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Crew Transfer Options for Servicing of Geostationary Satellites

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Abstract

In 2011, NASA and DARPA undertook a study to examine capabilities and system architecture options which could be used to provide manned servicing of satellites in Geostationary Earth Orbit (GEO). The study focused on understanding the generic nature of the problem and examining technology requirements, it was not for the purpose of proposing or justifying particular solutions. A portion of this study focused on assessing possible capabilities to efficiently transfer crew between Earth, Low Earth Orbit (LEO), and GEO satellite servicing locations. This report summarizes the crew transfer aspects of manned GEO satellite servicing. Direct placement of crew via capsule vehicles was compared to concepts of operation which divided crew transfer into multiple legs, first between earth and LEO and second between LEO and GEO. In space maneuvering via purely propulsive means was compared to in-space maneuvering which utilized aerobraking maneuvers for return to LEO from GEO. LEO waypoint locations such as equatorial, Kennedy Space Center, and International Space Station inclinations were compared. A discussion of operational concepts is followed by a discussion of appropriate areas for technology development.

Abbreviations

ACES	Advanced Common Evolved Stage
ACVe	Asymmetric Capture Vehicle
AML	Adaptive Modeling Language
AOTV	Aeroassisted Orbital Transfer Vehicle
APM	Ascent Propulsion Module
AVD	Aerospace Vehicle Design
CM	Command Module
CTV	Crew Transfer Vehicle
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DPM	Descent Propulsion Module
EELV	Evolved Expendable Launch Vehicles
EVA	Extra Vehicular Activity
GEO	Geostationary Earth Orbit
GYO	GraveYard Orbit
HEO	High Earth Orbit
HLLV	Heavy Lift Launch Vehicle
HSF	Human Space Flight
IOC	Initial Operating Capability
ISS	International Space Station
L/D	Lift/Drag
LEO	Low Earth Orbit
OTV	Orbital Transfer Vehicle
SBCM	Space Based Command Module
SEP	Solar Electric Propulsion
SM	Service Module
SSF	Space Station Freedom
TRL	Technology Readiness Level
UTA	University of Texas at Arlington

Contents

Introduction

In 2011 NASA and DARPA undertook a study to examine the capabilities and system architecture options which could be used to provide manned servicing of satellites in Geostationary Earth Orbit (GEO). The study focused on understanding the generic nature of the problem and examining technology requirements. It was not for the purpose of proposing or justifying particular solutions. The transfer of hardware and crew to the servicing location, combined manned and robotic servicing operations, and survival of the crew for long duration missions were primary functional concerns. A further study goal was to capture input from an organizationally diverse aerospace background. A large and organizationally diverse work force was put in place to capture input from NASA, DARPA, and Academia. Over 75 personnel from NASA, consulting service, and academic organizations provided the resource pool. Because of concerns over preserving the ability for possible future full and open competition of any follow-on procurement activity, industry participation was excluded from this activity.

This paper presents an overview of the entire study and a more in-depth presentation of the element trade space of possibilities required to perform the crew transfer function for Manned GEO Servicing (MGS) missions. The complete study documentation can be found in Reference [MOY2011].

Groundrules & Assumptions

The study's primary stakeholder offices are the DARPA Tactical Technology Office (TTO), the NASA Office of the Chief Technologist (OCT), and the [at that time] NASA Space Operations Missions Directorate (SOMD). The MGS study focused on identifying enabling or enhancing technologies for human tended satellite servicing in GEO. In addition to assessing and prioritizing technologies, the MGS team assessed notional mission architectures to provide context for the technology investment recommendations.

The study charter identified six questions to be addressed by this effort:

1. What are significant risks to human presence at GEO that are not addressed at LEO?
2. What are the major factors in human-based satellite servicing over and above human presence challenges that affect the overall mission architecture definition?
3. What are the major factors in transportation to and within GEO that affect the overall mission architecture
4. What are the major factors for returning humans to Earth from GEO?
5. What notional end-to-end mission architecture(s) enable the capabilities for human-based serving in GEO, and what design considerations in the architecture(s) can mitigate risk for human missions beyond GEO?
6. What are the most promising and enabling technology development opportunities in support of the identified mission architectures that warrant near-term funding to mature?

The crew transfer aspects of the study impacted primarily questions 3 and 4. Crew transfer options were assessed to support the broader mission architecture encompassed in question 5, and finally there was a focus on identifying useful crew transportation element technology opportunities, question 6.

There were several important assumptions and ground rules directed by the stakeholders that shaped the study. Primarily the study was directed to have a capability and technology focus. No particular satellite was selected for service and no vehicle point design details were solicited. Instead, the development of architectural concepts that could be evolved to service increasingly complex MGS missions was desired. The option of being unmanned was not an alternative though heavy use of robotics was implemented to enhance effectiveness of the manned contribution to servicing activities. The study was not constrained by requiring utilization of NASA's current exploration architecture, but was permitted to select a path appropriate to its goals. No assumptions of highly conceptual advances in launch vehicle capability were permitted, but use of data from NASA and commercial projects already in development was permitted. The stakeholders were intending to look outside of potential incremental improvements to create an MGS architecture. Innovation and currently unimplemented element configuration possibilities were highly encouraged. Capability improvement was also coupled to a goal of providing NASA's Human Space Flight (HSF) activities with enterprise extensibility. MGS infrastructure elements and associated implementing technologies were more highly valued if they also could contribute to a more productive HSF exploration path.

Crew Transfer Function

The broadest tradespace for crew transfer encompasses vehicle concepts that range from NASA Gemini-type capsules to winged entry vehicles of various L/D design classes. Exploring this tradespace was made possible by utilization of a university supplied, mission dependent, vehicle element design tool supplemented with additional physics based analyses, particularly in the trajectory, aerodynamic and aerothermodynamic discipline domains. Mass estimations were of primary importance in providing concept definitions. The function of crew transfer to GEO was considered to be implemented with or without secondary government or commercial entities providing earth surface to low earth orbit functionality. If crew transfer is studied only as an in-space functional requirement, then a multitude of Orbital Transfer Vehicles (OTV) and Aeroassisted Orbital Transfer Vehicles (AOTV) become relevant to meeting the crew transfer functional requirement. Results are shown for several vehicle classes along with the impacts of varied mission parameters such as crew-day, and delta-velocity (ΔV) requirements.

CTV Element Tradespace

Guided by study groundrules to assess multiple architectural approaches and seek unconventional solutions, a large Crew Transfer Vehicle (CTV) element definition trade space was proposed Figure 1. Crew transfer is enabled by providing ΔV to the CTV. The ΔV sources considered are primarily chemical propulsion and for velocity reduction only, aerodynamic forces. Solar Electric Propulsion was not considered for crew transfer because of the required long trip times, during which the crew would be subject to the radiation environment between LEO and GEO/HEO habitation/servicing sites.

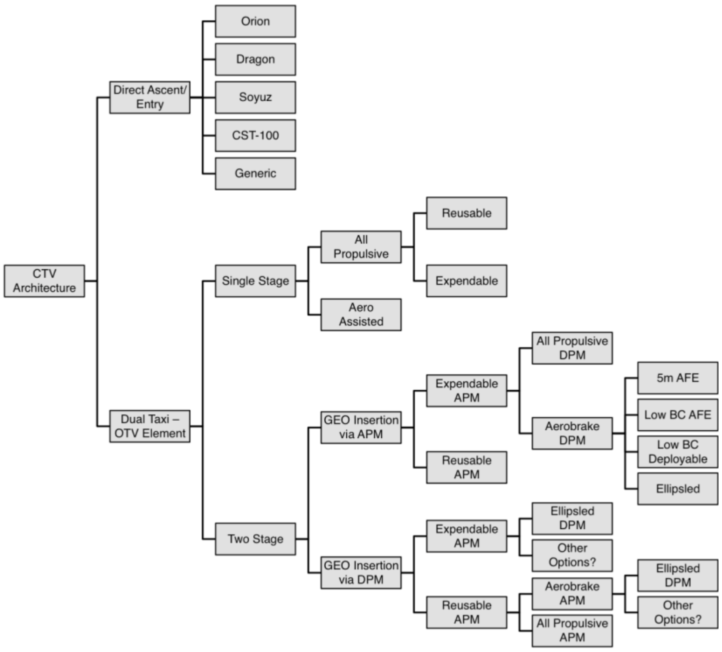


Figure 1 - Crew Transfer Vehicle Functional Tradespace

Terminology used to discuss the transfer vehicle trade tree is as follows:

Crew Transfer Vehicle (CTV) – this is the generic term for an architecture element which contains crew and facilitates their movement either between ground and orbital locations or between two orbital locations.

Orbital Transfer Vehicle (OTV) – Subclass of a CTV within this study. An in-space asset, most desirably a reusable element, which contains crew and has the ability to move between in-space locations/orbits.

Ascent Propulsion Module (APM) – a module which provides ascent propulsion for LEO to GEO transfers. This could be integrated with the OTV, or provided as a separable disposable module.

Descent Propulsion Module (DPM) – a module which provides descent propulsion for GEO to LEO transfers. Typically a disposable element when attached to an entry capsule, often a reusable integral component for OTV/AOTV configurations. The "GEO Insertion via DPM" branch of the trade tree uses the DPM propulsive system for both Ascent and Descent functions.

Aeroassited Orbital Transfer Vehicle (AOTV) – a type of OTV configured with entry thermal protection such that it can perform aerobraking maneuvers when transferring from GEO to LEO. AOTV and OTV distinctions will be made clear when element definition is discussed.

Aeroassisted Flight Experiment (AFE) – a particular historical AOTV concept that uses a rigid aerobrake structural concept.

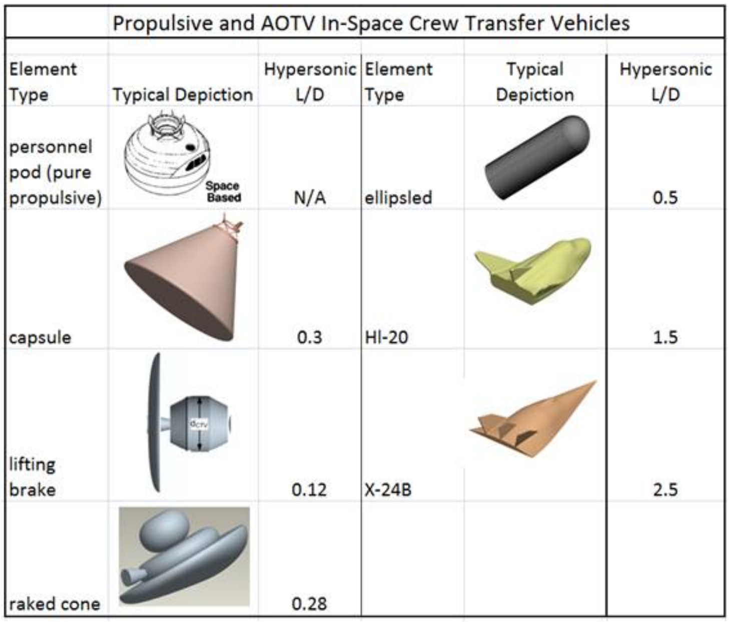
The simplest means of placing crew at the servicing location employs a capsule-based CTV, which transfers crew from Earth to GEO and returns them directly from GEO to Earth. These historical, existing, or near-existing assets (noted as "Direct Ascent / Entry" nodes in the trade tree), were examined first. Historical designs were slightly modified to meet specific requirements such as the propulsive performance (ΔV) necessary to accomplish all the required orbit changes, as well as systems upgrades as necessary. Direct Ascent / Entry approaches are demanding due to launch vehicle upmass limitations. In addition, they provide little flexibility for the buildup of reusable in-space architecture elements which could be applied to future sustainable HSF applications. For that reason, a dual-taxi approach was proposed as an alternative first-level branch in the trade tree.

		GEO to LEO-KSC (370 km, 28.5 deg)				
Element Type	Hypersonic L/D	Aerodynamic Plane Change	Propulsive Plane Change	ΔV (Deorbit + Plane Change)	ΔV (LEO Circ)	ΔV Total
	-	deg	deg	km/sec	km/sec	km/sec
Pure Propulsive	N/A	0.0	28.5	1.777	2.430	4.207
Capsule	0.3	4.5	24.0	1.755	0.109	1.865
Lifting Brake	0.12	1.8	26.7	1.811	0.109	1.920
Raked Cone	0.28	4.2	24.3	1.761	0.109	1.871
Ellipsled	0.5	7.5	21.0	1.699	0.109	1.808
Hl-20	1.5	22.3	6.2	1.517	0.109	1.626
X-24B	2.5	36.2	0.0	1.499	0.109	1.608

Table 1 - ΔV for Aerobraking & Propulsive GEO to LEO Transfers

In a Dual-Taxi architecture, the crew is moved from Earth to LEO on a crew-capable launch vehicle. In LEO, the crew transfers to an in-space OTV, which is sent to GEO for the servicing mission. After servicing is completed, the OTV returns the crew to LEO, where they rendezvous & dock with the Earth-to-LEO vehicle for descent to the Earth's surface. The "Dual Taxi" branch of the trade tree breaks into concepts of single and two-stage transportation between LEO and GEO. The single stage branch may be addressed with an all-propulsive in-space transfer, or through the use of an element with aeroassist capability. In the two-stage branch, the desire for high mass efficiency leads to consideration of in-space staging (i.e. separating the crew stage from a reusable or expendable propulsion stage, the APM). Table 1 illustrates the advantages of aerobraking to reduce required chemical ΔV thru utilization of aerodynamic braking to circularize the GEO to LEO orbit transfer. By controlling the lift vector of the vehicle during a single atmospheric pass, an aerobraking maneuver can be used to target a chosen apogee. The perigee of this post-aerocapture orbit is then raised to circularize the orbit. Higher L/D vehicles can fly the aerocapture such that some or all of the plane change is achieved during the maneuver, further reducing the propulsive ΔV requirement. More than 90% of the fuel required for the LEO circularization burn is eliminated via this aerodynamic braking maneuver. For example, a lifting brake element only requires 1.9 km/sec instead of 4.2 km/sec for a purely propulsive transfer, and the DV required for the LEO circularization is reduced from 2.4 km/sec to 0.1 km/sec.

Several inclination options were considered as potential LEO waypoints, including LEO-ISS (51.6 deg), LEO-KSC (28.5 deg), and LEO-0 degree. While ISS offers substantial existing infrastructure, the LEO-KSC orbit provides optimum mass to orbit for the KSC launch site, and LEO-0 doesn't have to perform a plane change to reach the target destination. However, launching assets for manned missions to a LEO-0 target would require major U.S. ground system infrastructure buildup. Inclination basing is not shown in Figure 1, but is included in the assessment process.



Propulsive and AOTV In-Space Crew Transfer Vehicles

Element Type	Typical Depiction	Hypersonic L/D	Element Type	Typical Depiction	Hypersonic L/D
personnel pod (pure propulsive)	Space Based	N/A	ellipsled		0.5
capsule		0.3	Hl-20		1.5
lifting brake		0.12	X-24B		2.5
raked cone		0.28			

Figure 2 - Crew Transfer Vehicle Classifications

A variety of operational concepts were considered for implementation through a selection of vehicle types drawn from the vehicle classes represented in Figure 2. The capsule category captured generic, existing, and near-term planned developments such as Soyuz, Dragon, and NASA Orion type vehicles. Other options included low L/D (e.g. lifting brake, raked cone), mid L/D (e.g. ellipsled, blunt wing body), and high L/D (e.g. sharp wing body) concepts. All sizings for return from GEO include a DPM. For the pure propulsive module, the DPM would be integrated with the crew compartment characterized in Figure 2 as the personnel pod, or Space Based Command Module (SBCM). Capsule designs employed a detachable DPM which is jettisoned prior to reaching the entry atmospheric interface. The lifting brake, raked cone, and higher L/D configurations included a DPM as integral in their design. Lifting bodies were identified as potentially advantageous because they could provide a reduction in on-orbit propellant requirements by using aeroassisted inclination changes between orbits. However, the blunt and sharp-winged body concepts were eventually eliminated from the trade space because the plane change (DV advantage) was small and the required TPS technology push was too high to satisfy potential near term flight test goals.

Crew Transfer – Operational Scenarios

Identified also in the MGS general study are two basic mission approaches, one which places a crew transfer vehicle with some possible additional elements directly into GEO for a "short term" servicing mission. Short term here refers to a mission under 2 week's duration. The second major category involves development of a habitat facility which is stationed in GEO. Crew is brought to this combination habitat/servicing element to live for 1 to 2 month mission durations. Servicing of multiple satellites in one "Long Term" mission is possible with this approach. Short or long term missions could be supported by either the direct ascent, or dual-taxi approach.

Figure 3 illustrates an operational concept of the direct (surface to GEO) approach for a long duration mission. Crew is sent to the Habitat/Servicer element without stopping at an intermediate waypoint. Launch is followed by an approximately 5.5 hr propulsive stage transfer to the geostationary orbit, and subsequent docking with the habitat element. Two day durations are allowed for this activity when performing vehicle sizing. The CTV transitions to a quiescent state while docked. It is then used again in approximately 30-60 days for crew earth return. A Direct launch is a simple operational concept, but it requires a very capable booster systems or additional operating complexities and timeline extensions to possibly incorporate in-space propellant transfer.

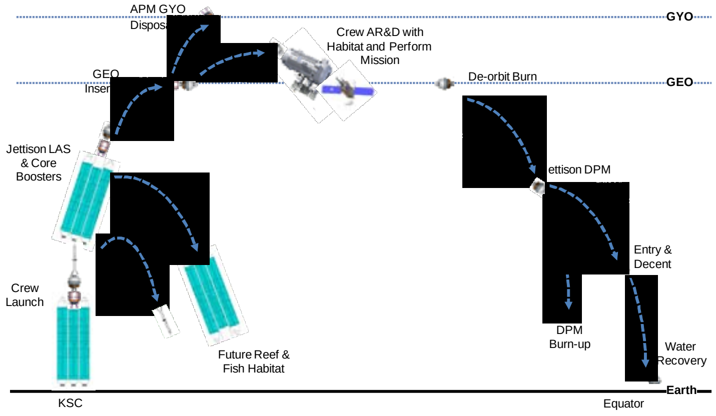


Figure 3 - Direct Launch Crew Transfer supporting a Long Duration Mission

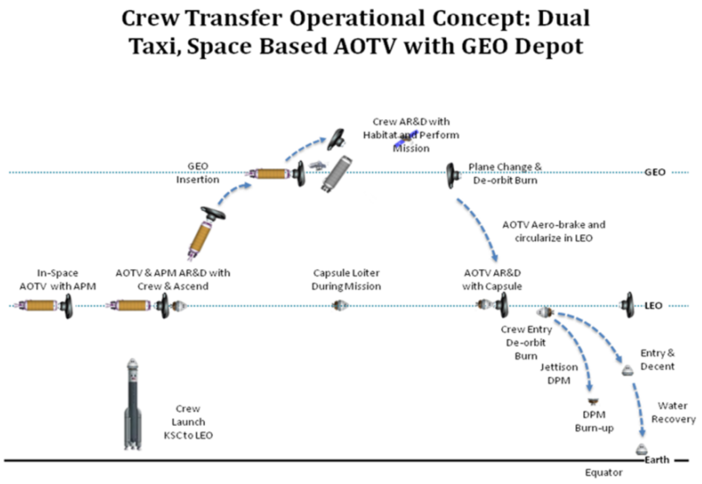


Figure 4 - Dual Taxi Crew Transfer supporting a Long Duration Mission

In the "Dual Taxi Crew Transfer" approach, Figure 4, the concept of in-space element reusability emerges. Crew transfer is divided into two primary transportation legs. First is the placement of crew from the launch site into LEO. This element fractioning of the full transportation leg enables multiple entities, such as new commercial ventures, international partners, or government launch vehicles to fulfill the first leg crew staging operation. In Figure 4, a capsule is shown performing this first transportation operation. Prior to the crew launch, additional assets have been placed in orbit, or in the case of reusable in-space elements, were placed in position upon completion of a prior mission. The Dual-Taxi approach embraces the design philosophy of building up an in-space infrastructure of reusable elements and so is aimed at enabling synergistic capabilities which may be desired by a future NASA HSF exploration architecture. For the second element of this fractionated architecture, an in-space OTV, an AOTV in the case of Figure 4, is maintained to perform the LEO-GEO transportation leg. Further details describing launch vehicle selections, upper stage selections, and the manifesting of crewed elements to complete MGS missions are described in the Appendix of [MOY2011].

They are summarized here as:

- **Capsule Direct** (Figure 3) – this is a single launch operation of a Delta IV Heavy Evolved with a generic capsule. This option employs launch capability which is not currently available. The generic capsule is a 3 person capable vehicle which will be later described.
- **Capsule – Dual Launch –** by employing a dual launch approach, existing launch vehicle and upper stage capability

can perform the mission using a generic capsule as the CTV. Employs Delta IV-H, Centaur, and Atlas 401 elements.

- **Capsule with GEO propellant depot and SEP Tug** – Enables a lesser capability launch vehicle but requires existence of an SEP tug. Utilizes a storable propellant depot, SEP tug, Atlas 501 (2), Atlas 551, and generic capsule. Still considered a "Direct" approach though LEO is utilized for element integration on the uphill side of access to the habitat. Crew return is direct to Earth.
- **AOTV with LEO propellant depot** – A "Dual Launch Approach". Utilizes an AOTV as CTV, Open supplier for Earth to LEO-KSC access. No SEP tug required, Delta IV-H capability and storable propellant depot required.
- **AOTV with GEO propellant depot and SEP Tug** – Dual Launch. Provides for lowest stressing of launch vehicle capability, but utilizes largest number of architecture elements. Utilizes Atlas 501, Commercial Crew LEO-KSC access, AOTV, Centaur, and a GEO storable propellant depot.
- **OTV with LEO propellant depot** – Dual Launch. Utilizes Atlas 551 (2), Commercial Crew access to LEO-KSC, OTV, Storable propellant depot with SEP tug. Requires development of ACES upper stage.
- **OTV with GEO propellant depot and SEP Tug** – Dual Launch. Utilizes Atlas 551 (2), Commercial Crew access to LEO-KSC, OTV, Storable propellant depot with SEP tug, Centaur.
- **Fully Reusable** – Meaning both APM and DPM are reusable elements**.** Assumes also a cryogenic propellant depot in LEO. Utilizes Atlas 551, Falcon 9 Heavy. Staging of DPM from APM is via GTO, no elements required to be placed in a GYO.

Table 2 - Launch and Docking Event Summary

Operational Concept	Commercial LEO Launches	Atlas 401/ 501	Atlas 551	Delta IV-H	Delta IV-H, RS68 ACES 130		Total Launches	AR&D Events
Capsule Direct					3		3	3
Capsule, Dual Launch		3		3			6	6
Capsule GEO Depot, SEP Tug		3	4				7	8
AOTV LEO Depot	3	1	1	3			8	15
AOTV GEO DEPOT SEP TUG	3	1	4				8	14
OTV LEO Depot	3	4	3		3		13	18
OTV GEO DEPOT SEP TUG	3	1	6				10	18
Fully Reusable APM and DPM	6		1				7	21

To compare these 8 operational concepts for a long term approach, a three mission campaign was assumed. Each mission is on the order of 30-60 days and services 3 satellites. Table 2 summarizes the number of launches and rendezvous events for each approach. The proposed storable propellant depot is capable of supplying enough propellants to the capsule or the AOTV to complete the three missions. From this assessment it was concluded that:

- The Generic Capsule Single Launch is the simplest operational concept with only 1 autonomous rendezvous and docking event per mission (at Habitat/Servicer), but requires development of new CM/SM and the Delta IV-H with the RS68A upgrade and the ACES 130 Upper Stage.
- Inclusion of a LEO depot provides some potential excess cargo to GEO capability and eliminates the need for an upgraded Delta IV-H for the capsule option.
- Operations utilizing a GEO depot would benefit from a rescue-ready tug to mitigate risk due to not having de-orbit propellant on board the crew transport during ascent to GEO. The SEP Tug efficiency eliminates need for any Delta IV-H resulting in potential launch cost savings.

Discipline Analyses

Several design disciplines have significant influence on CTV element sizing and technology level understanding. Enhancing to a basic element definition and sizing process, the disciplines of Aerodynamics, GN&C, Aerothermal and TPS received greater attention than may normally be required in an early-phase concept study. Space vehicles entering Earth's atmosphere from GEO encounter significantly higher heating rates than vehicles reentering from LEO. To understand the intensity and duration of that heating (and its impact on vehicle sizing) required an iterative development across interfaces between the trajectories, heating, and thermal protection system disciplines. Conceptual CAD definition provided general geometric information across discipline boundaries, heuristically-developed mass estimates, and associated general vehicle dimensioning. With this data, thermal protection system performance could be updated based on aerodynamic and aerothermal entry properties and realistic trajectory analysis.

Element Definition/Parameterization

For conceptual quantification of the problem space where specific vehicle information was unknown, a University of Texas at Arlington provided knowledge base / database approach was incorporated [CHU2010]. This Aerospace Vehicle Design (AVD) Lab process provided consistency in vehicle comparisons across a widely varying CTV design tradespace. The approach is grounded in the high TRL area of commercial aeronautics as well as in the lower TRL regime of hypersonic vehicle design. This study provided additional data which was incorporated into the Parametric Sizing segment of AVD. Capsule and hypersonic element design history already incorporated in the parametric sizing procedures was complimented by the addition of much of the knowledge documented over the 1970's thru 1990's on Aeroassisted Orbital Transfer Vehicles, [BOE86, BOE91, MAR87a] and the NASA HL-20 lifting body design. It is informative to the point of necessary to emphasize the large volume of material available for reference on AOTVs. Several hundred references for this topic are available on the NASA Aeronautics and Space Database. At the time of Space Station Freedom (SSF) development AOTV's were seen as a major architecture 3rd exploration component in the makeup of an 1) earth to LEO (Shuttle), 2) LEO waypoint (SSF), and 3) In-Space orbital transfer mechanism (AOTV) capability set. An early version of integrated mission sets based upon the FY89 Civil Needs DataBase and DoD Missions was once established [BOE91] to provide AOTV mission goals and encompass SSF waypoint based servicing missions from GEO to Molnyia to Polar inclinations.

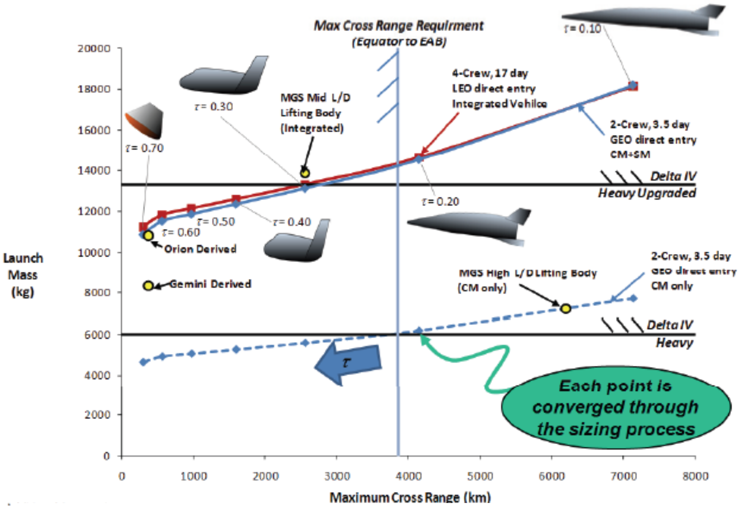


Figure 5 - AVD Vehicle Configuration Search Space

Utilizing personnel at the UTA/AVD laboratory, a suite of elements for crew transfer appropriate to characterize the capsule, lifting brake, raked cone, and ellipsled configurations from Figure 2 were developed. Figure 5 shows the utility of this early concept screening, a trade space of vehicles based upon a fineness ratio (tau) captures vehicle capabilities as a function of entry cross range for a fineness range varying from capsules to hypersonic high L/D configurations.

Multi-Disciplinary Analysis

Given an initial vehicle definition provided by the AVD process, it was next possible to calculate an aerodynamic database (integrated coefficients) to perform entry trajectory analyses. With vehicle definition and a defined nominal entry trajectory, the vehicle's entry heating rate and heating load profile over time were determined, and a multi-material thermal protection mass estimation was made.

For direct entry capsules, characterization of the entry heating environment from GEO was required to estimate adequate thermal protection system masses and define possible material solutions. For the AOTV problem solution space, it was necessary to also characterize the vehicles' ability to perform a controlled aerobraking maneuver in an acceptable entry corridor and then circularize in LEO with minimal ΔV penalty. This implied that the AOTV support the ability to maintain controlled flight in the disperse upper atmosphere, and that a significant amount of aeroheating (due to the GEO entry velocity) must occur to obtain the required velocity shedding to allow circularization at LEO.

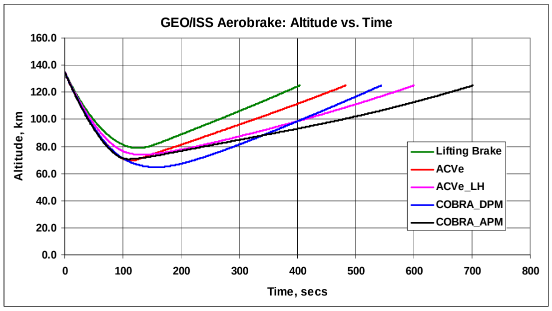


Figure 6 - Entry Trajectories, Altitude vs. Time

For direct entry, capsules and winged vehicles were analyzed. For the dual-taxi concept of operations, deployable lifting brakes, raked cones, and ellipsled configurations were also analyzed. To briefly illustrate the process, consider here the ACVe [BRO2008] lifting brake configuration. Figure 6 shows trajectory altitude vs. time results for multiple AOTV configurations. The lower ballistic coefficient lifting brake vehicles can fly higher and at lower dynamic pressure than the higher ballistic coefficient ellipsled. The ACVe concepts reside in a flight corridor between those two configurations extremes. ACVe – Asymmetric Capsule Vehicle is an entry shape used in MGS to define a rigid aerobrake concept, similar to the AFE [WIL1995] but with a shape slightly more optimized to minimize heating hot spots. Two versions of the ACVe trajectory are shown, with the second being a “Lower Heating” trajectory design to reduce the aerodynamic heating during the aerobraking maneuver. The lower heat rate trajectory results in a more lofted path as compared to the baseline ACVe. The more lofted approach reduces heat rate but incurs longer flight time, resulting in slightly higher integrated heat load. All of these considerations affect TPS sizing, the final step in the process.

With an entry trajectory defined, the aerothermal environment can be characterized for purposes of determining heating profiles as required for TPS sizing. Figure 7 shows max heat rate for ACVe TPS sizing. Working through the sizing process, with a pre-selection of potential reusable insulating TPS materials yields the results shown in Figure 8.

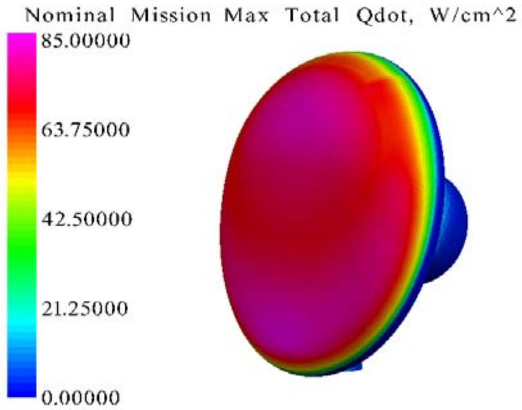


Figure 7 - ACVe Max Entry Heating Rates

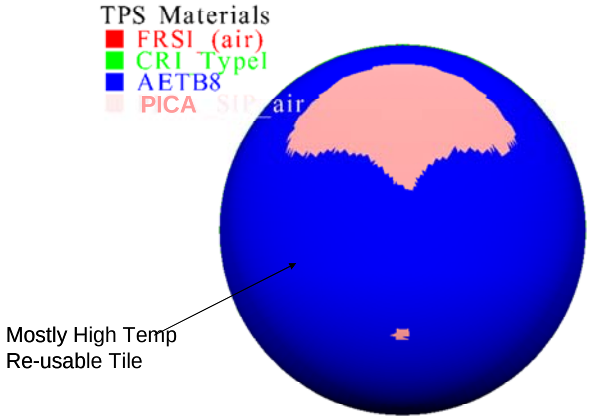


Figure 8 - ACVe Thermal Protection System Material Allocation

Closing the loop with the initial vehicle configuration definition, the knowledge-based design is updated to correlate its mass estimating relationship for TPS with the results calculated via the aero/aerothermal/TPS analysis process. Table 3 presents TPS surface area based weights for three different element configurations.

Table 3 - Thermal Protection System Areal Weights

Concept	Heat Shield (Windward) Areal Mass, kg/m^2	Back Shell (Leeward) Areal Mass, kg/m^2	Average Areal Mass, kg/m^2
Lifting Brake 4170	3.87	1.1	2.16
ACVe	11.4	1.1	5.64
COBRA DPM and APM	11.1	1.32	5.34

In-space trajectory analyses were performed to assess DV requirements, to assess use of lunar fly-by return trajectories, and examine the concept of cycler orbits. Neither of these latter two options appears to be advantageous to the MGS mission. Lunar flyby adds about 5.5 days to a one-way transfer. Depending on the inclination of the LEO waypoint, a 0-10% reduction in required ΔV could be achieved. However, this substantially increased the number of crew days requirement for the CTV, increasing both the system size and the operational risk to the crew.

Near the completion of the study, the element definition and integrated design steps explained above were organized under a common analysis framework, [ROB08]. Figure 9 shows the disciplines and how they interact under the Adaptive Modeling Language framework (AML). The AML core function provides some greater detail in element definition than the AVD process and is integrated with generation of concept descriptive CAD objects. Element sizing is parametric and Figure 10 shows the effect of simple user variation of applied rib and spar parametrics in conjunction with a variation in ballistic coefficient, and aerobrake aspect ratio. Formal implementation of federated NASA Simulation Based Acquisition and Design deployments was recognized as an appropriate future methodology for managing assessment of competing element concepts [JOH98, KEL11].

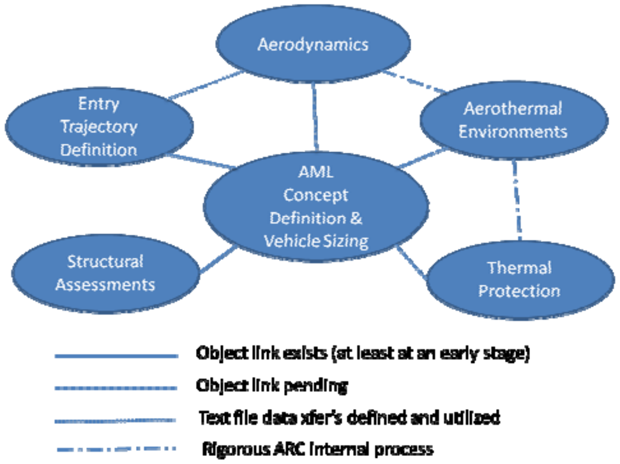


Figure 9- Adaptive Modeling Language Solution Control

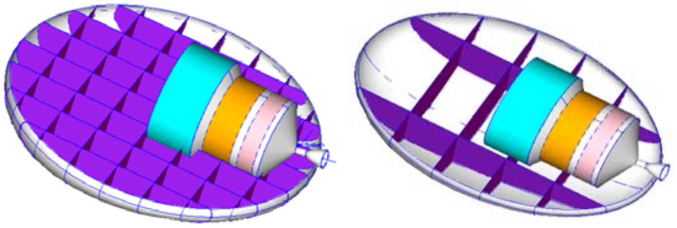


Figure 10 - Geometry and Structural Arrangement Parametric modeling via the Adaptive Modeling Language, (AML)

Element Solutions

In this section, the crew transfer element types are described, along with some quantification of requirements and operational considerations for candidate architecture elements. Combinations of crew size, operational concept, and vehicle selection resulted in more than 40 specific solution paths for meeting the crew transfer functional requirement.

Short Duration Missions

For short term mission architectures, NASA's planned Orion capsule was evaluated as a potential solution. Note that a short-duration MGS mission is more challenging for the CTV, which must serve as the crew habitat for the entire mission. In a short-duration concept of operations, missions were assumed to last approximately two weeks, and crew was accommodated in the crew transfer vehicle the entire time. As launch vehicle throw weight is at a premium for this mission, sizing did not address the need for an airlock element or EVA access. Most likely only some in-situ telerobotic capability would be provided, but a robotic servicer element could be assumed pre-positioned at the servicing location. NASA's Constellation organization provided an Orion-derived vehicle mass estimate (including command module and service module) for the following ground rules and assumptions:

- Crew size: 2-4
- Mission duration: 14-18 days
- HLLV and/or upper stage provides delivery of CTV to GEO (no CTV propellant required)
- CTV provides direct return to equatorial splashdown: 1515 m/s ΔV required

Results of this element sizing are held internal/pre-decisional at this time and so are not available for distribution. It can be said that for short-duration missions with Orion, the existing Delta IV infrastructure could be utilized with a four-launch procedure, in which the un-fueled CM/SM and DCSS elements are launched separately, with two additional launches to supply fuel. A lower number of launches, from three to ultimately one are feasible if the proposed EELV upgrades, noted in supplier payload planners guides [ULA10, ULA07], could be implemented [MOY2011].

Long Duration Missions

Where a habitat is in place to support crew over the life of an MGS mission, the reduction in CTV crew day requirements leads to a broader possibility of vehicle choices. Starting from an historical approach and requiring minimal CTV life support, a Gemini-class vehicle was characterized which provided access directly to GEO (two crew, four crew days) via a Delta IV-H launch [Appendix 2]. Several aggressive assumptions were required to enable this system to be placed into GEO by an existing EELV capability. Composite materials, advanced subsystems, and an assumed zero-growth margin are noted in Appendix 2.

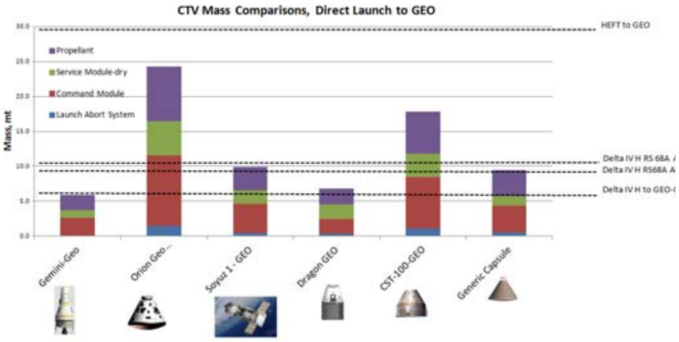


Figure 11 - Single Launch Crew Transfer Vehicles and Launch Vehicle Capabilities

A top level screening of additional capsule-based CTV's were performed; Figure 11 summarizes these options which via increased launch vehicle capability, could provide crew access direct to GEO. The two-person Gemini-class vehicle with advanced subsystem capability is the only concept assessed to have a low enough mass to be launched by an existing launch vehicle. Dragon, Soyuz, and a generic capsule (all with a 3-person crew) were judged to be systems which could be placed in GEO if a Delta IV-H with advanced engines and an advanced upper stage were available. The nature of this study precluded interaction between NASA and element developers. It is left for these developers to assess their own position with regards to MGS mission support. An Orion-class vehicle is shown based on publically available mass properties data, and illustrates that a new heavy lift vehicle would be required to support a single launch of this concept to GEO. For example, at the time of writing of this report, SpaceX corporation announced plans to develop a heavy lift capability of 53mt to LEO by 2014 [SPA2010]. This configuration would not get an Orion-class vehicle to GEO but most likely could place a Boeing CST-100 class vehicle there. Following is a summary of element definitions provided by AVD analyses.

Capsules

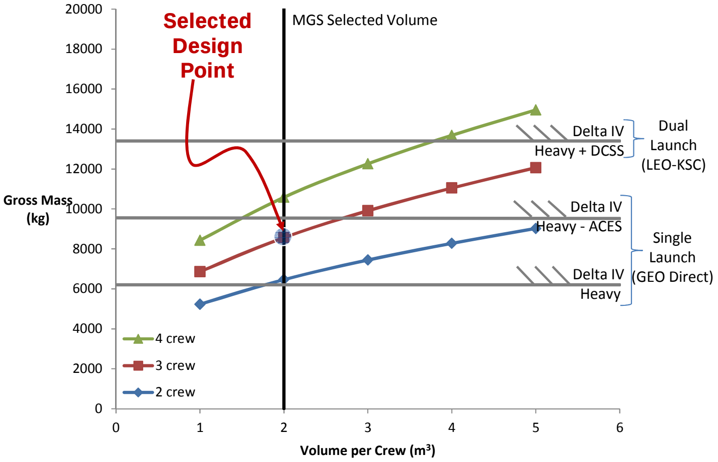


Figure 12 - Effect of number of crew and volume per crew on capsule plus service module gross mass

A generic capsule was utilized to initially characterize the effect of number of crew and volume per crew on CTV element size. Figure 12 compares 2, 3, and 4 crew capsules with varying crew volume to the Delta IV-Heavy maximum launch mass, Delta-IV Heavy with ACES upper stage and dual launch Delta IV heavy with a DCSS ascent propulsion module for transfer from LEO-GEO.

The selected MGS design point allows for three crew with 2m^3 of pressurized volume allocated per crew member. This allocation was determined acceptable for a 2 day transfer time allotment between GEO and LEO. The three crew configuration was selected as the minimum crew required for accomplishing the MGS long duration mission. This design point allows for a dual launch option using the Delta-IV Heavy with an ACES upper stage. Appendix 2 summarizes the mass breakdown for this design point. The mass Functional Breakdown Structure (FBS) of [JSC-26098] was used to tabulate masses for this study and provides commonality with other MGS elements, and historical reference data.

Orbital Transfer Vehicles, Pure Propulsive and Aerobraking Assisted

The OTV/AOTV elements support the long term missions utilizing a dual taxi, LEO waypoint approach. Baseline conditions assume that first leg, Earth to LEO elements have placed an OTV/AOTV at LEO-KSC inclination. OTV/AOTV designs are determined for transfer of crew from LEO at KSC inclination to GEO and back. Thus, a plane change and altitude change define the major ΔV requirements. The study work was broken into two tracks. First, an expendable Ascent Propulsion Module (APM) was assumed which can place the OTV/AOTV directly at the GEO servicing location. This minimizes propellant requirements for the OTV/AOTV having only to change to KSC inclination, deorbit from GEO, and circularize at LEO-KSC. The second track looked at the impact of placing additional ΔV on the OTV/AOTV by having the APM stage in a

GTO fashion. With this approach, the APM as well as the OTV/AOTV can be designed as in-space reusable elements. The APM would return and circularize at LEO-KSC after staging the OTV/AOTV from GTO.

GEO Placement Via an Expendable Ascent Propulsion Module

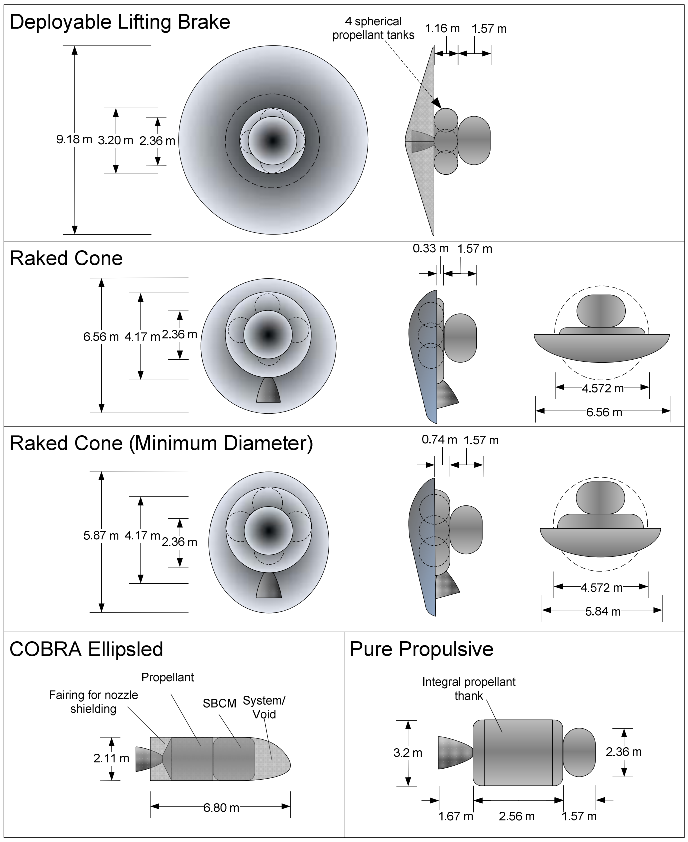


Figure 13- Geometric summary of Five CTV sized concepts

For the Expendable APM trade, five orbital transfer vehicle configurations were examined: a Deployable Aerobrake, Raked Cone, Minimum Diameter Raked Cone, Ellipsled, and a Pure Propulsive Orbital Transfer Vehicle, see Figure 13. The first four of these concepts are AOTV's and the fifth is in the larger category of a general OTV.

The Deployable Lifting Brake consists of a large diameter umbrella style aerobrake which allows for flexible insulator TPS installation over the majority of the brake, complemented with rigid high temperature TPS on the nose. A large deployable diameter reduces ballistic coefficient which enables a higher altitude aeropass, reduced dynamic pressure and aerothermal loads on the structure.

In structural concept contrast, the Raked Cone AOTV utilizes a rigid structure and TPS to increase the durability of the aerobrake while increasing L/D and controllability. This comes at the cost of increased brake mass, ballistic coefficient and packing issues for launch.

The Minimum Diameter Raked Cone is a Raked Cone implementation where sizing in terms of ballistic coefficient is pushed beyond historical design limits. This was done to determine if it was geometrically possible to fit a mission sized Raked Cone into an existing 5 m diameter fairing and what additional TPS technology might be required to handle the increased heat loads.

The Ellipsled AOTV is a scaled down concept from a Mars reentry concept [Gar2010]. High ballistic coefficient and small radii are inherent in this configuration. An attempt to alleviate these concerns was made by increasing the vehicle void volume. The vehicle was scaled up to 15m from the 6.8m required for initial packaging requirements. The result was a vehicle with 75% void volume. This mitigation was not effective and resulted in excessive dry mass increase which negated the propellant savings of the aerobraking concept. Essentially, the propellant required for orbit circularization of the pure propulsive OTV is slightly lighter compared to the aeroshell mass of the scaled-up Ellipsled. The pure propulsive concept is simply a Deorbit Propulsion Module (DPM) integrated with a Space Based Command Module, i.e.: a propulsion unit and crew quarters integration.

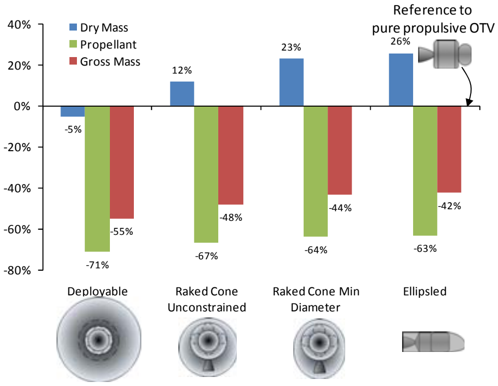


Figure 14 - Comparison of AOTV mass savings relative to a pure propulsive OTV.

Figure 14 provides a mass comparison of the five sized configurations. The reference Pure Propulsive option mass is 16.4 mt. The Deployable Lifting Brake 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, additional aerothermal analysis showed that these solutions were not viable for reusable TPS due to peak heating loads. The Deployable AOTV concept was lighter than the Raked Cone AOTV due to an inherently lighter structures concept and lower ballistic coefficient reduced TPS requirements. The unconstrained diameter Raked Cone was at the limit of current reusable thermal protection system technology.

ISS Waypoint

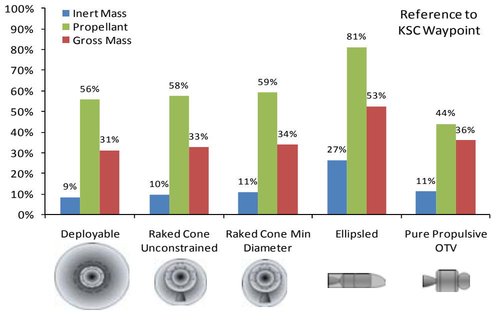


Figure 15 - Comparison of ISS design and KSC design mission AOTV's

The ISS is a potential infrastructure element in MGS missions as it could provide a base for reusable element, in-space repair, and refurbishment, as well as a crew staging location. Previous architecture studies for space exploration prior to the transition from a 28.5 deg inclination space station (Space Station Freedom) proposed this basic operating scenario [BOE91]. The primary penalty for this operational waypoint is the increase in ΔV required for a plane change between ISS and GEO. This penalty may be offset with the potential capability of commercial space companies to place mass at ISS and therefore not be considered as severe a penalty as in the past. That penalty, relative to a LEO-ISS inclination waypoint, is at least a 50% increase in propellant mass across all configurations (Figure 15Figure). The Deployable and Raked Cone AOTV configurations require only a small increase in aero brake diameter to compensate for the increase in propellant mass, whereas the Ellipsled AOTV wetted area increases faster with increasing propellant volume. The Ellipsled dry and propellant masses were more sensitive to increasing ΔV due to the requirement of the TPS to directly shield the SBCM and propellant tanks. Operation from an ISS vicinity waypoint holds attraction based on the potential for in-space crew and logistics staging and the potential to perform in-space reusable element refurbishments from an existing space asset. The penalty in dry mass and thus element development cost is small, but the utility of this location towards becoming cost effective depends on future up-mass propellant placement costs and must be traded against the cost of placing a refurbishment facility at another location. In general, the Deployable/Flexible Lifting Brake and Rigid Raked Cone AOTV shows promise for significant reduction of propellant mass for the crew return to LEO vehicle. The scaled Ellipsled AOTV for this Concept of Operations (ConOp) results in an impractical vehicle. This ConOp does not require enough volume to allow for reasonable large nose radii and sufficiently low ballistic coefficient for an Ellipsled.

GEO Placement via a Reusable Ascent Propulsion Module

For this concept of operations, the APM is now also a reusable system which stages the Crew Transfer Vehicle utilizing a GTO maneuver. The crewed vehicle performs the GEO insertion burn (plane change + circularization). The APM circularizes itself back at LEO-KSC and as before, the crew vehicle returns to LEO-KSC at the end of the mission. This ConOp balances the propellant utilization between the APM and DPM and increases element reusability by adding the APM to the list of reusable vehicles. This ConOp also eliminates the requirement to place the APM into a GYO. Hydrogen fuel is utilized for the APM because of the significant ΔV requirement from LEO to GTO. The crewed vehicle's propulsion system also uses hydrogen fuel for the GEO insertion burn (stored in drop tanks) and then uses methane for the deorbit burn, plane change, and LEO circularization requiring a common dual fuel LH2/CH4 Engine

Figure 16 shows the matrix of Crewed Vehicle and APM options studied for this operational concept. Three CTV's, the deployable lifting brake, raked cone AOTV's, and one pure propulsive OTV were chosen to provide crew accommodation and transport. Four concept vehicles were chosen for potential APM elements, the deployable lifting brake, raked cone, ellipsled, and propulsive options. The Ellipsled was reintroduced in this study because the increased propellant volume of LH2 and staging of payload (CTV) prior to aeropass reduces the ballistic coefficient and increases the body radii relative to the CTV from the expendable APM trade. The CTV option varies across the top of Figure 16, with the corresponding APM option down each row.

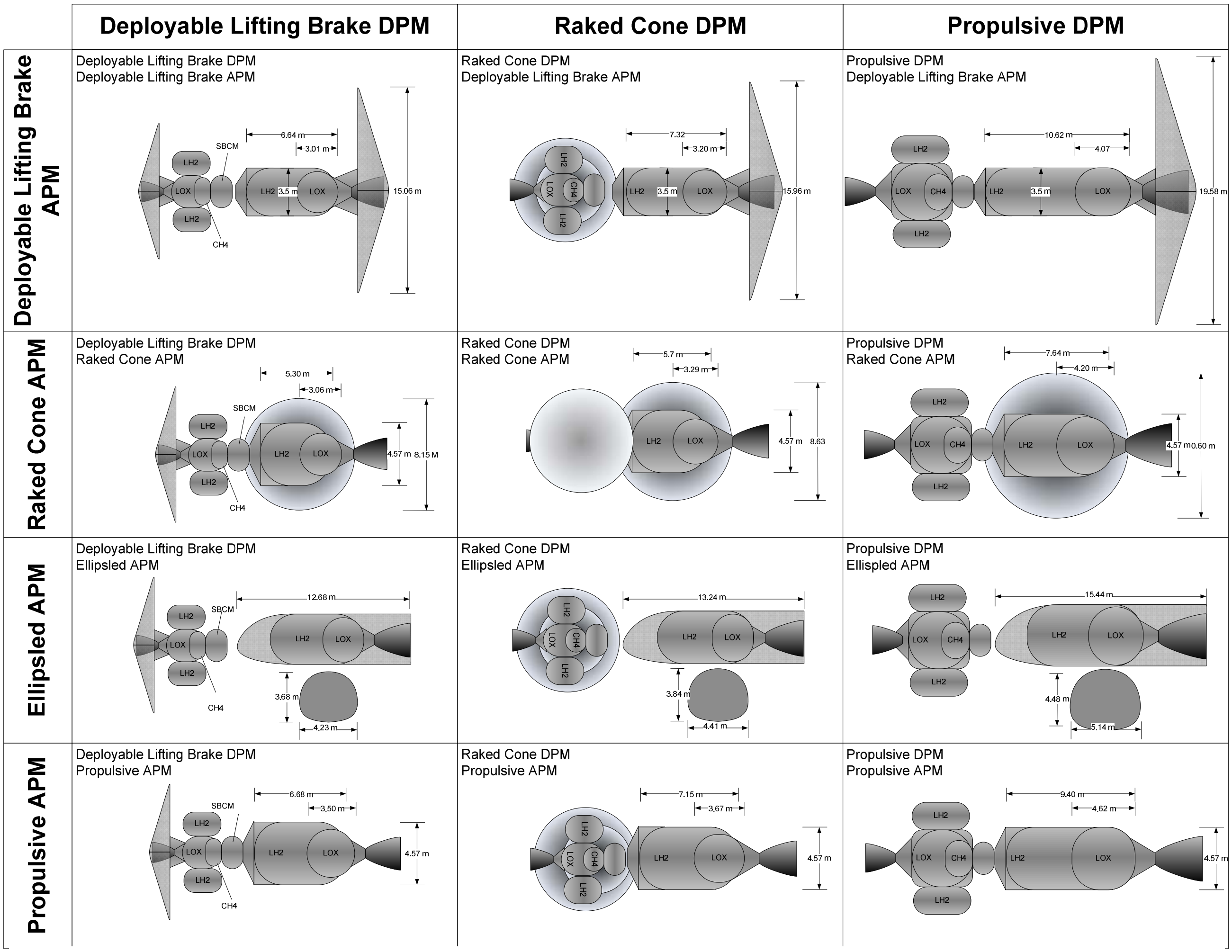


Figure 16 - Geometry summary of 12 CTV DPM+APM sized concepts

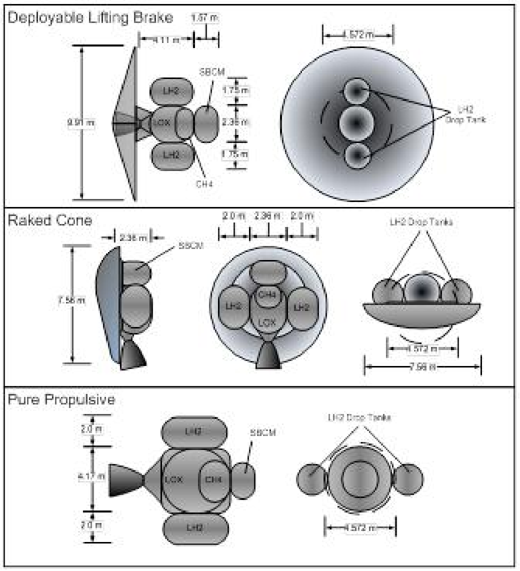


Figure 17 - Geometry summary of 3 CTV DPM sized concepts

Figure 17 shows geometric characteristics of the three sized CTV's, and Figure 18 presents the mass comparison. As with the CTV from the expendable APM trade, the larger GEO insertion CTV benefits greatly from aerobraking in terms of propellant mass. The Raked Cone rigid structure results in an increased dry mass relative to the Pure Propulsive AOTV; however, the reduction in propellant mass more than compensates for the dry mass increase. Overall, the AOTV concepts show significant gross mass reduction which will allow for decreased propellant and dry mass of the reusable APM as well.

The AOTV APM trades showed a 20% reduction in propellant mass, which is a much lower reduction as compared to the 50% propellant mass reduction found in the CTV (crewed element) trades. This reduced benefit is the result of the relatively low APM empty weight reentry mass as compared to the crewed element. The reduced down mass aids the propulsive OTV by decreasing the chemical energy required for LEO circularization. Since the AOTV-APM concepts utilize aerobraking to alleviate the chemical energy required for LEO circularization, the reduction in down mass benefits the propulsive OTV more than the AOTV concepts.

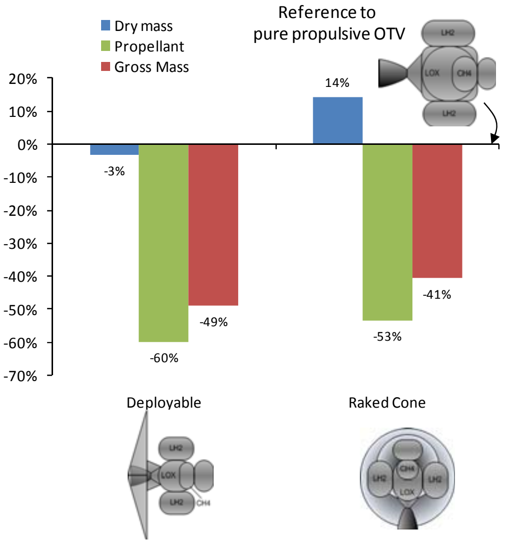


Figure 18- Mass Comparison of LEO CTV's for the reusable APM trades

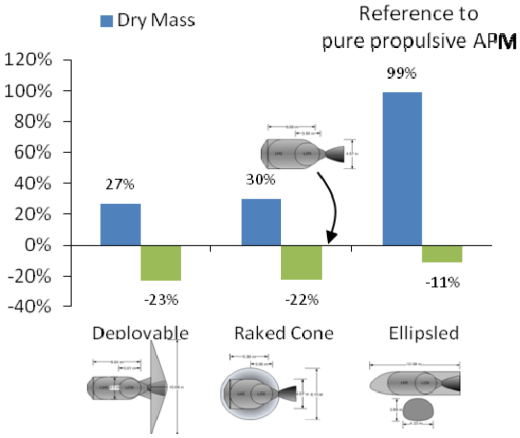


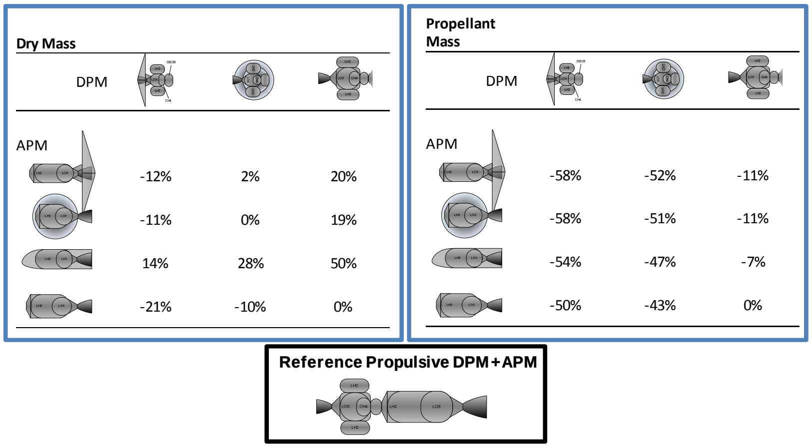
Figure 19 - Comparison LEO APM concepts sized for Deployable Lifting Brake AOTV

The Ellipsled suffers from a larger dry mass penalty compared to the Deployable and Raked Cone concepts. This results from the increased wetted area which must be shielded with reusable TPS. The volume requirement of LH2 allows for a larger and more practical Ellipsled, but requires a larger surface area which must be protected. Overall, the Ellipsled only offers half the propellant savings found with the Deployable and Raked Cone concepts (Figure 19). The Ellipsled may offer advantages in launch packaging, increased controllability during aeropass, and increased inherent durability, relative to a deployable lifting brake concept.

When comparing the dry, propellant and gross masses of the total APM+CTV system, it is clear that the primary driver for selecting the AOTV-CTV is the reduced total propellant mass with selection of the APM as a secondary driver (Figure 20). 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 having a 10 to 20% effect on the total propellant mass.

The Reusable APM and DPM trade space shows that the Deployable or Raked Cone DPM concepts will provide similar propellant mass, with the Raked Cone dry mass estimated at 10% heavier due to the rigid structure and a higher ballistic coefficient. The APM does benefit from an AOTV concept, however, the selection between the AOTV concepts may come from metrics such as reliability and/or reusability rather than mass alone. From a mass standpoint, all AOTV, APM, and DPM concepts could provide a propellant mass saving with a sufficiently high flight rate and reusable element space based maintenance costs. Cost comparisons were not a figure of merit in the MGS study.

The staging of the DPM results in a significant reduction in mass for LEO circularization. Thus, the pure propulsive OTV is not as severely penalized as found with the CTV element. As such, the AOTV's percent improvements were significantly lower than found with DPM. The Ellipsled has a greater TPS wetted area relative to the Deployable and Raked Cone concept. As such, the increased LH2 volume resulted in a significant increase in dry mass over the propulsive OTV. The resulting propellant savings is tempered to only 11 %



Dry Mass			
DPM			
APM			
	-12%	2%	20%
	-11%	0%	19%
	14%	28%	50%
	-21%	-10%	0%

Propellant Mass			
DPM			
APM			
	-58%	-52%	-11%
	-58%	-51%	-11%
	-54%	-47%	-7%
	-50%	-43%	0%

Reference Propulsive DPM+APM

Figure 20– Mass Comparison 12 DPM+APM concepts relative to the propulsive option.

CTV Selection Criteria

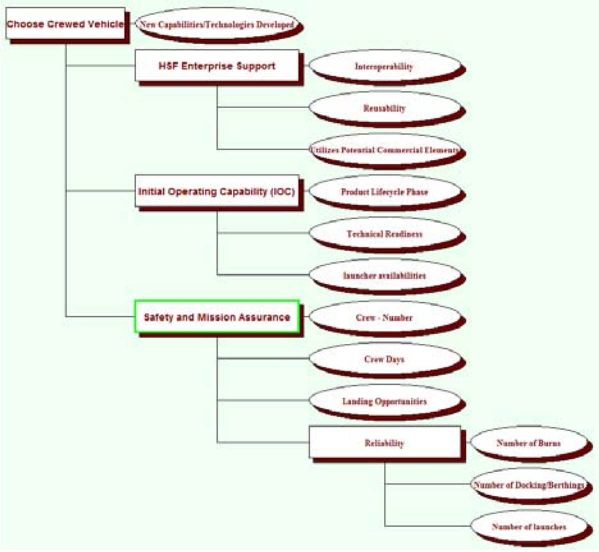


Figure 21 - Sample Figure of Merit Decision Hierarchy for a Crew Transfer Vehicle Selection

Selection of a particular crew transfer vehicle was not a goal of this study. However, an understanding of the influences on that decision process and its effecting factors was desired. A sample vehicle selection decision analysis hierarchy to illustrating possible figures of merit involved is shown in Figure 21.
The ultimate decision goal would be to choose a crewed vehicle to develop. Four possible main figures of merit that affect the decision for MGS are:

1) What new capabilities and technologies are developed for a particular crew vehicle selection?
2) How well are NASA's broader goals in future Human Space Flight enhanced by the decision?
3) How soon can the selected vehicle be in operation (IOC)?
4) How certain am I that the selection will perform adequately and with sufficient safety and reliability features?

Each factor can be assessed on its own merit as in the case of "new capabilities/technologies developed", or it can be assessed based on a role up of subfactors, as the remaining three are. Each of these three is assessed thru quantification of their second level factors. This process was facilitated through the use of commercial decision analysis software. The graphic is an implementation of the problem within the Logical Decision Works software [LOG2007] and displaying the decision hierarchy view.

It can be expected from a stakeholder viewpoint that certain of these factors may be more important to one stakeholder than another. For example, NASA's technology development organization, Office of the Chief Technologist (OCT) could be more interested in developing new capabilities then the [at that time] spaceflight operations directorate, SOMD. SOMD may be more interested in an early IOC. All may be equally interested in Safety and Mission Assurance (S&MA). To determine weighting factor impact on a decision, the figures of merit can be weighted by each stakeholder and a decision ranking performed. If the same vehicle were to be chosen despite variations in weighting inputs, all stakeholders might be equally satisfied. If different vehicles were better for each stakeholder, the process provides at least a mechanism to adjust, assess, and adjudicate weighting factor differences between stakeholders and arrive at a compromise solution. Figure 22 shows how different weighting values for the figures of merit may result in different selection outcomes. The left-hand graphic shows results of a notional SOMD weighted figure of merit set, where near term capsule vehicles may provide the best solution. If OCT more strongly influenced the factor weightings, the desire to push technology and develop in-space transportation capabilities might mean that an AOTV would be the preferred element to proceed with, as depicted in the right-hand graphic.

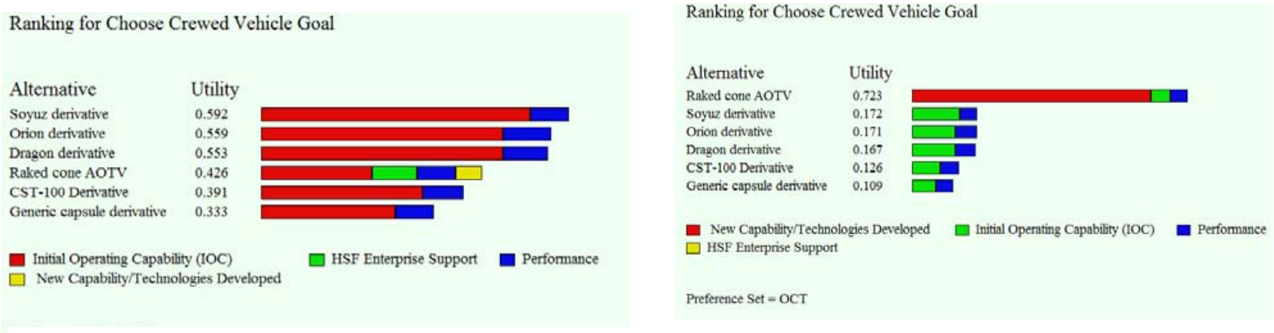


Figure 22 - Weighting Factor Impact on Vehicle Selection

Technologies

The primary study result was to identify those technologies that would either enable or significantly enhance the MGS mission and ideally simultaneously provide extensibility to future long term based Human Space Flight endeavors. Crew Transfer technologies were not judged to be enabling to an MGS mission as there are technology solutions available to satisfy some architecture options. The technology outlook for direct access crew transfer and return from GEO did not require any significant innovative solutions. Capsule vehicles have prior history in returning to Earth from energetic orbits beyond GEO. Capsule vehicles performing direct return are envisioned to require thermal protection system refurbishment if utilized in a reusable manner. The general approach to making capsule vehicles more fully reusable/refurbishable would be a technology focus for direct access capsule architectures. However two Crew Transfer Vehicle technology development items were characterized as Enhancing to the implementation of an MGS mission, Table 4 .

Table 4 – Crew Transfer Enhancing Technologies

Item #	Capability/Technology	Discussion
1	AOTV Capability	Several concepts are being or have been developed to early stages. MGS could provide flight validation to one or more.
2	High Temperature Capability Reusable Thermal Protection Systems	Required for AOTV elements. Possibly required as a refurbishable system for reusable capsule possibilities.

AOTV Capability: To build a reliable and efficient in-space crew transportation system, AOTV concepts are first identified as a propellant-efficient alternative to purely chemical propulsive elements. Experiments similar to those proposed in prior infrastructure development initiatives [Wil95] could be incorporated into the MGS DDT&E project tasking. Reusability pushes development of a suite of space transportation enhancing technologies, such as in-space maintenance, reusable engines, reusable manned composite structures, reusable cryogenic propellant tanks and reusable TPS. All of these technologies should be developed to an understandable and acceptable level of reliability thru unmanned element development such that later commitment to use in operationally manned vehicles becomes a lesser extension of a more matured technology.

High Temperature Capability Reusable Thermal Protection Systems: NASA’s exploration plans already have created a need for technology improvements in this area [Adl2010]. MGS identified use of TUFROC (Toughened Uni-piece Fibrous Reinforced Oxidation-resistant Composite), Multi-layer graded Ablators and high temperature flexible systems like PICA-Flex, and additional systems to improve system mass efficiencies and reusable characteristics. Current reusable TPS materials have limited temperature capability and are relatively heavy, typically in use for leading edge applications, as opposed to acreage application.

Table 5 lists six additional crew transfer function-derived technologies which arose through development of the tradespace but were not necessarily quantitatively assessed. For example, item #4 notes that OTVs will inherently require reusable engines. The degree to which that reusability exceeds the state of the art will depend on how an OTV/AOTV is utilized and how much operational maintenance might be available. This and the remaining items are listed to note possible technology developments which could contribute to a successful efficient MGS crew transfer capability but would have to be assessed as appropriate in more in depth concept development studies.

Table 5 – Additional Crew Transfer Technologies

Item #	Capability/Technology	Discussion
3	Reusable Composite Cryogenic Propellant Tanks	MGS could be a mechanism to demonstrate this currently TRL 6 capability as space operational. Though not required for most CTV approaches, a reusable APM could leverage this capability. If a reusable APM was pursued, or if the OTV DPM provided LOX/LH2 propulsion for insertion to GEO from GTO, then both reusable composite cryogenic LH2 and LOX and tanks could be in the development plans. Current NASA OCT technology

		studies are addressing the general question of trying to increase the TRL for composite cryogenic tanks [HOD2011].
4	Reusable engines, MMH/NTO and LOX/LH2, space based no/low maintenance	AOTVs need to demonstrate propulsion element reusability. DPM elements typically using MMH/NTO and reusable APMs utilizing LOX/LH2.
5	In space autonomous element integration	Unlike possible proven docking mechanisms, structures will have to be autonomously linked which may have much different interface definitions.
6	Propellant Transfer, Refuelable APM and DPM	Automated storable and cryogenic propellant transfer technologies could be perfected.
7	Reusable dual fuel lh2/methane engine	Useful for an AOTV which is staged at GTO and could propel itself to the GEO orbital position using LOX/LH2 for that burn. The storable LOX/LCH4 is used after the CTV on-habitat quiescent period to provide the deorbit plane change and descent burn. Saves mass by letting both propellant systems utilize the same propulsion engine(s).
8	Mid Air Recovery	Not studied – recognized as a means to provide operational flexibility to direct entry capsule elements.
9	Launch vehicle propellant cross feed	Noted in EELV payload planners documents that such capability is planned, provides significant throw weight to LEO capability and if developed eases the design mass limit burden for placing assets in orbit. Commercially implemented via plans for the Space-X Falcon 9 Heavy.

Exploration and HSF Extensibility

Another MGS study goal was to provide an understanding of technologies and capabilities proposed in relation to their support of NASA's Exploration and Human Space Flight goals.

Table 6 – Capability Commonalities of MGS Crew Transfer with OCT Critical EDL Capabilities

Mission	Critical EDL Capabilities	Comments
Crewed orbital velocity return	Large-scale Earth EDL	NASA and/or commercial vehicles
Lunar sample return	Lunar landing / Earth EDL of sample	New Frontiers
Asteroid sample return	Asteroid touch and go, proximity operations / Earth EDL of sample	New Frontiers
Venus lander	Extreme environment TPS	New Frontiers
Saturn probes	Low Mass Extreme environment TPS	New Frontiers
Mars sample return sample acquisition	1-2 t class Mars EDL	Advanced from MSL
ISS down-mass capability	Low cost TPS, deployable decelerators	HIAD testing and application
Crewed high-velocity Earth return	Low mass TPS	From HEO in preparation for asteroid mission
Mars sample return orbiter	High reliability TPS and SRC (planetary protection)	Planetary protection requirements
Mars sample return	Precision landing, deployable decelerators	Meets up with sample cache left on

surface rendezvous		surface
Crewed asteroid rendezvous and return	High-q low mass reliable TPS	Low gravity proximity ops, hover, touch, land
Mars network	Guidance, small low cost SRC	Seismology
Titan aerial vehicle, landers/splashers	Titan entry, descent and deploy, Titan EDL	Flagship mission
Crewed Mars orbiter	Aerocapture, possible crewed Phobos landing: Mid L/D or Large Deployable Decelerator for Aerocapture	
Crewed Mars surface	Mars large EDL: SRP, Mid L/D or Large Deployable Decelerator	~30 metric tons lander
Icy moon lander	Icy moon EDL	e.g., Europa, Enceladus

🟦 High commonality with OCT Critical EDL capabilities

🟨 Related commonality with OCT Critical EDL capabilities

Table 6 is taken from NASA's Office of the Chief Technologist's 2010 road mapping effort [ADL2010], and as highlighted, provides a mapping of MGS crew transfer capability to the Entry Descent and Landing Technology roadmap. These OCT identified missions and critical technologies can be mapped to MGS capabilities. Missions highlighted in green would highly benefit from capabilities and technologies which can be matured in a fast-paced MGS crew transfer demonstrator mission. The common link between MGS and this list is the fact that MGS can develop Entry Descent and Landing (EDL) technologies for thermal protection systems utilized for GEO return velocity or possibly even greater entry velocities, and could prove out integrated system testing of one or more aeroassisted entry concept vehicles. MGS CTV element maturation could proceed from unmanned to manned demonstrator missions to safely grow these capabilities. Missions highlighted in yellow could also benefit from MGS contributions to understanding of EDL solutions, but are not as directly applicable because they may be at an entry environment not based at Earth or have lower than GEO entry speeds. MGS CTV demonstrations can contribute understanding to 14 of the listed 16 missions; 6 of them by addressing the high speed entry problem while encapsulating some downmass, and 5 of these 6 are pertinent to an Earth entry environment.

Conclusions

Crew Transfer Vehicle analysis for MGS has identified possible technologies for future NASA planning activities, and also identified an array of elements and operating concepts that may be considered in government or commercial operational and architectural planning. These elements are not so conceptually new as to be out of reasonable reach, and in fact have a broad basis of support based on NASA's mission planning from the LEO Access, Space Station based, and In-Space Operations focused planning of the post-Apollo years. Near term access may be provided via capsule type elements while a longer term goal of building up in-space reusable infrastructure elements can be instantiated thru progressive development of propellant depots, unmanned and eventually manned OTV's and AOTV's. A "dual-taxi" mission leg fractionation enables more element providers; Government, commercial, and international, to participate by requiring CTV's for Earth to Orbit as well as for LEO waypoint to GEO operational site crew movement. Positioning the waypoint in the vicinity of ISS is operationally advantageous, but will require a greater capability to stage propellant in-space. Development of ISS and new refurbishment elements in the vicinity of ISS as noted in historical studies, improves the success outlook for implementation of in-space reusable transportation elements. Additional element developers might desire to consider how their product array can evolve to support the MGS mission.

Because of the large tradespace and multiple architecture solution approaches considered for MGS crew transfer, formal tracking and control of design studies was recognized as an analysis process which should be formally defined. A NASA Simulation Based Acquisition approach could provide this computational framework and permit integration and evaluation of transportation elements from multiple suppliers within a collaborative, distributed, NASA space operations federation. Such simulations would serve to evaluate element growth paths over time and quantify cost and schedule characteristics of competing and developing MGS and general NASA exploration activities. Simulations can also compare and contrast various element provider methods of supplying propellant needs to LEO and GEO operating sites. Initial utilization of storable propellant depots assists MGS crew transfer functionality. Evolution of this capability towards more advanced systems, such as cryogenic propellant storage depots, could be traded from a system figure of merit viewpoint.

Two technologies were identified as enhancing to the MGS crew transfer capability; AOTV's, and higher heat rate capable reusable thermal protection systems. AOTV's showed propellant mass efficiency promise for operating reusably and efficiently between LEO and GEO. Further study and industry insight is required to select between competing concepts, though a deployable lifting brake and a rigid raked cone appear feasible from this studies results. Winged bodies were identified as useful in that they can perform aeroassisted plane changes on entry. When used in a GEO to LEO circuit, they could also provide abort to earth entry capability which an AOTV based CTV cannot. However, the TPS technology is still recognized as incapable of supporting this mission without being at least refurbishable as opposed to fully reusable. Lightweight higher heat rate capable systems for thermal protection such as TUFROC and PICA-Flex will be needed to evolve to certain reusable AOTV solutions.

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Appendix 1

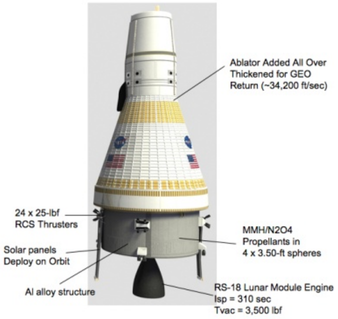
MGS - Crew Transfer - Contributors and Affiliations

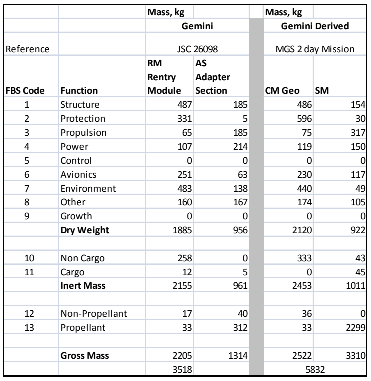
Name	Discipline	Affiliation
John Bergmann	Hypersonics Consultant	DARPA-SETA/Centra Technology Inc.
Jeff Bowles	Aero/Aerothermal/TPS	NASA ARC
Jeff Cerro	Task management	NASA LaRC
Bernd Chudoba	Concept Definition	University of Texas at Arlington
Gary Coleman	Concept Definition	University of Texas at Arlington
Tim Dawn	GN&C – In Space	NASA JSC
Veronica Hawke	Design	Science and Technology Corp.
Ryan Leo	Hypersonics Consultant	DARPA-SETA/Centra Technology Inc.
Mark McMillin	Concept Definition	NASA LaRC
Steve Nunez	Constellation Program	NASA JSC
Roger Schwarz	Technology	NASA JSC
Ron Sostaric	GN&C – entry	NASA JSC
Ted Talay	Concept Definition	John Frassanito & Associates
Alexander Te	Design	Science and Technology Corp.
Carlie Zumwalt	GN&C – entry	NASA JSC

Appendix 2

Element Functional Mass Breakdowns

Long Duration MGS Mission, (short endurance CTV) Element sizing estimated from a baseline NASA Gemini capsule [JSC26098].





		Mass, kg		**Mass, kg**	
		Gemini		**Gemini Derived**	
Reference		JSC 26098		MGS 2 day Mission	
FBS Code	**Function**	**RM Rentry Module**	**AS Adapter Section**	**CM Geo**	**SM**
1	Structure	487	185	486	154
2	Protection	331	5	596	30
3	Propulsion	65	185	75	317
4	Power	107	214	119	150
5	Control	0	0	0	0
6	Avionics	251	63	230	117
7	Environment	483	138	440	49
8	Other	160	167	174	105
9	Growth	0	0	0	0
	Dry Weight	1885	956	2120	922
10	Non Cargo	258	0	333	43
11	Cargo	12	5	0	45
	Inert Mass	2155	961	2453	1011
12	Non-Propellant	17	40	36	0
13	Propellant	33	312	33	2299
	Gross Mass	2205	1314	2522	3310
		3518		5832	

- 2 Crew, 4 Crew-Day capacity
- Allowance made for increased thermal protection system mass to cover GEO entry heating
- Composite main structures vs metallic baseline
- 10% Avionics mass reduction
- Hypergolic bi-prop descent propulsion system replaced with a LOX/LCH4 system, RS-18 @ Isp 345s
- No Growth Allocation

Table 7 - Design Mass Summary for Generic Capsule

mass, kg

-

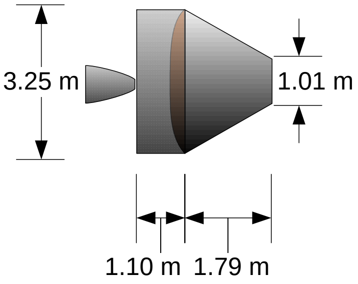
FBS code	Function	CM	SM	Total	Geometry
1	Structure	570	237	807	
2	TPS	188	-	188	
3	Main Propulsion	0	385	385	
4+5+6+7	Systems	1827	474	2300	
8	Other	155	0	155	
9	Growth	556	219	775	
	Dry Weight	3295	1315	4610	
10	Non Cargo	420	0	420	
11	Cargo	45	0	45	
	Inert Mass	3760	1315	5075	
12	Non-Propellant	70	0	70	
13	Propellant	0	3384	3384	
	Gross Mass	3830	4698	8528	

Table 8 - Summary for 5 CTV Vehicles

Mass (kg)

FBS code	CTV	Deployable	Raked Cone	Raked Cone (min diameter)	Ellipsled	POTV
1	Structure	864	865	939	918	516
	SBCM+DPM2	473	463	467	918	516
	Aerobrake	166	402	472	-	-
2	TPS	224	412	595	550	-
3	Propulsion	421	479	517	526	795
4,5,6,7	Systems	1441	1453	1480	1617	1537
8	Other	0	0	0	0	0
9	Growth	571	671	738	755	627
	Dry Mass	3296	3880	4268	4367	3475
			0			
10	Non Cargo	420	420	420	420	420
11	Cargo	45	45	45	45	45
	Inert Mass	3761	4345	4733	4832	3940
12	Non-Propellant	70	70	70	70	70
13	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		

Grayed out entries violate solution space entry heating capabilities.

Table 9 - Mass Summary for the 3 DPM vehicles of the Reusable APM trade

Mass (kg)

FBS code	CTV	Deployable	Raked Cone	POTV
1	Structure	802	1144	530
	SBCM+DPM2	587	612	530
	Aerobrake	215	533	-
2	TPS	273	396	-
3	Propulsion	1286	1461	2063
4,5,6,7	Systems	1705	1788	1614
8	Other	0	0	0
9	Growth	780	923	802
	Dry Mass	4846	5713	5009
10	Non Cargo	420	420	420
11	Cargo	45	45	45
	Inert Mass	5311	6178	5474
12	Non-Propellant	70	70	70
13	Propellant	9345	10871	23263
	Reentry Mass	5381	6267	-
	Gross Mass	14725	17120	28807

Table 10- Reusable APM Mass Summary, 4 APM concepts by 3 DPM Concepts

mass, kg FBS Code	Function	Deployable Lifting Break APM			Raked Cone APM		
		Deployable DPM	Raked Cone DPM	Propulsive DPM	Deployable DPM	Raked Cone DPM	Propulsive DPM
1	Structure	1036	1186	1904	1220	1392	2215
	PM	740	854	1404	743	856	1408
	Aerobrake	296	332	500	478	536	807
2	TPS	512	574	864	416	205	308
3	Propulsion	2158	2415	3575	2164	2422	3585
4+5+6+7	Systems	480	513	666	487	521	677
8	Other	0	0	1	0	0	1
9	Growth	898	1008	1517	919	1032	1552
	Dry Weight	5084	5697	8528	5206	5571	8337
10	Non Cargo	0	0	0	0	0	0
11	Cargo	14725	17121	28807	14725	17121	28807
	Inert Mass	19809	22818	37335	19931	22692	37144
12	Non-Propellant	0	0	0	0	0	0
13	Propellant	15376	17704	28931	15477	17818	29101
	Reentry Mass	5526	6201	9332	5656	6348	9550
	Gross Mass	35185	40522	66266	35408	40510	66245

mass, kg FBS Code	Function	Ellipsled APM			Propulsive APM		
		Deployable DPM	Raked Cone DPM	Propulsive DPM	Deployable DPM	Raked Cone DPM	Propulsive DPM
1	Structure	2104	2279	3026	449	485	659
	PM	2104	2279	3026	449	485	659
	Aerobrake	-	-	-	-	-	-
2	TPS	1534	1657	2183	-	-	-
3	Propulsion	2301	2560	3723	2397	2666	3877
4+5+6+7	Systems	626	665	835	428	450	554
8	Other	0	0	1	0	0	1
9	Growth	1384	1513	2080	722	798	1142
	Dry Weight	7949	8674	11847	3996	4400	6233
10	Non Cargo	0	0	0	0	0	0
11	Cargo	14725	17121	28807	14725	17121	28807
	Inert Mass	22674	25795	40654	18721	21521	35040
12	Non-Propellant	0	0	0	0	0	0
13	Propellant	17698	20117	31623	19943	22670	35685
	Reentry Mass	8513	9306	12795	-	-	-
	Gross Mass	40372	45913	72277	38664	44191	70725

Biography:

Jeff Cerro has 30 years of experience at the NASA Langley Research Center. He is currently a structural and vehicle systems analyst in the Vehicle Analysis Branch and is supporting work to advance NASA's initiatives in the areas of space exploration and orbital access. In 2011 Mr. Cerro was the team lead for the "Crew Transportation" portion of the subject Manned GEO Servicing study. This document is a consolidation of the work performed on that task by the team members identified in the appendix of this report. Mr. Cerro is a registered Professional Engineer with a Masters in Mechanical Engineering from Rensselaer Polytechnic Institute. He is currently Executive Vice-President of the SAWE, and a member of the International Council on Systems Engineering, and the American Institute of Aeronautics and Astronautics.