467E+12

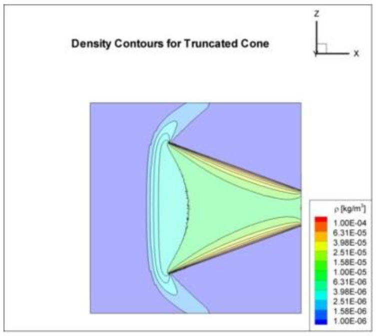


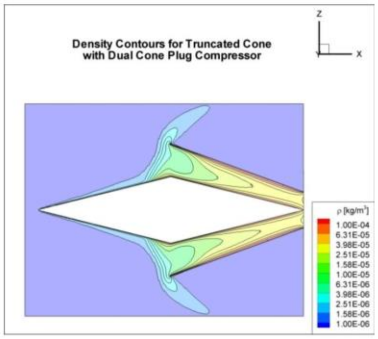
- •Max diameter: 5 m
- •Length: 5 m
- •Min diameter: 1.36 m



- •Compressor length: 10 m
- •Compressor max diameter: 2.5 m
- •Truncated cone length: 5 m
- •Truncated cone max diameter: 5 m
- •Truncated cone half angle: 20°

Inlet Analysis





Density at end of inlet improves by a factor of 3 with the introduction of the compressor

Inlet Analysis

Inlet Type	Drag Force (N)	$C_{D,geom}$
Truncated Cone	547	1.7
Cone with Compressor	552	1.7

- $C_{D,geom}$ estimates made from nominal values of density, velocity, and area
- Introduction of compressor did not significantly increase drag, while it improved compression (by a factor of 3)

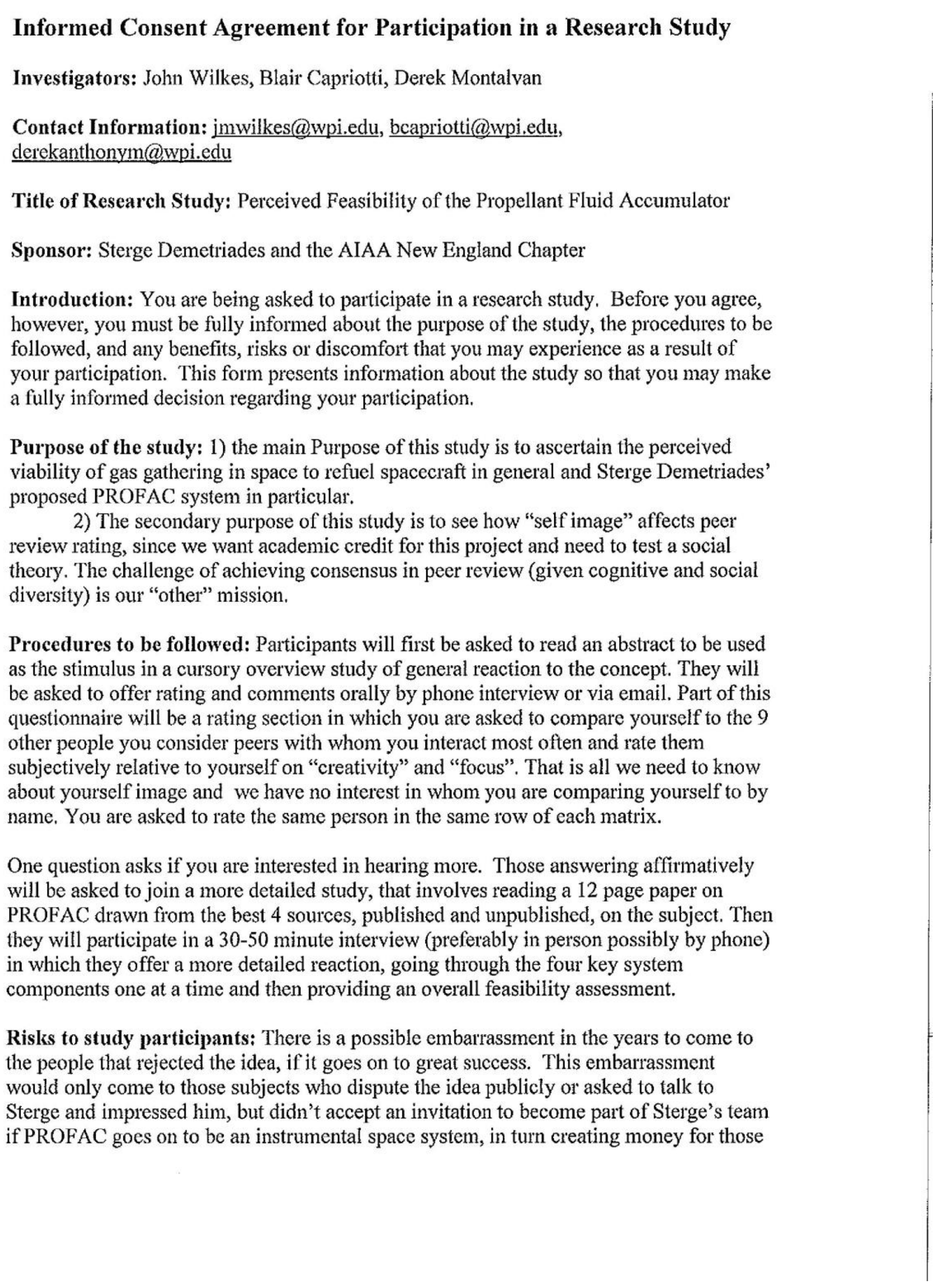
Continuing Work

- Collector Design
  - Inlet characterization: optimize geometry; estimate behavior in transition regime
  - Propulsion: model MHD and other propulsion systems as well as vehicle flowthrough paths
  - Thermal Systems: analyze heating loads on inlet, liquefaction system, propulsion, aeroheating
- Extensibility
  - Applications for Moon, satellite refueling, orbital debris collection, etc.
  - Use for Mars-side collection for Earth return vehicle

Summary

- Performance requirements for PHARO analyzed over a range of potential parameters for a nominal mission
- Two candidate inlet geometries compared
- Notable trends include:
  - Increasing storage fraction increases Isp requirement while lowering thrust requirement
  - Increasing number of collectors reduces thrust requirement, but diminishing returns

Appendix D



Informed Consent Agreement for Participation in a Research Study

Investigators: John Wilkes, Blair Capriotti, Derek Montalvan

Contact Information: jmwilkes@wpi.edu, bcapriotti@wpi.edu, derekanthonym@wpi.edu

Title of Research Study: Perceived Feasibility of the Propellant Fluid Accumulator

Sponsor: Sterge Demetriades and the AIAA New England Chapter

Introduction: You are being asked to participate in a research study. Before you agree, however, you must be fully informed about the purpose of the study, the procedures to be followed, and any benefits, risks or discomfort that you may experience as a result of your participation. This form presents information about the study so that you may make a fully informed decision regarding your participation.

Purpose of the study: 1) the main Purpose of this study is to ascertain the perceived viability of gas gathering in space to refuel spaccraft in general and Sterge Demetriades' proposed PROFAC system in particular.

2) The secondary purpose of this study is to see how "self image" affects peer review rating, since we want academic credit for this project and need to test a social theory. The challenge of achieving consensus in peer review (given cognitive and social diversity) is our "other" mission.

Procedures to be followed: Participants will first be asked to read an abstract to be used as the stimulus in a cursory overview study of general reaction to the concept. They will be asked to offer rating and comments orally by phone interview or via email. Part of this questionnaire will be a rating section in which you are asked to compare yourself to the 9 other people you consider peers with whom you interact most often and rate them subjectively relative to yourself on "creativity" and "focus". That is all we need to know about yourself image and we have no interest in whom you are comparing yourself to by name. You are asked to rate the same person in the same row of each matrix.

One question asks if you are interested in hearing more. Those answering affirmatively will be asked to join a more detailed study, that involves reading a 12 page paper on PROFAC drawn from the best 4 sources, published and unpublished, on the subject. Then they will participate in a 30-50 minute interview (preferably in person possibly by phone) in which they offer a more detailed reaction, going through the four key system components one at a time and then providing an overall feasibility assessment.

Risks to study participants: There is a possible embarrassment in the years to come to the people that rejected the idea, if it goes on to great success. This embarrassment would only come to those subjects who dispute the idea publicly or asked to talk to Sterge and impressed him, but didn't accept an invitation to become part of Sterge's team if PROFAC goes on to be an instrumental space system, in turn creating money for those working on making it operational. This would be a technological "fish that got away" story. The risk is not serious and public embarrassment would not be caused by the study but only if one goes on to be a public figure in the debate by choice,.

Benefits to research participants and others: As PROFAC was lost to the open literature for close to 60 years, it is only an idea on paper right now. But if it was able to be built and put into use, it could revolutionize the space industry, cutting cost of space travel and opening multiple doors to further exploration and space colonization. Because PROFAC has chance to change the economics of space travel, it has the potential to generate a lot of money.

Subjects that interview and are interested in the idea and would like to see it moved on to the next step of creation may be offered to join a special team Sterge Demtriades is forming. If this team is able to move PROFAC into later stages of creation and end up putting it into implementation in future years, there is a big potential payoff for those subjects. Subjects that just interview and give us their feedback would not receive any benefits from our study. There is only a small possibility to those that would accept being part of a team to help bring the PROFAC idea to fruition, and earn rewards through the actual accomplishment of turning the idea into a reality.

Record keeping and confidentiality: Paper forms, computer files and audio tapes will be left with our advisor professor Wilkes. John Wilkes will have full access and Sterge Demetriades will have partial and controlled access to those records. Information from an individual the study will only be reported to Sterge Demetriades at the request of the respondent. He will have access to the distribution of responses. Records of your participation in this study will be held confidential so far as permitted by law. However, the study investigators, the sponsor or it's designee and, under certain circumstances, the Worcester Polytechnic Institute Institutional Review Board (WPI IRB) will be able to inspect and have access to confidential data that identify you by name. Any publication or presentation of the data will not identify you.

Compensation or treatment in the event of injury: There is no expected injury. You do not give up any of your legal rights by signing this statement.

For more information about this research or about the rights of research participants, or in case of research-related injury, contact: John Wilkes, Email: jmwilkes@wpi.edu, Blair Capriotti, Email: bcapriotti@wpi.edu, Derek Montalvan, Email: derekanthonym@wpi.edu, IRB Chair (Professor Kent Rissmiller, Tel. 508-831-5019, Email: kjr@wpi.edu) and the University Compliance Officer (Michael J. Curley, Tel. 508-831-6919, Email: mjcurley@wpi.edu).

Your participation in this research is voluntary. Your refusal to participate will not result in any penalty to you or any loss of benefits to which you may otherwise be entitled. You may decide to stop participating in the research at any time without penalty or loss of other benefits. The project investigators retain the right to cancel or postpone the experimental procedures at any time they see fit.

By signing below, you acknowledge that you have been informed about and consent to be a participant in the study described above. Make sure that your questions are answered to your satisfaction before signing. You are entitled to retain a copy of this consent agreement.

Study Participant Signature

Date: ____________________

Approved by WPI IRB
From: 4/18/2012
To: 4/17/2013

Study Participant Name (Please print)

Signature of Person who explained this study

Date: ____________________

Appendix E

Transforming the Economics of Space: The PROFAC Plan

By Demetriades, Wilkes, Montalvan, Capriotti and Peake

What is the Propulsive Fluid Accumulator or PROFAC? Sterge Demetriades proposed the device in the open literature for the first time in the Journal of the British Interplanetary Society (JBIS, Jan 1959). In its most straightforward and immediate application in LEO (he envisioned other versions designed for the moon, other planets and space) he describes it as follows. "It is a device that orbits at an altitude of roughly 110 km, collects atmospheric gases, stores the oxygen to refuel devices for high-thrust space missions, thus eliminating the need to lift oxidizer to orbit, while using the nitrogen in an Electromagnetic thruster (powered by solar cells, nuclear power or other means) to overcome drag and maintain orbit and/or use for propulsion in space where higher specific impulse is required." He envisaged order of magnitude reductions of takeoff weight and other large advantages for space travel. For instance, according to calculations made in one of the original articles, to land a one-pound payload mass on the Moon with a multistage chemical rocket requires approximately 3000 lb of takeoff mass (assuming no return to orbit around the earth)...The PROFAC scheme, on the other hand, would require only 300 lb of takeoff mass per pound of payload for the entire trip to the Moon and back." If the system were left in orbit, "subsequent trips to the Moon and back would require only 150 lb of takeoff mass". Clearly this capability would transform the economics of space, but Sterge estimates that this capability, 20-25 years away when he proposed it, remains 10-20 years away today.

A similar idea, actually a derivative of PROFAC, recently surfaced as PHARO (Propellant Harvesting of Atmospheric Resources in Orbit), an entry in the NASA and NIA sponsored 2010 RASC-AL Forum Graduate Student Design Contest. The PHARO team, from Georgia Tech in collaboration with the University of Virginia and advised by Dr. Alan Wilhite placed second in that contest. Key members of the student team including team leader Christopher Jones and the adviser Alan Wilhite of Georgia Tech (and others) later published an article which further details the concept and acknowledged the intellectual lineage back to PROFAC, essentially putting it back on the table.

It is not clear that PHARO is a more sophisticated system or concept than PROFAC but it has a dramatically different power source. While Demetriades knew there were different ways to power the system, he preferred a nuclear reactor whereas PHARO is designed to use solar power. Hence, the associated infrastructure for the two gas gathering and refueling systems is quite different.

Significant progress has been made in developing the components that make up a Propulsive Fluid Accumulator (PROFAC) system in the last few decades. In particular, more capable and durable electromagnetic thrusters and much more efficient solar cells are available today than were available when the concept was first presented in the open literature of the early 1960’s. Further, the time has come to start considering the case for space infrastructure investments that will pay off over time given the growing level of space activity. In that sense, the time has finally come to reexamine the feasibility case for PROFAC while the original inventor is available.

[Controversial section on a ten-year plan to produce PROFAC removed at the request of Sterge Demetriades. Those interested can contact him directly.]

Concurrently with this (at least) ten year technical feasibility development project envisioned by Demetriades and Wilkes (and proposed to NIAC in 2011), Capriotti and Montalvan propose that the next generation get used to the idea and explore its implications. They propose another student contest be sponsored by the AIAA to let undergraduates in aerospace start brainstorming the range of possible applications PROFAC could have. They should assume this capability and build on it to design missions and infrastructure additions for 2023 and beyond that in combination would transform the economics of space in a decade. The goal is the reintroduction of PROFAC into current aerospace literature, so that the next generation of aerospace workers has heard of the idea of gas gathering in LEO, some of those in mid career then will then have looked into the idea thoroughly and started to design around the idea of fuel depots in space. The proposed student contest would ask the contestants to plan a mission that is only feasible, possible or only becomes economical enough to do assuming the existence of a PROFAC system or another system that transforms the economics of space and results in cost effective refueling in LEO. Technical experts in the field would be on the panel of judges and hopefully Demetriades himself will review the finalists and select the winner personally. The contest would show the advantages of PROFAC and the limitations the field faces without it, in hopes that people in the field can see just how important successfully developing this technology would be.

Appendix F

Will PROFAC and PHARO Transform Space Economics and Mission Design?

By Derek Montalvan, Brian Capriotti and Natasha Peake of WPI

Space travel beyond earth orbit, due to the current necessity for lifting far more fuel mass than payload, is exponentially expensive. Orbiting fuel depots are a viable solution, but refilling them would require either bringing resources up from Earth's surface or acquiring them in space. If the need for lifting resources from Earth could be reduced or eliminated without the requiring a massive extraction and delivery infrastructure on the moon or an asteroid, the result would be a breakthrough. It would transform the economics of space activity and have massive implications for both spacecraft and mission design.

At least two technical proposals exist in the current literature that focus on the gathering of gas resources in low earth orbit (LEO). The first, by at least 50 years, is PROFAC, invented by Sterge Demetriades (published in 1959), but this idea somehow dropped out of sight for a generation. It wasn't until an independent reinvention of a gas gathering system known as PHARO (by a team led by Alan Wilhite) was entered into a RASCAL contest and awarded second place that this idea was reintroduced. Both PROFAC (in its most straightforward and immediate application in LEO) and PHARO require the collection of atmospheric gases in order to overcome drag to maintain orbit and fuel high impulse and chemical rockets. Demetriades (JBIS, 1959) describes PROFAC as follows, "It is a device that orbits at an altitude of roughly 110 km, collects atmospheric gases, stores the oxygen to refuel devices for high-thrust space missions, thus eliminating the need to lift oxidizer to orbit, while using the nitrogen in an Electromagnetic thruster (powered by solar cells, nuclear power or other means) to overcome drag and maintain orbit and/or use for propulsion in space where higher specific impulse is required." He envisaged order of magnitude reductions of takeoff weight and other large advantages for space travel.

We will contend that the field is finally ready for this technology. PROFAC/PHARO is now in the open literature and Wilhite claims that he was prompted to look into the concept by NASA's Chief Technologist. While the majority position in the field is still that in-situ resource utilization in LEO is impossible, clearly that view is breaking down or at least being questioned in some important places. Significant progress has been made in developing the components that would make up such a gas-gathering system in the last few decades, which could lead to its realization faster than expected. Demetriades himself estimated it at 10-20 years from the start of a well-funded technology development program, about mid career for our generation.

Additionally, we would like to get aerospace professionals of our generation thinking about this technical capability and designing accordingly. Thus, we propose a student contest assuming the existence of a PROFAC-like device. Contestants would be asked to plan a mission that is only possible or economically feasible given PROFAC as infrastructure. This would highlight the advantages of the system and limitations the field faces without it. By exploring what could be achieved in space after this breakthrough, the case for developing it is made.