# PHARO—Propellant Harvesting of Atmospheric Resources in Orbit

Christopher Jones
Georgia Institute of Technology
National Institute of Aerospace
100 Exploration Way
Hampton, VA 23666
757-325-6881
Christopher.jones@nianet.org

David Masse
Georgia Institute of Technology
National Institute of Aerospace
100 Exploration Way
Hampton, VA 23666
757-325-6815
David.masse@nianet.org

Christopher Glass
NASA Langley Research Center,
Hampton, VA, 23681-2199
757-864-1350
C.E.Glass@nasa.gov

Alan Wilhite
Georgia Institute of Technology
National Institute of Aerospace
100 Exploration Way
Hampton, VA 23666
757-325-6810
Alan.wilhite@nianet.org

Mitchell Walker
Georgia Institute of Technology
270 Ferst Drive
Atlanta, GA 30322-0150
404-385-2757
Mitchell.walker@aerospace.gatech.edu

*Abstract*—Collection and storage of propellant on-orbit has the potential to dramatically reduce launch mass for future exploration missions.[1 2] A proposed method for this collection utilizes an orbiting vehicle that collects ambient air at a high altitude and uses a fraction of the air for orbital maintenance while storing the remainder for exploration propellant. The derivation of the relations governing propulsion requirements of thrust and specific impulse is presented. Initial requirements for the collector are defined through design maps based on a notional Mars mission.

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## 1. INTRODUCTION

The major impediment to space exploration is delivery of the in-space transportation system with its propellant and payload from Earth to orbit. Because propellant is approximately 80 percent of the mass delivered to orbit, utilization of propellant from orbital atmospheric collection has great potential for reducing the mass and cost of Earth-to-Orbit launch systems.

In 1959, Sterge Demetriades of Northrop published a paper on his propulsive fluid accumulator (PROFAC) [1]. This system consisted of three major elements: the accumulator (or PROFAC) itself, which collected air and liquefied it; the orbital vehicle, which maintained the orbit of the PROFAC

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using a nuclear-powered magneto-gasdynamic (MGD) propulsion system driven by a similar air collection system; and a space vehicle, which would receive the collected liquid air and use it for on-board propulsion for other missions (e.g. Lunar mission).

However, because of the stigma associated with orbiting nuclear reactors, other concepts with safer propulsion approaches have been studied, such as electric propulsion concepts powered by beamed solar energy, solar or magnetic sails, or on-board solar power systems [2].

The present study's goal is to derive the requirements of an orbiting propellant collector to support one of NASA's future missions such as human Mars exploration [3]. This mission will serve to establish the requirements for an atmosphere collector and the associated enabling advanced technologies for the purposes of this paper.

The present concept uses an orbiting atmosphere collection vehicle (ACV) to acquire orbital altitude atmospheric species from the upper atmosphere, liquefy it, and store it at an orbiting propellant depot. To counter the drag of capturing the air with the ACV, a unique high-power propulsion system is required because the collected gas, on its own, is a non-combustible propellant.

Several key variables are relevant to the consideration of this system. Both the drag experienced by the vehicle and the amount of mass that can be collected are dependent on the density of the atmosphere. This, in turn, is related to the altitude at which the ACV operates. The choice of a particular altitude (for a circular orbit) or altitudes (for an elliptical orbit) depends on the capabilities of the ACV's propulsion system, and the required collected mass.

Another key parameter is the drag profile of the vehicle, related to the coefficient of drag. At relevant altitudes and velocities, hypersonic aerodynamics are required, with consideration of both continuum and free molecular flow analyses. The geometry of the collecting inlet drives the value of drag, as it is envisioned that the rest of the vehicle would be "hidden" behind the inlet, and thus experience only minimal additional drag.

For the proposed concept, the collected gases could be used directly as propellant for the collector; it is envisioned they could also be used for the exploration trans-Earth transportation vehicles depending on engine power requirements and resulting thrust and specific impulse. Another alternative is to separate two different fluids derived from the incoming stream – nitrogen and oxygen. The nitrogen could be used for the collector propellant and the oxygen could be used as the oxidizer in a conventional high-thrust cryogenic rocket engine. Thus, the proportion of the atmosphere that is used for propulsion is dependent of the required thrust to overcome drag, specific impulse to minimize propellant mass consumption, and the mass of the propulsion systems for both the collector and the trans-Earth transportation systems.

Additional considerations for the ACV include the electrical power system used by the propulsion system, cooling hardware, and other on-board systems; the hardware that provides for compression, liquefaction, separation, and storage of the oxygen; and the design of the depot and collector-depot interface. This paper focuses only on the general performance requirements as well as consideration of initial inlet designs; future work will develop these other systems in detail, as well as forming a complete conceptual design of the proposed architecture.

## 2. CONCEPT OF OPERATIONS

One possible concept of operations, shown in Figure 1, is 1) orbit the collector at an optimum circular orbit, 2) liquefy and separate the gases for storage into propellant tanks, 3) continue collection using a fraction of the collected propellant energized with beamed power until the collector storage tanks are full, 4) reboost collector to a stable orbit to offload the collected propellant into an orbital propellant storage depot, 5) continue operation until the propellant depot tanks are full and 6) transfer propellant to the space exploration transportation system.

Prior to the deployment of the collection vehicle (ACV) and depot, orbiting power assets (as required) would be launched using currently available vehicles. The ACV would then be launched into orbit around the Earth by any of several potential launch vehicles (Titan IV, Falcon 9, Ares V), depending on its final size and configuration. If necessary, more than one collector can be deployed to have a size compatible with the launch vehicle shroud..

Atmospheric density at high altitudes is low (on the order of $10^{-7}$ kg/m$^2$ at 100 km). At these densities, continuum fluid assumptions are no longer entirely valid, and a proper analysis of the behavior of the upper atmosphere requires consideration of free molecular flow aerodynamics.

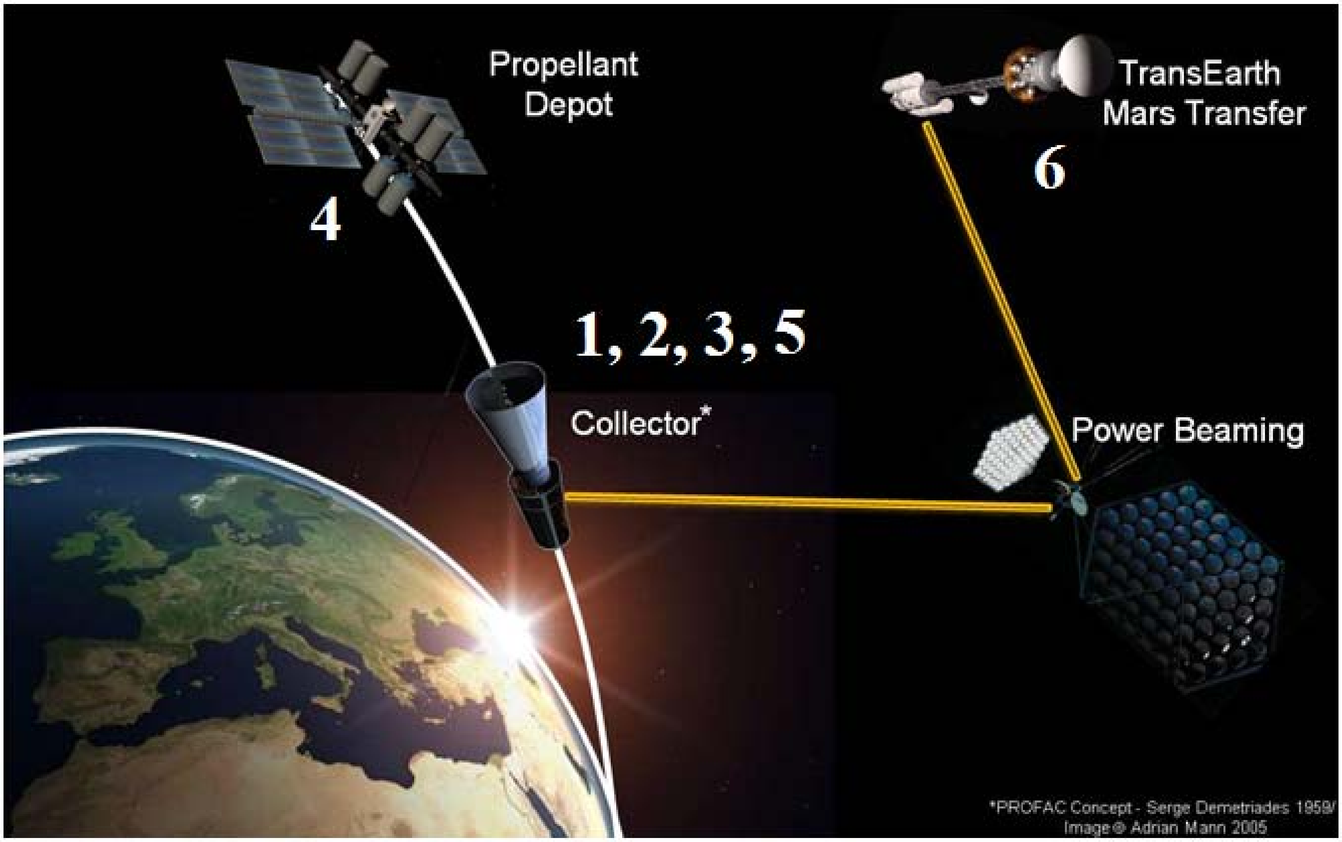


**Figure 1-- PHARO Concept of Operations**

Ambient atmospheric air is ingested by the inlet, where it is compressed into a continuum gas. After the inlet, the flow will be further compressed and slowed by passing through a supersonic diffuser. This will serve to bring the flow into the continuum regime. This conditioned flow can then proceed to the liquefaction and storage phase. Depending on the particular concept (direct air use or separation into oxygen and nitrogen), the flow would be separated either before or after the cooling stage.

For cooling and liquefaction of either stream, an ultra-compact heat exchanger, such as is described by Sebens et al. [4] could be used to cool and liquefy the fluid. Such a heat exchanger, based on initial analysis, should have a volume of significantly less than 1 $m^3$, and with a mass on the order of tens of kilograms based on the mass flow rate established later in the paper. Additional hardware for eliminating the heat in the refrigerant is estimated by the method in Larson and Pranke [5] to be no more than a thousand kilograms (dominated by the radiators), and requiring only a few cubic meters of volume.

This would then lead to either a supply of liquid air, or a two-phase mixture, dominated by liquid oxygen and gaseous nitrogen. The liquefied fluid would then be pumped into a storage tank for eventual transfer to the depot. The bypass gas or nitrogen, meanwhile, would be fed into the propulsion system.

When the collector's storage tank is full, the ACV transfers to the orbit of the depot. There, it docks with the depot and transfers the liquid propellant to the depot's onboard storage tanks. The ACV then returns to its collection orbit to resume operations.

## 3. Performance Requirements

To define the performance requirements for the ACV, the collection mission requirements need to be defined: $m_{total}$, the total mass to collect, and $t_{total}$, the total time available to collect it. This leads to the required storage rate

$$\dot{m}_{storage} = \frac{m_{total}}{t_{total}} \quad (1)$$

Of the total mass collected by the ACV, some fraction ε will be stored, leading to the term above, while the rest will be used for the propulsion system. Thus, the overall incoming mass collection rate $\dot{m}_{overall}$ can be defined as

$$\dot{m}_{overall} = \frac{\dot{m}_{storage}}{\varepsilon} \quad (2)$$

The overall mass collection rate is related to the atmospheric density ρ, inlet area $A$ (the upper limit of which is fixed by available launch vehicles), and vehicle velocity $V$ by the definition of mass flow rate:

$$\rho = \frac{\dot{m}_{overall}}{\alpha AV} \quad (3)$$

where α is an inlet efficiency factor, related to the amount of mass actually collected compared to the integrated incident mass in the envelope defined by the inlet. In all of the analysis presented below, α was set at 1 for consideration of the ideal case wherein all theoretical mass is captured within the inlet; work is ongoing to estimate the actual value of α for various nozzle geometries.

Determination of the required altitude is thus dependent on density, inlet area, and incident velocity. The velocity depends on the altitude; thus, a recursive scheme is required to converge on the altitude. From atmospheric tables [6], a correlation between altitude (in km) and density (in $kg/m^3$) can be empirically approximated as:

$$h = -7.489 \ln \rho - 7.540 \quad (4)$$

This in turn is used to compute the circular orbital velocity, which feeds back into Eq. 3, leading to a converged solution for the altitude and density.

In a circular orbit, with no thrust vectoring, the thrust force required to sustain the orbit is balanced by the drag force experienced by the spacecraft. For the collector, this drag consists of two major elements: the aerodynamic drag due to the geometry of the vehicle (specifically the inlet, given the assumption that the rest of the vehicle is shielded by the inlet), and the ram drag caused by the requirement of stopping the air that is being collected. Setting these terms equal to the thrust required yields

$$T_{required} = \frac{1}{2}\rho AV^2 C_{D,geom} + \alpha\rho AV^2 \quad (5)$$

where $C_{D,geom}$ is the drag coefficient due to the geometry of the inlet. Thus, from the geometry of the vehicle ($C_{D,geom}$, α, and $A$) and the mission requirements (giving ρ and $V$), the thrust requirement for the propulsion system is determined.

Determination of the required specific impulse (Isp) is based on the mass flow rate out. This is simply

$$\dot{m}_{out} = \dot{m}_{overall} * (1 - \varepsilon) \quad (6)$$

The definition of Isp can be rearranged to give

$$T_{required} = \dot{m}_{out} g_0 Isp_{required} \quad (7)$$

with $g_0$ the Earth surface gravitational acceleration.

Combining equations 3, 5, 6, and 7 yields

$$Isp_{required} = \frac{\left(1 + \frac{C_{D,geom}}{2\alpha}\right)V}{g_0(1 - \varepsilon)} \quad (8)$$

Thus, from the same geometry and mission parameters, the Isp requirements are determined.

From equations 4 and 8, then, the performance requirements that guide analysis and selection of a propulsion system are determined. Trade study results based on a notional mission supporting a Mars cargo transfer vehicle will be presented below, along with a discussion of possible propulsion options.

The above discussion pertains to circular orbits. For elliptical orbits, only a short portion of the time is spent in the low part of the orbit, where collection is viable. As such, the periapsis altitude must be lower than a circular altitude for the same mission, increasing the drag and thus propulsion system requirements.

## 4. INLET ANALYSIS

*PROFAC-Derived Design*

One candidate inlet design is based on the concept described by Demetriades [7]. In this design, shown in Figure 2, the truncated cone geometry can be described by three parameters: the inlet diameter $d_i$, the outlet diameter $d_o$, and the length $l$. These values guide the determination of $C_{D,geom}$ for the inlet; this value is then assumed to hold for the entire vehicle, as the rest of the spacecraft is assumed to be within the area of the inlet. This permits the reference area for the above drag calculations to be equal to the inlet area.

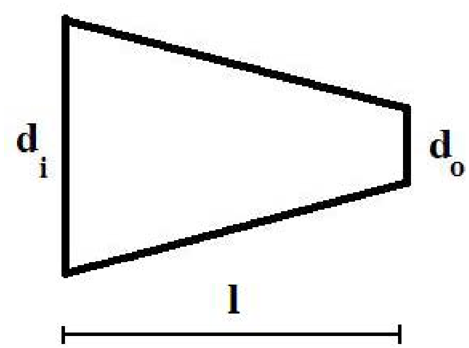


**Figure 2--Notional view of PROFAC-derived inlet**

Direct Simulation Monte Carlo (DSMC), as described in [8], was used for inlet analysis. A notional inlet was defined, with $d_i$ = 5m, $d_o$ = 1.36m, and $l$ = 5m. This inlet analysis was run for an altitude of 100 km, with a velocity of 8 km/s. The atmosphere [6] was assumed to contain the following species in number density ($\#/m^3$): O (3.995E+11), $O_2$ (2.025E+12), N (2.020E+5), and $N_2$ (8.467E+12).

A second geometry considered used a dual cone compressor introduced in the above inlet. This was done to facilitate increased compression, and also to study the effect on total drag. The relevant geometry is shown in Figure 3.

The two geometries were compared using DSMC. Drag forces were computed based on the results. Additionally, the DSMC analysis shows the compression performance of the two geometries. These results are presented in the following section of the paper.

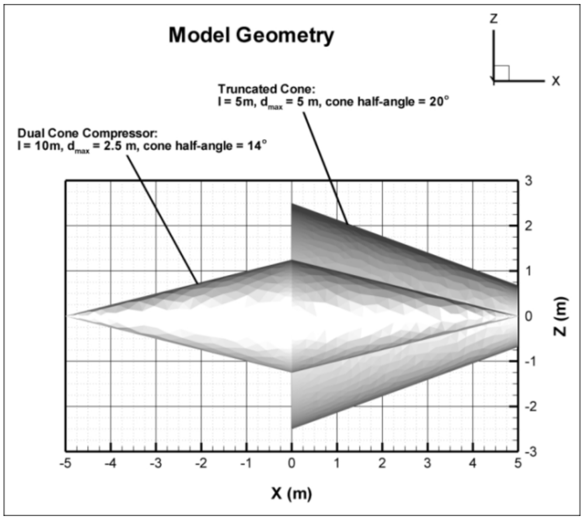


**Figure 3--Inlet geometry with dual cone compressor.**

## 5. Results and Discussion

*Inlet*

The DSMC analysis generated plots of air density around and within the inlet. Figures for the truncated cone and truncated cone with an external diffuser are shown below.

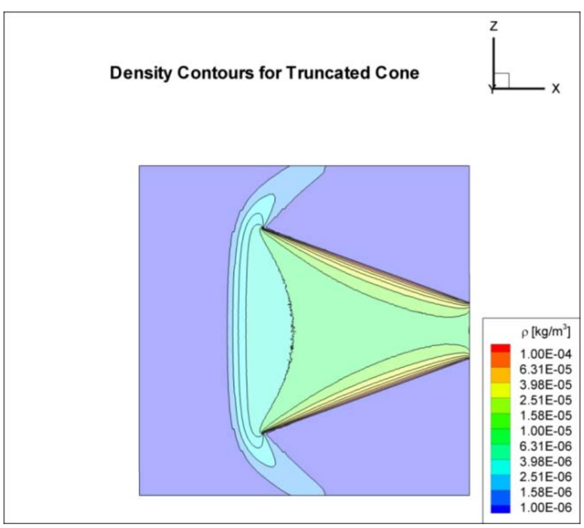


**Figure 4--Density contours for truncated cone.**

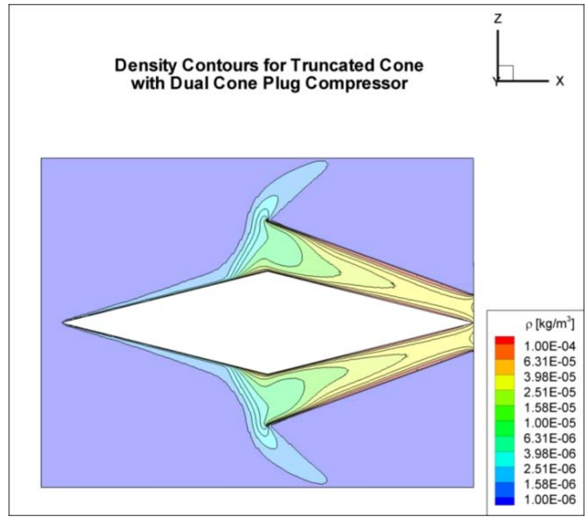


**Figure 5--Density contours for truncated cone with compressor.**

By comparing the densities observed at the smaller end of the inlet, it is seen that introduction of the diffuser increases the compression by a factor of 3. Figure 4 shows that the truncated cone has densities above $10^{-5}$ kg/m$^3$ only in close proximity to the wall, while Figure 5 shows that such densities occur throughout much of the interior region of the inlet. Thus, use of the diffuser facilitates the increase of the incoming flow density to the point that it can be handled as a conventional flow throughout the remainder of the system.

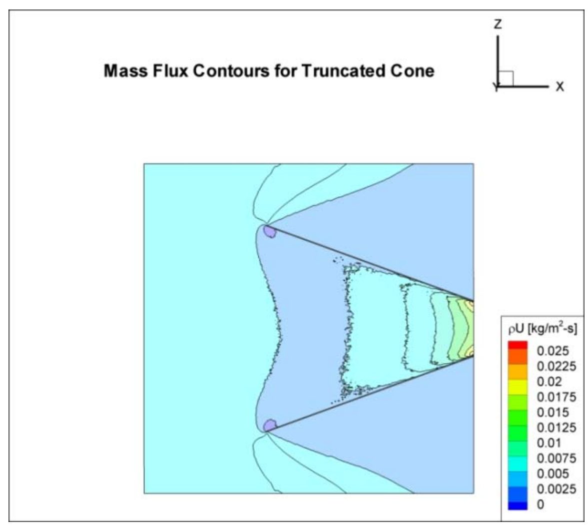


**Figure 6--Mass flux contours for truncated cone.**

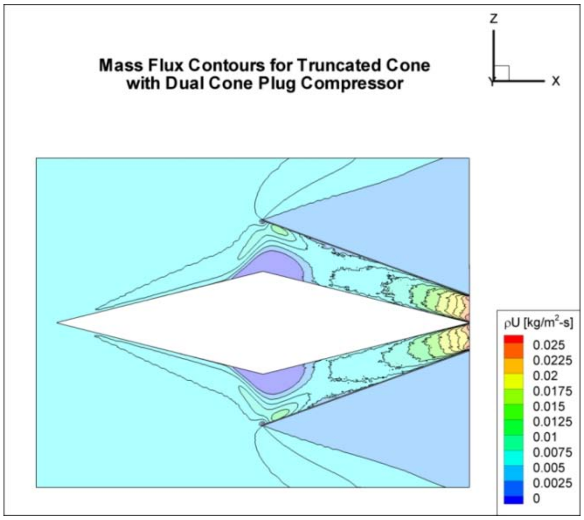


**Figure 7--Mass flux contours for truncated cone with compressor.**

As would be expected, the mass flux also is improved with the introduction of the diffuser. Figure 6 shows the flux contours for the truncated cone, which are mostly limited below 0.02 kg/m$^2$-s. By comparison, that value is reached by the full interior of the inlet with diffuser after a certain area reduction, as shown in Figure 7.

The DSMC analysis gave drag forces of 547 N for the truncated cone geometry, and 552 N for the truncated cone with compressor geometry. At 100 km, a density of 5.15e-7, and an area of 19.6 m$^2$, the resulting inlet drag coefficient, $C_{D,\ geom}$ is approximately 1.7 for both geometries. Hence, use of the diffuser did not significantly affect drag, but did improve compression of the flow.

Future work will optimize the design of the nozzle by varying the geometry, as well as examining the effects at varying altitudes. Additionally, other inlet geometries will be considered, such as those used for other hypersonic air-breathing vehicle designs. It is expected that other geometries may serve to reduce $C_{D,geom}$ while still achieving satisfactory levels of compression

*Performance*

The performance analysis was applied to the design of a ACV for support of a Mars mission. The mission architecture was based on the latest NASA architecture [3]. The ACV was designed to support fueling a single cargo transfer vehicle's demand of 300 MT of propellant (oxygen) in the span of 1 year. The maximum area of the inlet was constrained to fit within the payload shroud of an Atlas V rocket, giving an area of 19.6 m$^2$ [9].

To study the performance requirements, the drag coefficient $C_{D,geom}$ was varied from 0.3 to 1.8 and the collection fraction ε was varied from 0.04 to 0.64. Based on these two parameters, along with the mission requirements given above, thrust and Isp demand data were generated.

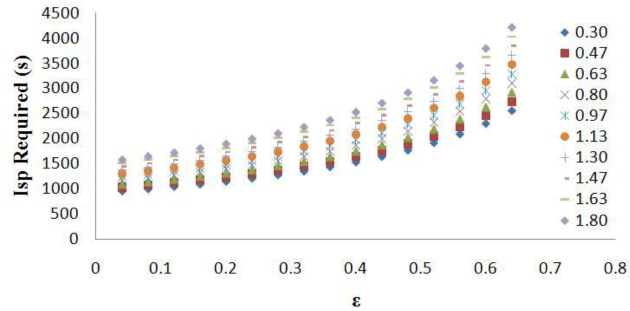


**Figure 8--Isp required as a function of ε (x-axis) and $C_{D,geom.}$ (markers). Isp requirements increase as ε increases.**

Figure 8 shows the general increase in Isp required as collection fraction and drag increase. This is consistent with expectations, as the greater the drag force to be overcome, the higher performance will be required. Likewise, storing more of the incoming fluid requires a greater specific impulse for the remainder of the flow.

For this mission, even the most optimistic conditions with respect to performance (minimum drag and low storage fraction) require more than 950 seconds of Isp. With increasing storage percentage, and more realistic drag coefficients, Isp requirements approach 1500 seconds.

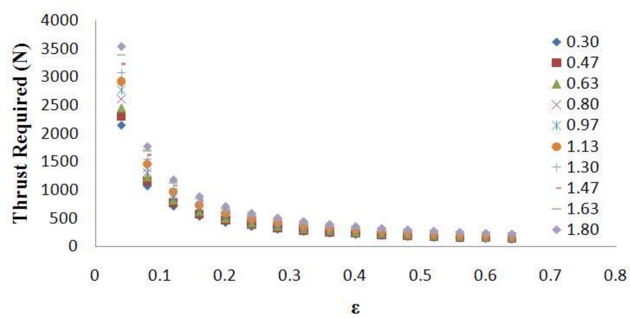


**Figure 9--Thrust required as a function of ε (x-axis) and $C_{D,geom.}$ (markers). Thrust requirements decrease as ε increases.**

Figure 9 shows the behavior of the thrust requirement. As expected, higher drag coefficients lead to an increase in the thrust requirement. However, increases in storage percentage drive a decrease in the required thrust. Although this result may appear counterintuitive, it follows from the above derivation. For a fixed value of $\dot{m}_{storage}$, as defined by the mission parameters, an increasing value of ε leads to a decrease in $\dot{m}_{overall}$. This in turn serves to lower the density requirement and increase the maximum allowable altitude. The net effect is a reduction in the drag terms that govern the thrust requirement.

Hence, a trade exists when selecting ε: low values lead to a high thrust requirement with low Isp demands, while high values reduce the thrust requirement and increase the Isp. For design purposes, the goal would be to minimize both requirements; however, there is a threshold to how low each of these values can be. This behavior is visible in Figure 10.

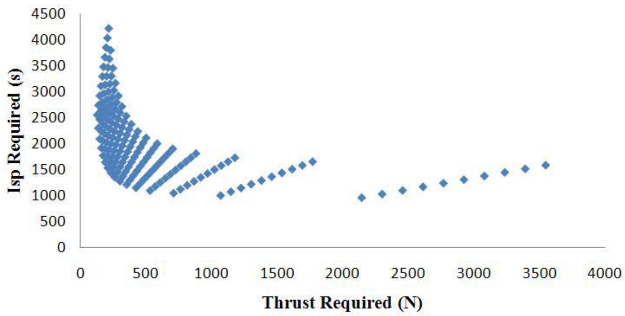


**Figure 10--Spread of Isp and thrust requirements for Mars mission. Minimum performance requirements cases are in the lower-left corner of the plot. The spread results from the range of $C_{D,geom}$ and ε values considered.**

Figure 10 shows a clear Pareto front that indicates the best possible scenarios (those with $C_{D,geom}$ = 0.3 and values of ε varying between 0.04 and 0.64). From the plot, it is evident that there is a minimum possible thrust that can accomplish the mission (approximately 134 N, with corresponding Isp of 2550 seconds). This appears to rule out most single-thruster electric propulsion options, as these are typically limited below 100 N, and in many cases are orders of magnitude less [10]. Multi-thruster clusters may help alleviate this problem, but have not yet been investigated sufficiently for the authors to pass judgment.

Various magnetohydrodynamic augmented propulsion concepts show some possibility of providing the necessary thrust and Isp to enable missions as described above [11]. These systems utilize a thermal first stage to increase the enthalpy of the flow. This hot flow is then ionized, using an injected seed, and passed through electric and magnetic flows to further increase the flow speed by the Lorentz force. The resulting system obtains some of the benefits of both thermal and electric propulsion.

One method to reduce the performance demands is to increase the number of collectors that are operating. By doing so, $m_{total}$ is effectively reduced, leading to reductions in the thrust required to perform the mission. Figure 11 illustrates the gains that can be achieved with multiple collectors assuming values of 1 for $C_{D,geom}$ and alpha.

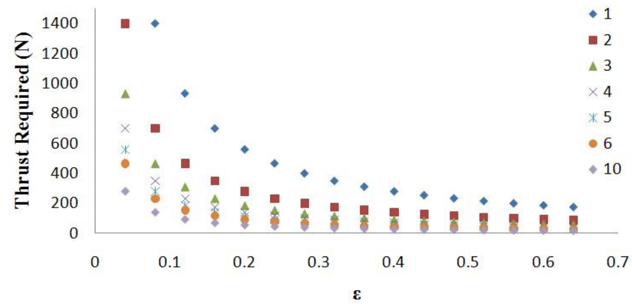


**Figure 11--Variation in thrust required for multiple collectors. Each set of markers represents a different number of collectors.**

Figure 11 shows that, especially for low values of ε, introduction of additional collectors dramatically reduces the thrust requirements of each of those collectors. Even at extremely high values of ε, significant thrust reductions can be realized through the use of multiple ACVs. Additionally, multiple collectors allows for redundancy in the overall architecture; a single failure need not represent a complete loss of mission.

The benefits of adding collectors exhibit diminishing returns; for example, there is little change in the required thrust in going from six collectors to ten. With six collectors, the best-case thrust requirement is 29 N, while with ten collectors, the best-case thrust requirement reduces to 17 N. Further, the additional cost and operational complexities of using multiple ACVs must be weighed against the reduction in performance requirements.

Variation of the number of collectors has no change on the Isp requirements for the ACV; for a given $C_{D,geom}$, that value is still dependent on ε, but is independent of the number of collectors.

## 6. CONCLUSIONS

An analysis has been performed of the design requirements for an atmospheric propellant collection vehicle. Minimum requirements for Isp and thrust were derived and related to geometrical parameters (inlet area, coefficient of drag) and altitude parameters (atmospheric density, orbital velocity). An examination of two potential inlet designs was performed using the DSMC method to determine possible values for $C_{D,geom}$ in the rarefied upper atmosphere. Performance requirements were calculated for a notional Mars mission based on a parametric sweep of values for $C_{D,geom}$ and storage fraction.

For the mission considered, a Pareto front emerged governing minimum values of Isp and thrust required for the collector. This front establishes that Isp needs to be greater than 1000 seconds, and that thrusts must be on the order of hundreds of Newtons. The thrust requirement can be reduced by use of multiple collectors, as this permits division of the amount of propellant that need be collected, thus raising the operational altitude. Required Isp, however, is independent of the number of collectors.

Future analysis includes consideration of other inlet geometries, in hopes of reducing $C_{D,geom}$. Additionally, modeling of other vehicle systems (propulsion, power, liquefaction and storage) is currently underway, the goal being to achieve a systems-level model of the entire vehicle.

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## BIOGRAPHY

***Christopher Jones*** *received his B.S. in Mechanical Engineering from the University of South Carolina in 2007, and his M.S. in Aerospace Engineering from the Georgia Institute of Technology in 2009. He is currently working on his doctoral dissertation at Georgia Tech, performing research in the requirements and design of an orbital propellant collection vehicle. His previous research has included studying the performance of in-situ resource utilization systems for the human Mars missions, as well as analysis of surface support infrastructure for Lunar human outposts.*

***David Masse*** *received his B.S. in Aerospace Engineering from the University of Texas at Arlington. Currently, he is working towards a M.S. in Aerospace Engineering from the Georgia Institute of Technology. His current research includes incorporating aerodynamic analysis into the conceptual design using parametric models and the Aerodynamic Preliminary Analysis System.*

***Christopher Glass*** *is a research aerospace engineer in the Aerothermodynamics Branch (AB) at the NASA Langley Research Center currently working on hypersonic re-entry flow interactions with reaction control thrusters for the Constellation program. He began his career at Langley as an experimentalist in the 8' High Temperature Tunnel in the Aerothermal Loads Branch (ALB) studying detailed flow phenomena that cause highly localized heating to support programs such as the NASP. Upon transferring to the AB, full vehicle experiments were performed in the Langley 20" Mach 6 air, 20" Mach 6* $CF_4$*, and 31" Mach 10 tunnels to support programs such as the X-33. When unable to further perform experiments, he became a computationalist studying rarefied flow with the Direct Simulation Monte Carlo (DSMC) technique and continuum flow with the Computational Fluid Dynamics (CFD) technique to support Earth and Mars missions. Dr. Glass graduated from Old Dominion University with a BSME and an MS and from The Pennsylvania State University with a PhD.*

***Alan Wilhite*** *is the Langley Distinguished Professor in the School of Aerospace Engineering at Georgia Tech and also serves as the co-Director of the Georgia Tech Center for Aerospace Systems Engineering (CASE). He currently resides at the National Institute of Aerospace in Hampton, Virginia teaching graduate classes and conducting research at NASA Langley Research Center. He teaches and supervises research in Systems Engineering and Aerospace Systems Design. He had numerous published articles and several book chapters in these areas. He has served as a researcher, systems program manager, and senior executive involved in the design and development of NASA space and aeronautic systems. He is an AIAA Associate Fellow and has served on several AIAA Technical Committees such as Space Systems, Space Transportation and Computer Aided Design. He is also a member of the International Astronautical Federation on the Systems Engineering committee. He conducts research in systems of systems architecture design, robust design, aerodynamics, propulsion, MDO, operations, cost, systems engineering, and risk. He has served as NASA's external chair for systems engineering and conducts research supporting NASA's vision in space exploration.*

***Mitchell Walker****'s primary research interests lie in electric propulsion, plasma physics, and hypersonic aerodynamics/plasma interaction. He has extensive design and testing experience with Hall thrusters and ion engines. He performed seminal work in Hall thruster clustering and vacuum chamber facility effects. His current research activities involve both theoretical and experimental work in advanced spacecraft propulsion systems, diagnostics, plasma physics, helicon plasma sources, magnetoplasmadynamic thrusters, and pulsed inductive thrusters. He also teaches the undergraduate Jet & Rocket Propulsion course, as well as the graduate level Rocket Propulsion and Electric Propulsion courses.*