Conceptual Architecture Planning for Manned Geo Satellite Servicing

Lex Gonzalez, Gary Coleman, Eric Haney, Amit Oza, Vincent Ricketts, Bernd Chudoba

Mechanical and Aerospace Engineering Department
University of Texas at Arlington

Paul Czsyz

Hypertech Concepts LLC

Abstract

In an effort to quantify the feasibility of candidate space architectures for manned geostationary (GEO) satellite servicing (MGS), NASA and DARPA have teamed up with the Aerospace Vehicle Design (AVD) Laboratory at the University of Texas Arlington (UTA) in order to provide a conceptual assessment of architecture/concept of operations/technology combinations. The primary challenge has been the exploration of past, present, and future in-space investments in the context of mission performance, mission complexity, and industrial capability. Consequently, this study necessitated the use of a simulation capability to assess and visualize the physical design drivers and sensitivities of the operational and technical domain.
The overall goal of the study has been the development of a system with the capability to transfer payload to and from GEO. To this end the following concepts of operations (ConOp) have been studied: direct insertion/reentry (ConOp 1), and launch to low earth orbit (LEO), at Kennedy Space Center (KSC) inclination angle, with an orbital transfer to/from GEO (ConOp 2). The technology elements traded varied between hardware for in-space maneuvers, aero-assisted maneuvers, and reentry vehicles.

This report introduces the AVD Laboratory's product development and technology forecasting methodology as applied to the problem introduced above. Because the focus of this activity has been on the exploration of the available solution space, a unique screening process has been employed to assess the implication of (a) the mission, (b) hardware/technology selection, and (c) the operational scenarios on key research objectives to be defined.
The study concludes that a Capsule + Descent Propulsion Module (DPM) system sized for the MGS mission is feasible for a direct insertion/reentry concept of operation. Vehicles sized for orbital transfer from LEO-KSC to GEO-0, and back to LEO-KSC (ConOp 2) show a total mass savings when utilizing Aero-assisted Orbital Transfer Vehicle (AOTV) DPM options compared to the pure propulsive baseline case. Overall, the selection between AOTV concepts and a

reusable/expendable Ascent Propulsion Module (APM) must come from considerations of their maintenance/durability and total cost of operation with an associated flight rate.

Nomenclature

OTV = orbital transfer vehicle

AOTV = aero-assisted orbital transfer vehicle

CTV = crew transfer vehicle

TPS = thermal protection system

UNW = unit weight

β = ballistic coefficient

C_D = drag coefficient

L/D = lift-to-drag ratio

GEO = geostationary earth orbit

LEO = low earth orbit

KSC = Kennedy Space Center inclination orbit

APM = ascent propulsion module

DPM = descent propulsion module

SBCM = space-based crew module

Introduction

The current study, manned GEO servicing (MGS), has been conducted as part of a joint research activity between NASA and DARPA in order to assess technology development and investment by both agencies. The goals of the MGS study are technology, concept, and architecture assessment/forecasting for manned servicing missions within the next 5 to 10 years.

The MGS research project is decomposed into five constituents; Team 1 - Hardware to GEO, Team 2 - Crew to and from GEO, Team 3 - Human Presence, Team 4 - Human/Robotics Synergy, and Core Team - Project Definition and Synthesis. As a member of Team 2, the Aerospace Vehicle Design Laboratory (AVD Lab) is responsible for the assessment of technology/vehicle requirements to transfer crew to and from GEO. This article summarizes the

AVD Lab systems-level solution space screening process and solution space screening for the variety of crew transfer and return vehicle concepts and technology for the two primary MGS concept of operations considered; (1) direct insertion and return from GEO, and (2) orbital transfer to and from GEO.

AVD Sizing Process

The AVD sizing process is a 'best-practice' methodology based on parametric sizing processes developed from a comprehensive review of commercial transport aircraft, hypersonic cruisers, expendable and reusable launch vehicles from 1936 to the present [1]. This process has been applied to transonic commercial transports, supersonic business jets, hypersonic cruisers, launch vehicles, re-entry vehicles and in-space elements. The generic process is shown in Figure 1 with highlighted modifications for in-space elements required for the current MGS study.

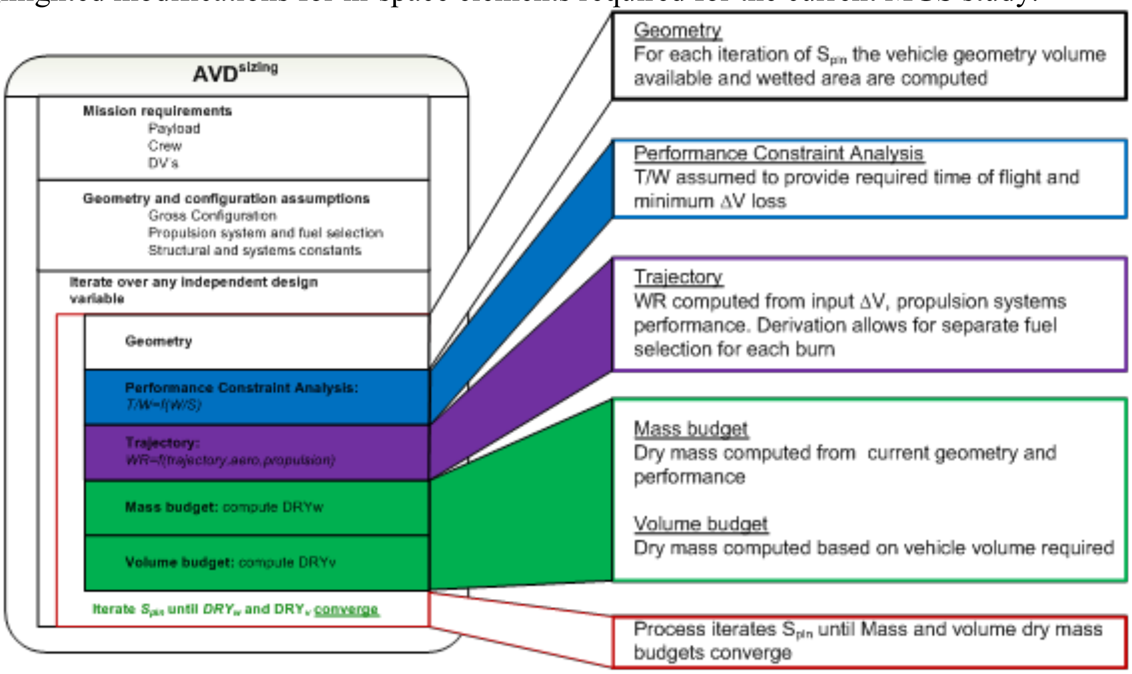


Figure 1. AVD parametric sizing process applied to in-space element sizing.

The sizing process is implemented in modular FORTRAN 77/90 source code consisting of 194+ subroutines linked with a dedicated database management system (DBS). Within the execution of one convergence cycle, a text file database is produced of all relevant vehicle parameters. If a module requires information which is not passed directly to the subroutine, it can access and rewrite the current vehicle database. This straight forward DBS system allows for easy integration of multi-platform and multi-language disciplinary methods.

The final piece of this process is the Aerospace Sizing Disciplinary Methods Library. This library consists of 70+ documented and implemented methods for geometry, aerodynamics, propulsion, mass and balance, performance, etc. This library serves as quick reference for each method's assumptions, application, and Input-Analysis-Output (I-A-O). This library is not a static document. The Methods Library is used to document experience with disciplinary methods, including accuracy, runtime, and additional applicability discovered. The result is a living document to communicate design and disciplinary experience that allows for correct usage of disciplinary analysis. Together, the generic convergence logic, modular implementation, and dedicated methods library allow for timely parametric sizing to address early design stage solution space screening and decision making.

Concept of Operations Descriptions

Team 2 explored two primary ConOps for MGS crew transportation to and from GEO. The minimum mass and complexity ConOp 1 consists of a crew capsule directly launched and returned from GEO is considered. The second is a reusable transfer system ConOp 2 utilizes a refuelable AOTV which transfers crew from LEO to GEO.

It is a focus of the current study to place all launch activities in the context of a production or near-production vehicle, notably the Delta IV class of rockets. This choice of launch vehicle constrains the diameter of all payloads launched to 5 m [13] and, along with the upper-stage propulsion module selected, defines the maximum payload insertion mass.

ConOp 1 - Direct Return Capsule Results

This ConOp is intended to be the minimum mass, minimum complexity mission. The upper stage of the launcher inserts the crew capsule + expendable descent module to GEO. After completion of the servicing mission, the descent module then transfers the crew to a direct reentry return. As such, this ConOp requires three in-space elements: (1) an expendable upper stage for insertion into GEO, (2) a crew capsule, and (3) an expendable de-orbit propulsion module (DPM). The study of ConOp 1 includes two primary components: (1) parametric capsule definition based on historical review, and (2) generic capsule and DPM sizing to the specific MGS mission.

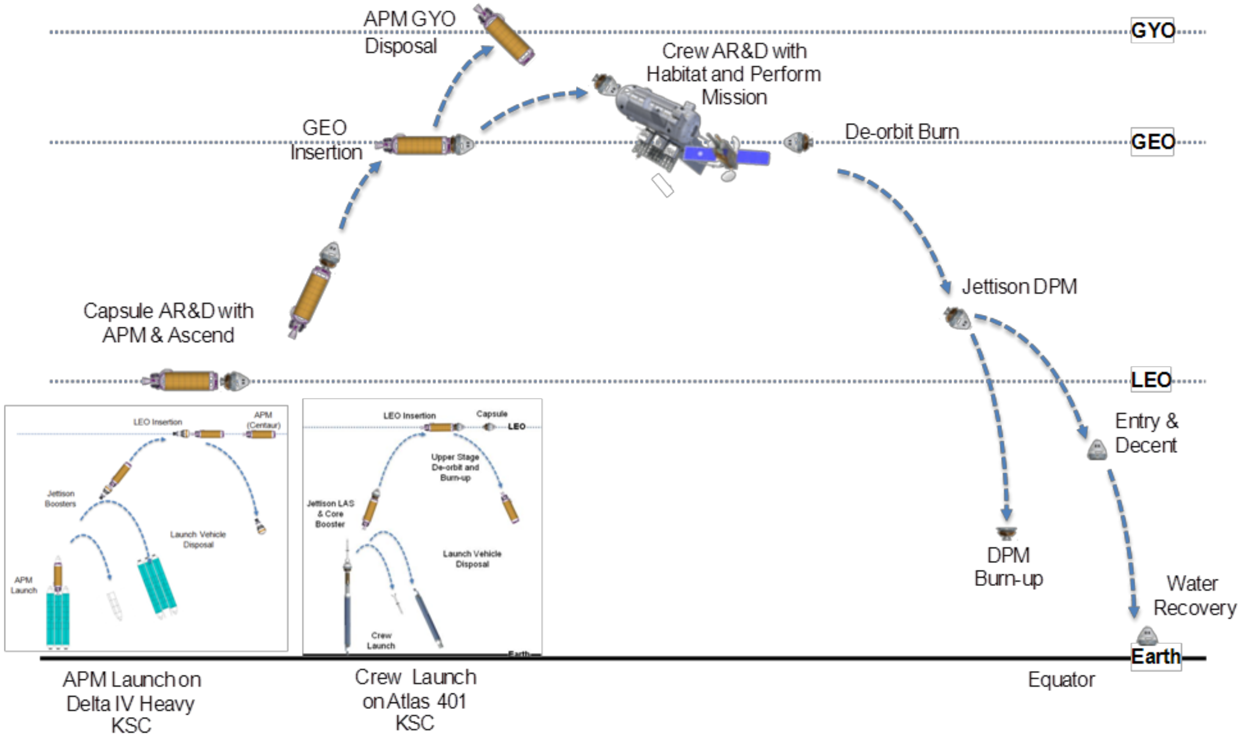


Figure 2. Direct insertion and return concept of operation. [3]

<u>ConOp 1 Trade-Study Ground Rules</u>

- Hypergolic fuels are utilized for commonality with other MGS elements. Early trade-studies demonstrate that methane does not provide a significant benefit for this ConOp.
- A volume of 2 m^3 per crew member with 4 days worth of provisions are provided (2 days up, 2 days down). The capsule volume is sized for a 2 consecutive day mission, rather than a 4 consecutive day mission.
- ILIDS docking mechanism assumed (211 kg).
- Attempt to keep CTV dry mass or inert mass under maximum Delta IV Heavy launch mass to LEO-KSC.
- Attempt to comply with Delta IV Heavy 5 m diameter faring.
- Attempt to keep peak heating and integrated heating loads under reusable TPS limits.

ConOp 2 - Aero-Assisted Orbital Transfer Vehicle LEO-KSC / GEO-0 / LEO-KSC

ConOp 2 explores the elements required for roundtrip transfer of crew from LEO (at KSC inclination) to GEO and back. It is assumed that an additional, standalone crew vehicle launches the crew from ground to LEO-KSC. This study is broken into two operational tracks: (1) an expendable Ascent Propulsion Module (APM) and (2) a reusable APM. Figure 3 represents an operational concept diagram for ConOp 2. It should be noted that a pure propulsive variant of ConOp 2 is included as the baseline for comparison with aerobraking concepts.

Expendable Ascent Propulsion Module

For this ConOp 2 branch, the expendable APM is launched, docked with the crew vehicle, and then transfers and inserts the crew vehicle to GEO before being discarded. The crew vehicle's integral DPM transfers the crew back to GTO, an aerobrake maneuver is accomplished with the AOTV structure, and a small LEO insertion burn is performed to return the crew to LEO (except in the pure propulsive case where propellant is utilized in place of the aeromanuever to complete LEO insertion). A commercial crew return vehicle is then required to dock with the AOTV for crew return to Earth.

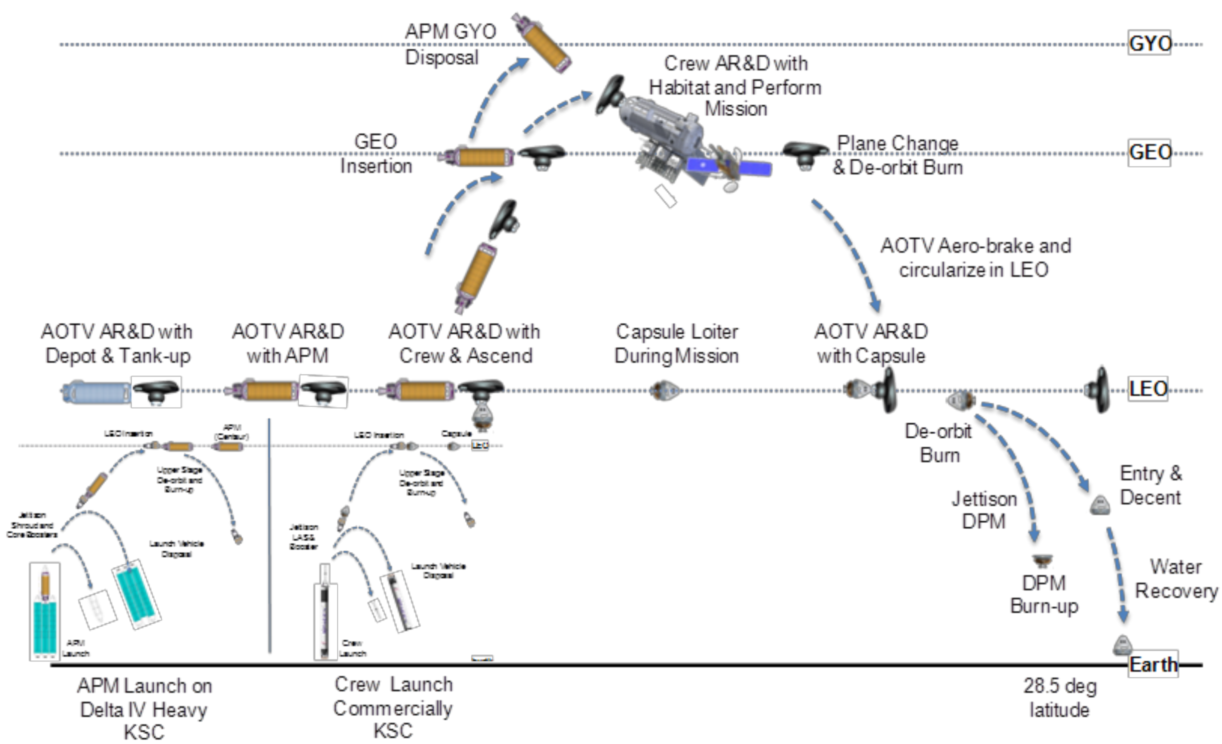


Figure 3. LEO insertion, orbital transfer to/from GEO, LEO return concept of operation. [3]

Reusable Ascent Propulsion Module

Hydrogen is utilized for the APM to reduce the fuel mass required to reach GTO. The DPM uses hydrogen for the GEO insertion burn (stored in drop tanks) and then uses methane for the de-orbit, plane change, and LEO circularization burns, requiring a dual-fuel LH2/CH4 Engine. The

APM will separate from the payload and DPM at GEO, autonomously perform an atmospheric pass to reduce orbital altitude, and re-circularize at LEO to be used for future missions.

ConOp 2 Trade-Study Ground Rules

- A volume of 2 m^3 per crew member with 4 days' worth of provisions is provided (2 days up, 2 days down). Early studies show that greater crew volume results in an excessive mass penalty. Thus, the capsule volume is sized for a 2 consecutive day mission, rather than the 4 consecutive day mission.
- ILIDS docking mechanism assumed (211 kg).
- Attempt to keep CTV dry or inert mass under maximum Delta IV Heavy launch mass to LEO-KSC.
- Attempt to comply with Delta IV Heavy 5 m diameter faring.
- Attempt to keep peak heating and integrated heating loads under reusable TPS limits.

Vehicle Concept Description

In order to apply the sizing process described in Section II to the specific mission and vehicle combinations in Section III, an analytic description of the geometry and weight of each vehicle element is needed. A literature review of established space vehicle projects pertaining to the vehicle elements required for MGS establishes a database and knowledge-base that is the basis for all vehicle and architecture sizing activities presented.

Capsule

The capsule utilized for the minimum-complexity ConOp 1 demands parametric geometry and mass descriptions. Figure 4 shows the capsule geometry parameterization consisting of a spherical cap connected to a conical frustram, Equations 1-6 derive the geometric relations of the needed parameters to the overall diameter of the capsule, and Table 1 shows the non-dimensional values assumed based on reference vehicles [4]. The TPS configuration of a capsule involves a high-temperature ablative material located on the windward spherical cap, whereas the leeward conical frustram features a low-temperature ceramic tile TPS, both of which are high-maturity technologies. It is shown from both theory and practice that the mass of TPS per surface area remains relatively constant for capsules [4], therefore areal weights are assumed constant for current TPS technologies as well as for structural support. All areal weight values assumed are shown in Table 2.

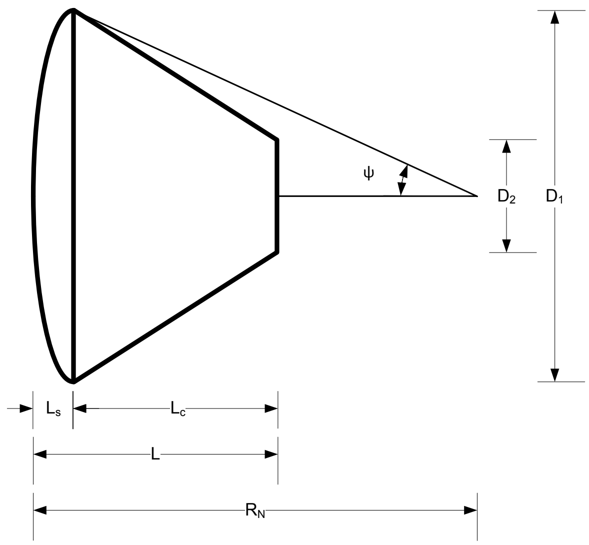


Figure 4. Geometry parameterization of generic re-entry capsule.

1) $\psi = \arcsin\left(\frac{\frac{1}{2}}{R_N/D_1}\right)$

2) $L_s/D_1 = R_N/D_1 - \frac{\frac{1}{2}}{\tan(\psi)}$

3) $S_{\text{spherical cap}}/D_1^2 = 2\pi\, R_N/D_1\, L_s/D_1$

4) $L_C/D_1 = L/D_1 - L_s/D_1$

5) $S_{\text{conical frustram}}/D_1^2 = \pi\left(\frac{1+D_2/D_1}{2}\right)\sqrt{\left(\frac{1-2\,D_2/D_1+\left(D_2/D_1\right)^2}{2}\right)+\left(L_c/D_1\right)^2}$

6) $UNW_{avg} = \frac{UNW_{ablator}S_{\text{sperical cap}}+UNW_{Sidewall}S_{\text{conical frustram}}}{S_{\text{sperical cap}}+S_{\text{conical frustram}}}$

Table 1. Capsule geometry relations

Geometry	Value
R_N/D_1	1.20
L/D_1	.65
D_2/D_1	.30
Ψ	24.70°

Table 2. Capsule areal weights

Component	UNW, kg/m^2
Ablator TPS	6.59
Tile TPS	8.98
Average TPS	8.04
Structure [5]	24.40

All-Propulsive OTV

As a baseline configuration for ConOp 2, an all-propulsive OTV is established in order to assess the delta- improvement in propellant mass of an aerobraking OTV. The mass of the all-propulsive OTV is dominated by the propellant mass as a direct result of the ΔV budget allotted for the mission.

Aerobraking OTV's

Aerobraking vehicles are subject to a demanding aero-thermal environment, and to ensure both the physical and logistical feasibility of vehicle and architecture designs, constraints are implemented into both the computational sizing process and the off-line analysis. The aero-thermal constraints considered for the MGS study are: (1) wake impingement heating, and (2) stagnation point nose heating.

Wake Impingement Heating

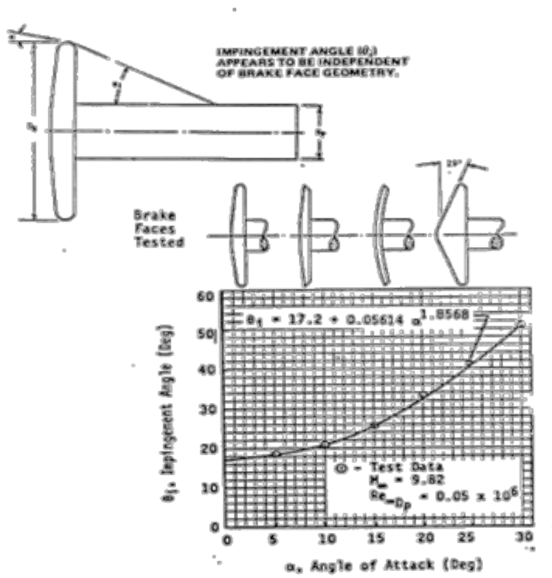


Figure 5. Wake impingement angle versus angle of attack for open aerobrake vehicles [8]

Afterbody heating is a major consideration in the TPS layout development of OTV concepts. Past studies have shown that in open aerobrake structures (deployable and raked cone aerobrake vehicles), the angle between the edge of the forebody structure and the area of increased heating is a known function of angle of attack (Fig. 12). By implementing this impingement angle as an active constraint on the vehicle layout, the aerobrake geometry can be sized such that the payload and systems located behind the main aerobrake structure do not require a high-temperature, high-density TPS.

Stagnation Point Nose Heating

Stagnation point heating at the nose of a re-entry vehicle governs the TPS material required, which in turn affects the reusability and weight of the vehicle system. As a first order approximation, an empirical relation between ballistic coefficient, hypersonic *L/D*, nose radius, and stagnation point heat transfer rate has been developed for aerobraking vehicles [7]. This relationship has been utilized to identify areas of unreasonable heating environments within the vehicle trade space. In the context of equation 7, maximum heating rate is known as a function of TPS material selected, while the ballistic coefficient and hypersonic *L/D* are determined from the geometry/mission definition of the vehicle. Equation 7 then yields the minimum feasible nose radius for a given combination of vehicle configuration and technology.

$$\dot{q}_{MAX}\sqrt{R_N} = 7.3(\beta)^{.467}\left(\frac{L}{D}\right)^{-.242} \quad \left[\frac{W\sqrt{m}}{cm}\right]$$

Off-line, Team 2 hypersonic aerothermodynamic analysts at NASA Johnson performed computational mission-specific trajectory and heating simulations. This information was incorporated into the sizing knowledge-base and led to more accurate TPS material requirements and overall vehicle mass estimates.

AOTV Concepts

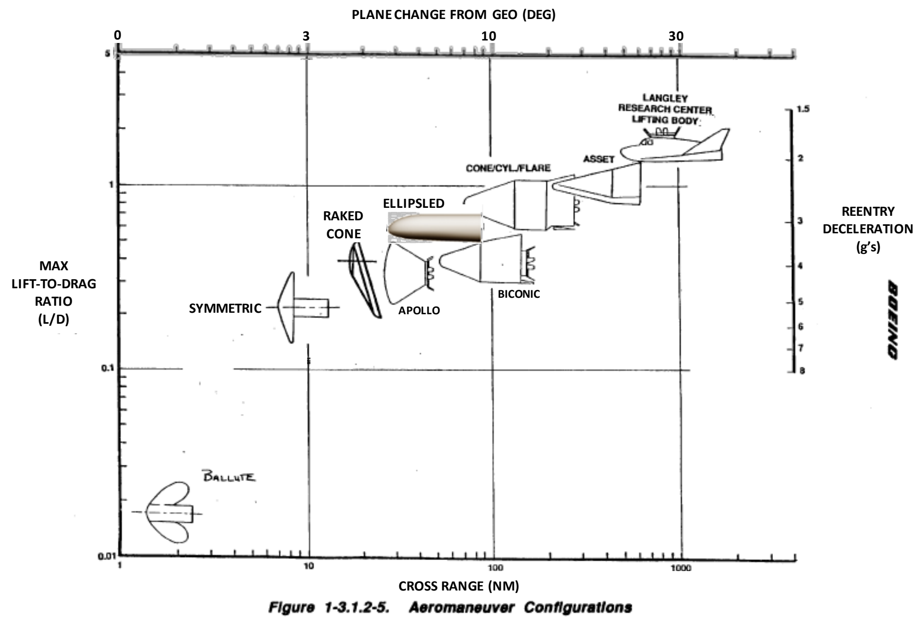


Figure 6. Relative performance of aerobraking and re-entry vehicle concepts (modified from [6])

Aerobraking performance is governed by the ballistic coefficient [β], defined as the mass of the vehicle divided by the product of the drag coefficient and the reference area, and the hypersonic *L/D*. As β decreases, the greater deceleration the vehicle will encounter when passing through the atmosphere and as *L/D* increases, control authority improves, as does the ability to perform a propellant-free plane change maneuver during the atmospheric pass as shown in Figure 5. The current project involves three distinct aerobraking OTV concepts that allow for a range of performance to be quantified into a trade space by overall vehicle size and weight. The concepts, from low to high performance: (1) deployable symmetric aerobrake, (2) raked cone aerobrake, and (3) COBRA ellipsled aerobrake.

Deployable Symmetric Aerobrake

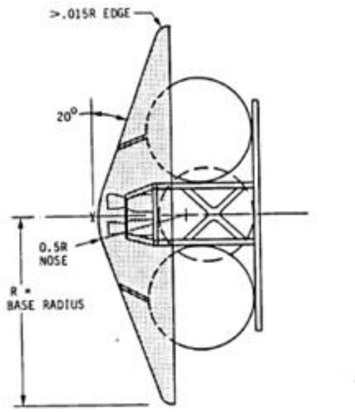


Figure 7. Symmetric aerobrake geometry [6]

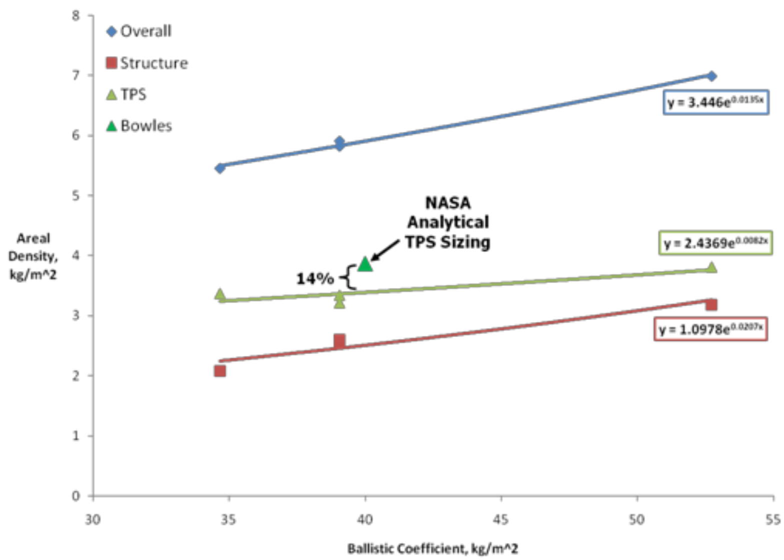


Figure 8. Parametric mass breakdown of deployable aerobrake [8, 9]

The first vehicle concept is the axis-symmetric conical aerobrake, which has the lowest aerodynamic performance (hypersonic *L/D* of approximately .12). The classical geometric shape has been well-studied theoretically, in hypersonic wind tunnels, and in production research spacecraft [7] (i.e., the Stardust and Hayabusa re-entry capsules). The axis-symmetric geometry shown in Figure 6, utilizes an operational scheme for in-space deployment of a portion of the aerobraking structure [8,9]. This concept has a flexible, TPS-supported, deployable outer substructure that is opened like an umbrella prior to the aeromanuever. By confining the rigid structure and TPS to only the centermost section of the aerobrake, this deployable structural configuration lessens the launch vehicle diameter constraints as well as reducing heating environments by increasing the allowable planform area of the aerobrake. Figure 7 shows a parametric assessment of structure and TPS areal masses derived from a data-base of deployable symmetric aerobrake concepts.

Raked Cone Aerobrake

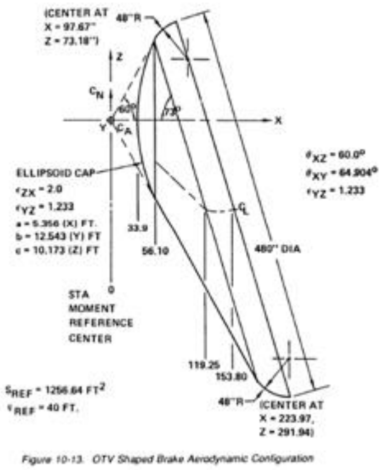


Figure 9. Raked cone aerobrake geometry [10]

As an alternative to the deployable aerobrake structure, a vehicle concept based on an existing-capability rigid structural layout was also considered. Through work for the Aeroassist Flight Experiment [8], NASA developed an asymmetric aerobrake concept (referred to as 'raked cone') with the intent of increasing hypersonic *L/D* to roughly .3. This increase in aero-performance comes at the price of higher ballistic coefficients, and therefore more extreme heating environments. A mass database of rigid aerobrake configurations [6, 8, 9, 10] develops a functional variation of structure and TPS masses with ballistic coefficient (Fig. 9), and is implemented within the sizing logic for mass estimation of raked cones.

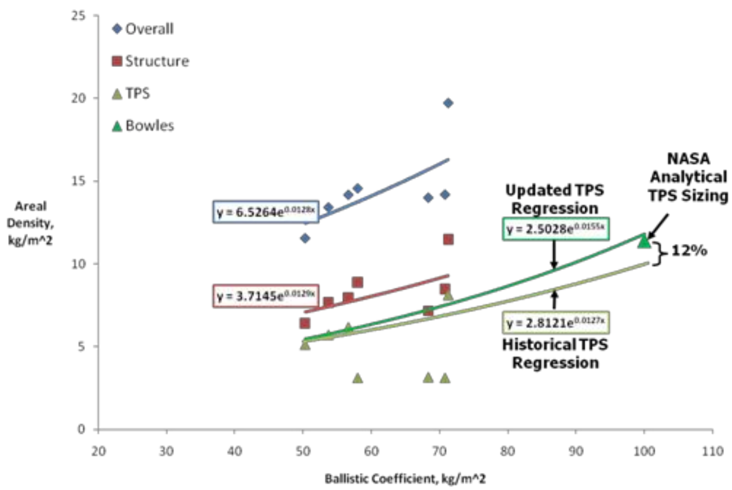


Figure 10. Parametric mass breakdown of raked cone aerobrake [6, 8, 9, 10]

COBRA Ellipsled Aerobrake

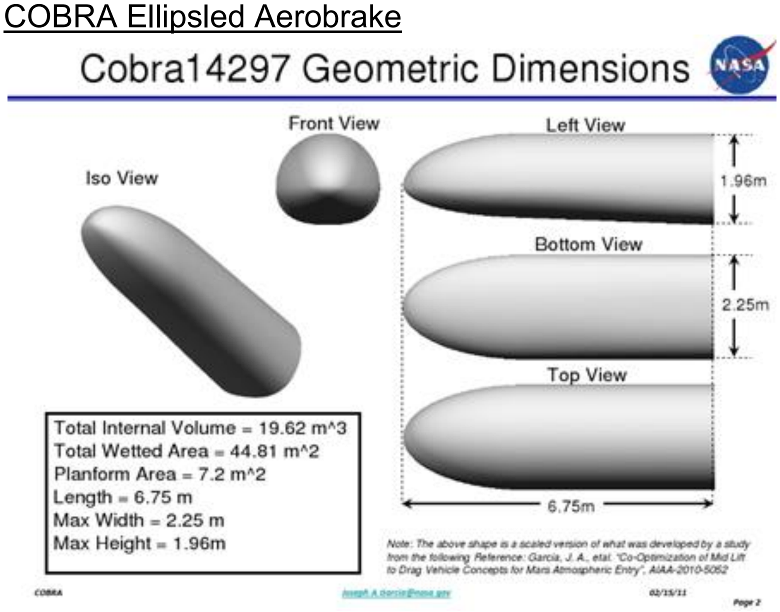


Figure 11. Ellipsled geometry [11]

The highest performance (hypersonic *L/D* of .5) aerobrake considered is the COBRA Ellipsled. This vehicle configuration is an enclosed aeroshell and therefore does not have a wake impingement constraint for protecting the payload. Because of this, the ellipsled aerobrake shows the potential to have the smallest cross-sectional diameter, allowing for easier launch packaging. However, this vehicle concept has increased TPS and structure areal mass densities, resulting in higher ballistic coefficients. The geometry required for an MGS payload results in smaller relative nose radii, producing extreme heating environments that exceed reusable TPS levels. The configuration may hold merit for design payloads with a volume requirement exceeding that of MGS; increase in vehicle size, relaxes the aeroheating constraint. The aeroshell definition and subsequent performance and mass estimates are based on the COBRA Ellipsled series of vehicle publications [11, 12].

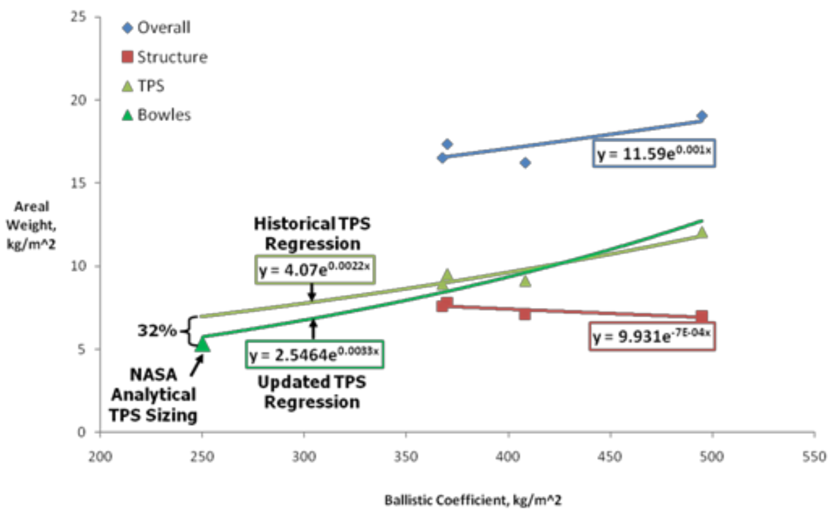


Figure 12. Parametric mass breakdown of ellipsled aerobrake [11]

Solution Space Visualization

Conop 1 – Direct Insertion/Reentry

The parametric generic capsule is utilized to explore the effect of number of crew and volume per crew on the size of an MGS Capsule. Figure 13 compares two-, three-, and four-crew capsules with varying crew volume. Passive gross mass constraints corresponding to Delta IV-Heavy maximum launch mass, Delta-IV Heavy with ACES upper stage, and dual launch Delta IV heavy with a delta cryogenic second stage (DCSS) ascent propulsion module for transfer from LEO-GEO are plotted in the trade space.

The selected MGS design point allows for three crew members with 2 m^3 allocated per crew member. The three-crew configuration was selected as the minimum required to perform the MGS mission (Team 3), and 2 m^3 per crew was determined acceptable for a two day trip going and two day trip back from GEO. As a result, this design point allows for two launch options: (1) dual launch of an existing Delta-IV Heavy, and (2) a single launch with a proposed Delta-IV Heavy with ACES. Table 3 summarizes the mass breakdown for this design point.

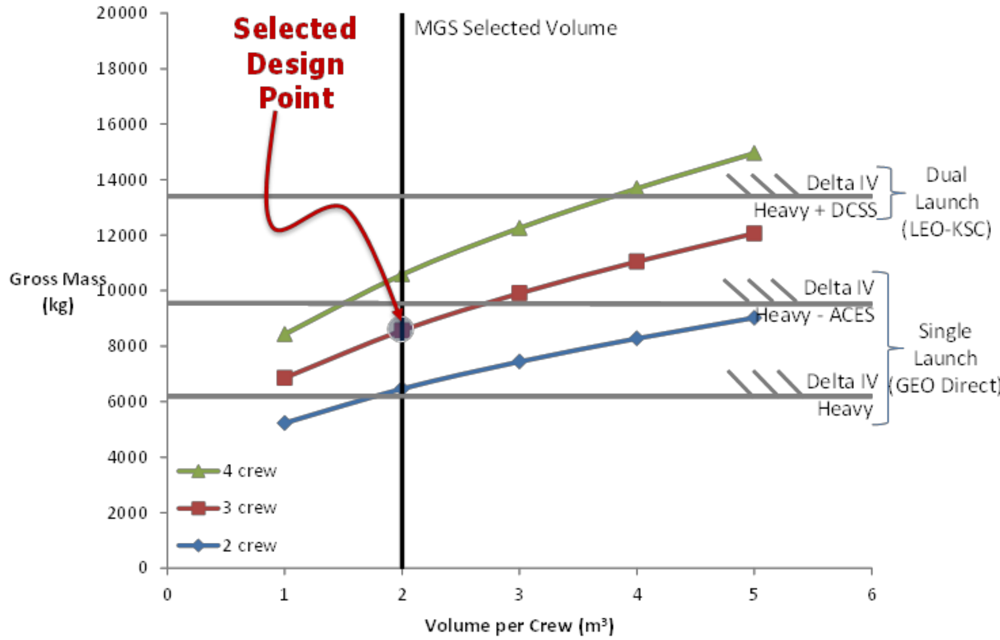
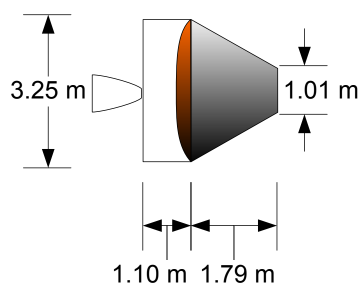


Figure 13. Effect of number of crew and volume per crew on capsule service module gross mass

Table 3. Design Mass Summary for Generic Capsule

Function	CM, kg	SM, kg	Total, kg	Geometry
Structure	570	237	807	
TPS	188	-	188	
Main Propulsion	0	385	385	
Systems	1827	474	2300	
Other	155	0	155	
Growth	556	219	775	
Dry Mass	3295	1315	4610	
Non Cargo	420	0	420	
Cargo	45	0	45	
Inert Mass	3760	1315	5075	
Non-Propellant	70	0	70	
Propellant	0	3384	3384	
Gross Mass	3830	4698	8528	

Summary of Results and Recommendations

The direct entry capsule represents the simplest ConOp explored for this study,
1. Crew volume and number of crew are primary drivers in the scale of the capsule.
2. MGS generic capsule shows feasibility with current Delta IV-Heavy launch vehicle

Conop 2 – Expendable Ascent Propulsion Module

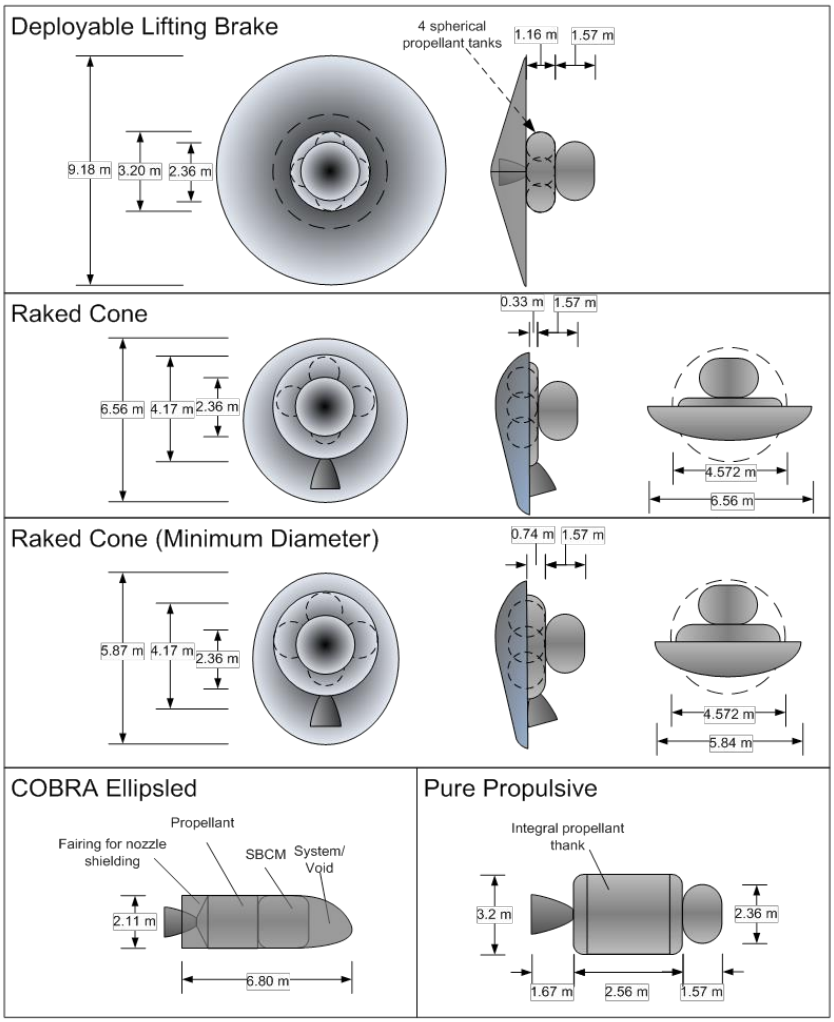


Figure 14. Geometric summary of OTV concepts – Expendable APM

For the Expendable APM branch of ConOp 2, five orbital transfer vehicle configurations are traded: (1) Deployable Aerobrake, (2) Raked Cone Aerobrake, (3) Minimum Diameter Raked Cone Aerobrake, (4) Ellipsled Aerobrake, and (5) Pure Propulsive Orbital Transfer Vehicle

(POTV). The Minimum Diameter Raked Cone is an extrapolation of lifting break regressions towards a high ballistic coefficient Raked Cone (~125 kg/m2). This has been done to determine if it is geometrically possible to fit a Raked Cone into the 5 m diameter Delta IV Heavy fairing and what (if any) TPS technology can handle these heat loads. All five concepts are summarized in Table 4 and Figure 14.

Table 4. Design Mass Summary for OTV Vehicles – Expendable APM

CTV	Deployable, kg	Raked Cone, kg	Raked Cone (min diameter), kg	Ellipsled, kg	POTV, kg
Dry Mass	3296	3880	4268	4367	3475
Propellant	3560	4100	4462	4553	12402
Reentry Mass	4101	4724	5140	5192	-
Gross Mass	7391	8515	9265	9454	16412
			Excessive Peak Heating No Convergence with TPS Analysis		

Comparison of Concepts

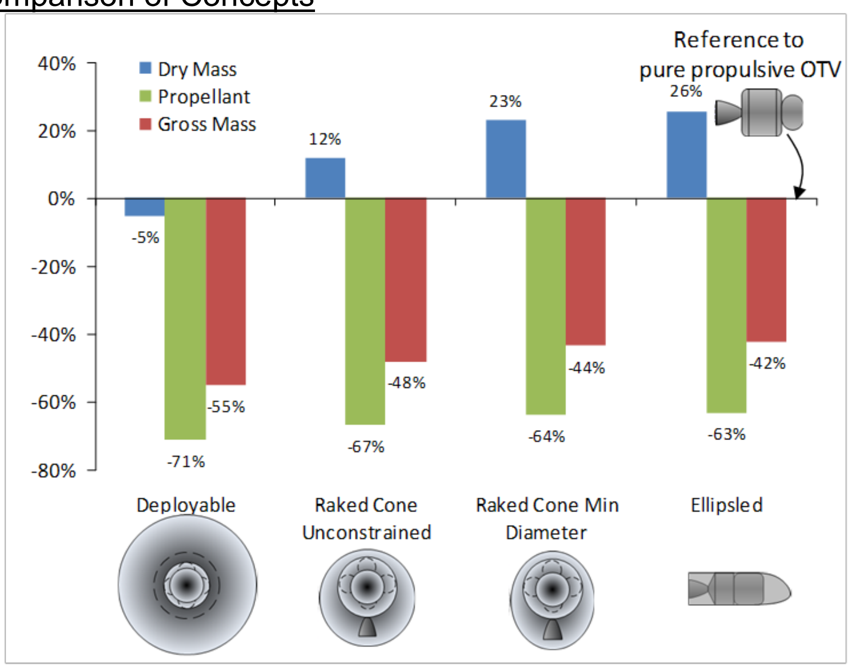


Figure 15. Comparison of AOTV mass savings relative to POTV – Expendable APM

In general, all converged AOTV concepts show promise for significant mass savings over the pure propulsive OTV. Figure 15 compares all four AOTV concepts to the pure propulsive OTV. The Deployable aerobrake shows the greatest propellant and dry mass savings with the Raked Cone showing similar propellant mass savings. Although the Raked Cone (Minimum Diameter) and Ellipsled also show mass savings, later aero-thermal analysis demonstrates that these solutions are not viable for reusable TPS due to peak heating loads. In addition, the Minimum Diameter Raked Cone still could not meet the 4.57 m constraint from Delta IV Heavy 5 m faring. Therefore, the unconstrained Raked Cone is suggested for further study, requiring some assembly in-space, or modification to the Delta-IV Heavy 5 meter fairing.

All things considered, AOTVs (Deployable or Raked Cone) show promise for this ConOp. Further study is required to select between the lighter but possibly less-durable Deployable AOTV, and the rigid, in-space assembled Raked Cone AOTV.

Conop 2 – Reusable Ascent Propulsion Module

Element mass estimation for ConOp 2 requires that DPM concepts be sized first, and then APM concepts can be sized based on the required up-mass of the entire system. Because several concepts for both the DPM and APM are considered, a matrix of possible architecture solutions is obtained.

Descent Propulsion Module

For this trade of ConOp 2, three OTV configurations are explored as possible descent propulsion module options in Table 5 and Figure 16: (1) Deployable, (2) Raked Cone, and (3) Pure Propulsive. The Minimum Diameter Raked Cone and COBRA Ellipsled have been excluded based on the results from the Expendable APM study, which concludes that these vehicles are impractical due to aero-thermal and small body radii considerations.

Table 5. Design Mass Summary for DPM OTVs – Reusable APM

CTV	Deployable, kg	Raked Cone, kg	POTV, kg
Dry Mass	4846	5713	5009
Propellant	9345	10871	23263
Reentry Mass	5381	6267	-
Gross Mass	14725	17120	28807

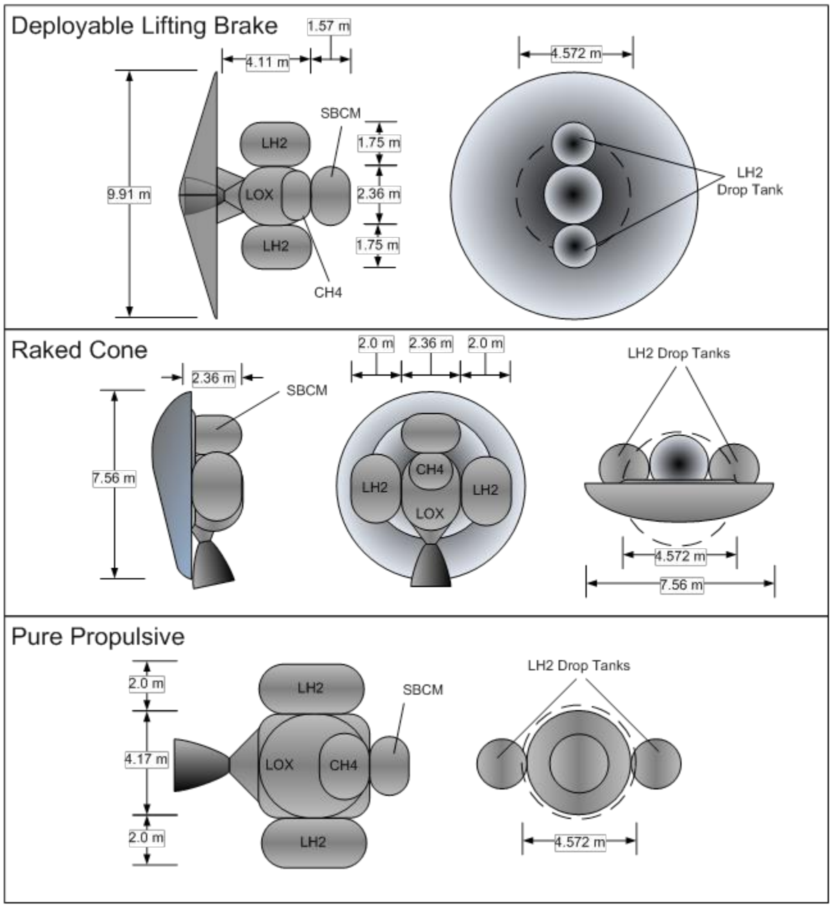


Figure 16. Geometry summary of OTV DPM concepts – Reusable APM

Comparison of DPM Concepts

As with the Expendable APM trade, the larger GEO insertion DPM benefits greatly from the AOTV concept in terms of propellant mass (Figure 17). The rigid Raked Cone structure results in an increased dry mass relative to the Pure Propulsive AOTV; however, the reduction in propellant mass more than compensates. Overall, the AOTV concepts show significant gross mass reduction which will allow for decreased propellant and dry mass of the reusable APM.

Ascent Propulsion Module

For this trade, four APM OTV configurations are explored: (1) Deployable, (2) Raked Cone, (3) Ellipsled, and (4) Pure Propulsive. The Ellipsled AOTV is reintroduced in this study because the increased propellant volume of LH2 and staging of payload (DPM) prior to aeropass reduces the ballistic coefficient and increases the body radii relative to the crew DPM from the Expendable

APM trade. Each APM is sized for each DPM possibility discussed in the previous section, leaving 12 total system configurations sized (4 APM x 3 DPM) (Table 6 and Figure 18).

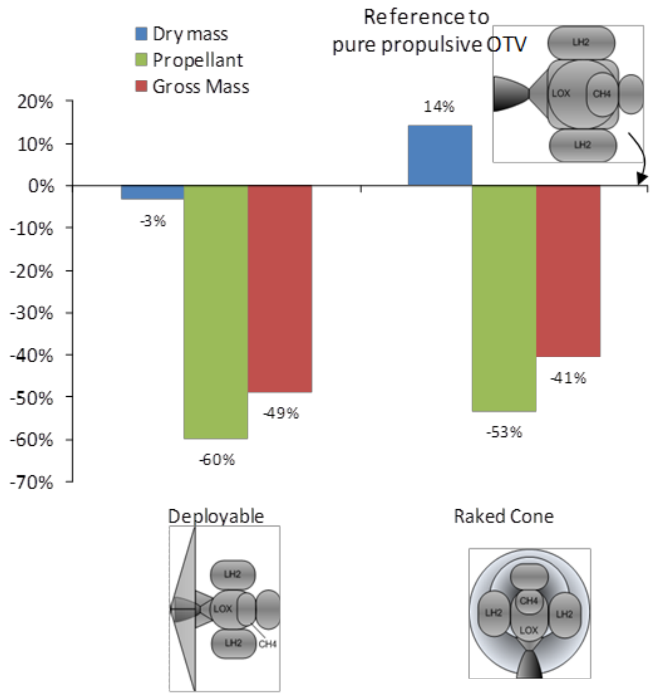


Figure 17. Comparison of AOTV DPM mass savings relative to POTV – Reusable APM

Table 6. Design Mass Summary for APM+DPM OTVs – Reusable APM

	Deployable Lifting Break APM			**Raked Cone APM**		
Function	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg
Dry Weight	5084	5697	8528	5206	5571	8337
Propellant	15376	17704	28931	15477	17818	29101
Reentry Mass	5526	6201	9332	5656	6348	9550
Gross Mass	35185	40522	66266	35408	40510	66245

	Ellipsled APM			**Propulsive APM**		
Function	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg	Deployable DPM, kg	Raked Cone DPM, kg	Propulsive DPM, kg
Dry Mass	7949	8674	11847	3996	4400	6233
Propellant	17698	20117	31623	19943	22670	35685
Reentry Mass	8513	9306	12795	-	-	-
Gross Mass	40372	45913	72277	38664	44191	70725

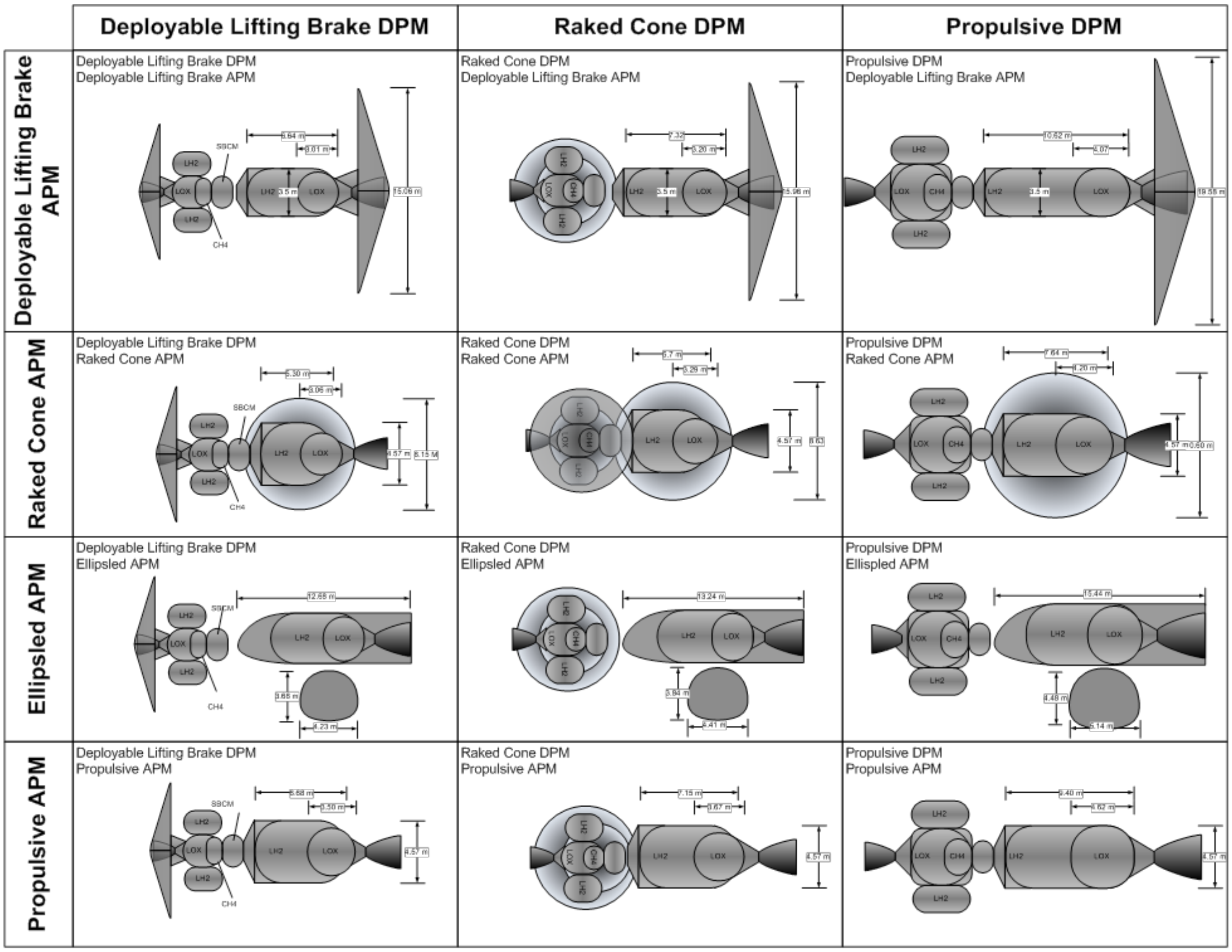


Figure 18. Geometry summary of OTV DPM+APM concepts – Reusable APM

When comparing the dry, propellant, and gross masses of the total APM+DPM system, it is clear that the primary driver for the AOTV DPM is the reduced total propellant mass, with the secondary driver being the APM concept (Figure 19). The selection of a Deployable or Raked Cone DPM results in roughly a 50 to 60% propellant reduction relative to the all propulsive systems, with the selection of the APM only having a 10 to 20% effect on the total propellant mass over its corresponding all propulsive concept.

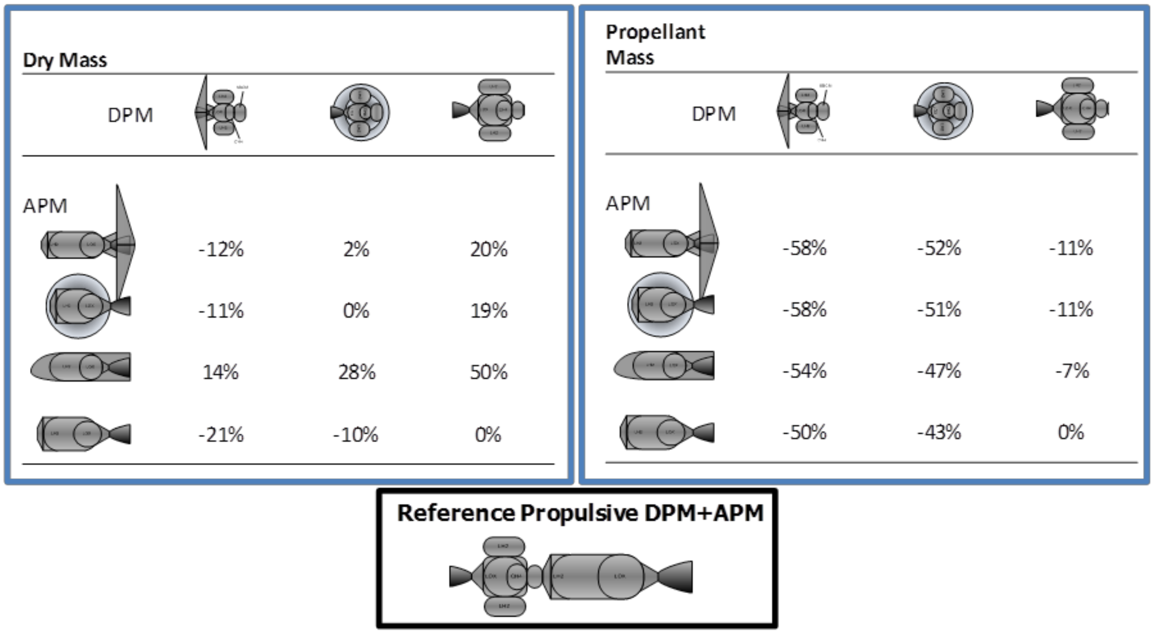


Figure 19. Comparison of 12 DPM+APM concepts relative to propulsive DPM+APM

The Reusable APM and DPM variation from ConOp 2 shows that the Deployable or Raked Cone DPM concepts will provide similar propellant mass, while the Raked Cone dry mass is 10% heavier due to the rigid structure and higher ballistic coefficient. The APM can certainly benefit from an AOTV concept, however, the selection between AOTV concepts must come from metrics other than mass alone. From this standpoint, all AOTV APM and DPM concepts could provide an operational benefit with a sufficiently high flight rate and low maintenance costs. Such cost comparison is beyond the scope of this study, but is required for realistic comparison between reusable and expendable crew transfer architectures.

Summary of Results and Recommendations for ConOp 2

Expendable APM Trade:

1. Deployable and Raked Cone aerobrake concepts show promise for reducing propellant mass in the crew return vehicle for return from GEO-0 to LEO-KSC.
2. Minimum Diameter Raked Cone and Ellipsled concepts present a reusable TPS material problem due to their high ballistic coefficient and small radii.

Reusable APM Trade:

1. APM concepts sized for LEO - GTO transfer with Deployable DPM.
2. The staging of the DPM results in a significant reduction in mass at LEO circularization. Thus, the pure propulsive OTV APM is not as severely penalized as the POTV DPM, which must return the SBCM. As such, use of an AOTV shows less mass-reduction

potential in APMs than in DPMs.

3. The Ellipsled has a greater TPS wetted area relative to the Deployable and Raked Cone concepts. This attribute along with the increased volume required to store the LH2 propellant results in a significant increase in dry mass over the propulsive OTV. As a consequence, propellant savings over the baseline is reduced to only 7 % for the Ellipsled.

Summary and Conclusions

The results from the ConOp 1 study show that a Capsule+DPM designed for MGS is technologically feasible and of a size comparable with past and proposed capsules. Current launch capability allows for an MGS architecture under this concept of operations.

ConOp 2 has two branches: (1) Expendable APM and (2) Reusable APM. In both branches the AOTV DPM shows significant propellant mass savings. Overall, the selection between AOTV concepts and reusable/expendable APM must come from consideration of their maintenance/durability and cost of operation with an associated flight rate. Based on mass alone, the expendable system will always demonstrate lower propellant mass per mission. Reusability is appealing only if the flight rate such that the propellant and maintenance costs of the reusable system under-bid the launching of an expendable APM each mission.

For both ConOp 1 and 2, if the flight rate to GEO is low, an expendable launcher and DPM with a direct reentry capsule will show the lowest mass and complexity per mission. This conclusion holds unless the flight rate is high enough to benefit from a more complex reusable architecture.

Acknowledgments

The authors would like to acknowledge Jeff Cerro (NASA Langley - Vehicle Analysis Branch) for providing guidance as team lead for the study.

References

1. Coleman, G., Aircraft Conceptual Design – An Adaptable Parametric Sizing Methodology, University of Texas at Arlington, 2010.
2. Czysz, P., HYPERSONIC CONVERGENCE: Volumes 1 through 10, Saint Louis University, Parks College, Aerospace Engineering Dept: Course AE-P493-50 1992-93 and Purdue University Short Course "Integration of Winged Flight Vehicles" , 1989. AE-P493-50
3. Anon., Manned Geosynchronous Earth Orbit (GEO) Servicing (MGS) Joint NASA/DARPA Study – Final Report
4. Anon., NASA Exploration Systems Architecture Study, 2005, NASA-TM-2005-214062
5. Heinemann, W., Design Mass Properties II, Mass Estimating and Forecasting for Aerospace Vehicles Based on Historical DATA, National Aeronautics and Space Administration, Lyndon B. Johnson Space Center, Houston, Texas, 1994. JSC-26098
6. Anon., Space Transfer Vehicle Concepts and Requirements Study – Volume II, Book 1 Final Report – Concept Definition and Evaluation. Boeing Aerospace Company for NASA, 1991. NAS8-37855

7. Scott et al., Design Study of an Integrated Aerobraking Orbital Transfer Vehicle, 1985. TM-58264
8. Anon., Orbital Transfer Vehicle Concept Definition and Systems Analysis Study, Executive Summary Supplement, 1986. Martin Marietta for NASA, 1986. NAS8-36108
9. Anon., Space Transfer Vehicle Concepts and Requirements Study – Volume II, Book 1-2. Martin Marietta for NASA, 1991. NAS8-37856
10. Anon., Orbital Transfer Vehicle Concept Definition and Systems Analysis Study, Final Report – Phase 1, Volume II, Book 3 - Configuration and Subsystem and Trade Studies. Boeing Aerospace Company for NASA, 1986. NAS8-36107
11. Garcia et al., Co-Optimization of Mid Lift to Drag Vehicle Concepts for Mars Atmospheric Entry, 2010. AIAA-2010-5052
12. Lafluear and Cerimele, Angle of Attack Modulation for Mars Reentry, 2009. AIAA 2009-5611
13. Isakowitz, Hopkins, Hopkins Jr., International Reference Guide to Space Launch Systems. ISBN 1-56347-591-X

Lex Gonzalez
Mr. Gonzalez currently serves as a graduate research assistant at the University of Texas at Arlington

Gary Coleman
Dr. Coleman currently serves as a Mechanical Engineer at RSG AeroDesign

Eric Haney
Mr. Haney currently serves as a graduate research assistant at the University of Texas at Arlington

Amit Oza
Mr. Oza currently serves as a graduate research assistant at the University of Texas at Arlington

Vincent Ricketts
Mr. Ricketts currently serves as a graduate research assistant at the University of Texas at Arlington

Bernd Chudoba
Dr. Chudoba currently serves as an Assistant Professor of Aerospace Engineering at the University of Texas at Arlington

Paul Czsyz
Mr. Czysz currently serves as a consultant through Hypertech Concepts LLC