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Evaluation of Applications of ESAS Cargo Launch Vehicle to Manned Mars Mission

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This paper reports on an investigation of possible Launch and Trans-Mars Injection options using the Exploration Systems Architecture Study (ESAS) Cargo Launch Vehicle (CaLV) and Earth Departure Stages (EDS) for crewed Mars missions The purpose of such an investigation is to characterize some of the potential challenges and technological needs for modifying the present lunar architecture for transport to Mars. An analysis was performed to provide a relationship between the payload placed in orbit, usable propellant available in orbit, and the required propellant to perform the Trans-Mars Injection. This relationship was used to investigate several payload manifests and launch strategy options and to perform some trades to identify advantageous launch solutions. The Mars Design Reference Mission from 1998 was used to provide a representative Mars payload and mission architecture for the study. It was found that 6 and 5 launch solutions are possible without the implementation of any new technologies. It was also found that adding the ability to efficiently transfer propellants between Earth Departure Stages and developing boil-off elimination technologies improves performance to 4-launch solutions. Further reduction of launches exceeds constraints on the launch vehicle such as payload capacity and height constraints.

Nomenclature

Acronyms

APAS = Aerodynamic Preliminary Analysis System
CEV = Crew Exploration Vehicle
CaLV = Cargo Launch Vehicle
CLV = Crew Launch Vehicle
DIPS = Dynamic Isotope Power System
DRM = Design Reference Mission
EDS = Earth Departure Stage
ERV = Earth Return Vehicle
ESAS = Exploration Systems Architecture Study
EVA = Extra-Vehicular Activity
FOM = Figure of Merit
IMLEO = Initial Mass in Low Earth Orbit
ISRU = In-Situ Resource Utilization
LEO = Low Earth Orbit
LSAM = Lunar Surface Access Module
MER = Mass Estimating Relationship
MOI = Mars Orbit Insertion
MR = Mass Ratio
NTP = Nuclear Thermal Propulsion
SRB = Solid Rocket Booster
SSME = Space Shuttle Main Engine
TLI = Trans-Lunar Injection
TMI = Trans-Mars Injection
TXI = Generic Injection Burn

Symbols

g_0 = Gravitational Constant (Earth Sea Level Gravity), m / s^2
I_{sp} = Specific Impulse, s
L_{tank} = Tank Length, m
m_{ab} = Aerobrake Mass, mT
m_{cargo} = Cargo Mass, mT
m_{crew} = Crew Mass, mT
m_{dry} = Stage Dry Mass, mT
m_{ecrv} = Earth Crew Return Vehicle Mass, mT
m_P or m_p = Propellant Mass, mT
m_{misc} = Miscellaneous Payload Mass, mT
$m_{P/L}$ = Payload Mass, mT
m_{pyld} = Mars DRM v.3.0 Trans-Mars Injection

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NTR	=	Nuclear Thermal Rocket
PVA	=	Photo-Voltaic Array
PMAD	=	Power Management And Distribution
POST	=	Program to Optimize Simulated Trajectories
RCS	=	Reaction Control System
ROI	=	Return on Investment
		Payload Element Mass, mT
m_{retHab}	=	Earth Return Vehicle Habitat Mass, mT
m_S	=	Stage Empty Mass, mT
m_{stage}	=	Trans-Mars Injection Stage Mass, mT
$m_{transHab}$	=	Crew Lander Transfer Habitat Mass, mT
ΔV	=	Change in Velocity, m/s

Introduction

Mars mission planning has been offering solutions to the human Mars exploration problem for the past 50+ years.[1] The proposed concepts have ranged from practical stances seeking to utilize only currently available infrastructures and technologies to the far-reaching concepts requiring a technological leap into the future beyond the state-of-the-art. While both have been useful in shaping the way such planning has evolved over the years, the current programmatic desire to minimize cost and risk drives the desire to reuse as much of the currently available infrastructure as possible in future planning efforts. The advantages of reusing available resources are transparent. For example, suppose it is possible to use a currently existing launch vehicle. This results in significant overall cost reductions. Lower development cost result since the system has already been designed and rated for space. Production costs decrease since the facilities, tooling, and production methods already exist. A decrease in operations costs occurs when the familiarity exists with the current system saving training costs, launch facility costs, etc. Risk is also reduced since the system has already been tested and flown.

In response to the desire to reuse currently available systems, the primary purpose of this paper is to determine advantageous solutions to achieve manned Mars exploration with little to no modification to the recently proposed infrastructure and technologies of the Exploration Systems Architecture Study (ESAS).[2] This paper also seeks to identify the most advantageous technology investments and any time critical technological implementations to ensure the success of Mars exploration efforts. The focus of this paper is to report upon an investigation into the Launch and Trans-Mars Injection (TMI) possibilities using the current Cargo Launch Vehicle (CaLV). The goals are to first determine if it is possible to perform the mission at all with the current launch vehicles and upper stages, then to characterize the best ways to accomplish the ascent and TMI burn with the current architecture to minimize launches necessary and increase the flexibility for larger payloads. This paper first discusses the currently available infrastructure to understand what vehicles and technologies are desired. The paper then discusses the manned Mars architecture and a representative Mars payload and associated assumptions used for the purpose of this study. Then a launch vehicle capability analysis is described to allow for several payload manifests and launch strategies to be investigated. Several of these architectural and payload trades are then discussed leading to the conclusions that can be drawn from the observances about sending payloads to Mars most effectively.

I. Currently Available Architecture[2]

In the fall of 2005, NASA released the Exploration Systems Architecture Study[2] (ESAS), which suggests a possible architecture to return to the Moon and fulfill the President's Vision for Space Exploration. This study suggests a 1.5 launch solution, which uses two types of launch vehicles as illustrated in Figure 1. The first vehicle, the Cargo Launch Vehicle (CaLV or Ares 5), is used to launch the lunar lander known as the Lunar Surface Access Module (LSAM) to Low-Earth Orbit (LEO). The launch vehicle consists of a first or "core" stage which is equipped with 5

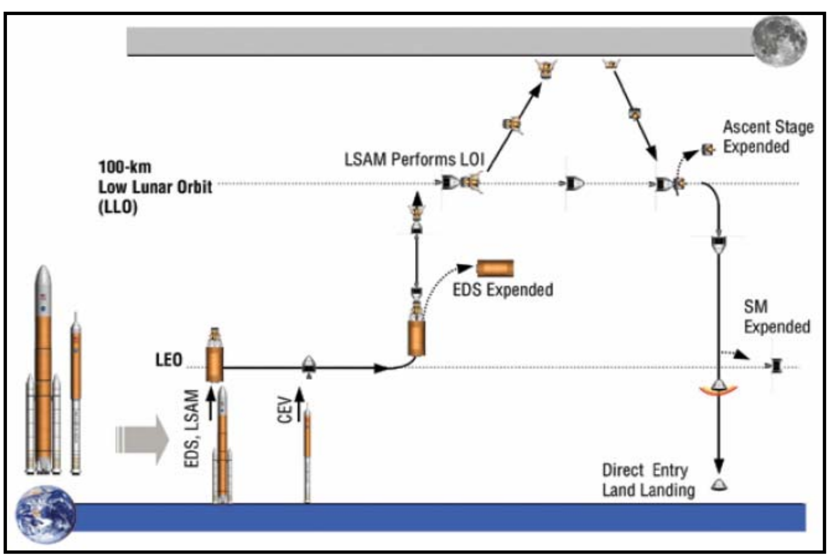

Figure 1. ESAS Lunar Concept of Operations (Ref. 2 page 7)

Space Shuttle Main Engines (SSMEs) which fire along with two side-mounted, 5-segment Solid Rocket Boosters (SRBs). These SRBs separate from the core stage at a point in the ascent and leave the core stage performing a portion of the ascent. After this stage expends its propellant, it is staged and an upper stage known as the Earth Departure Stage (EDS) consisting of two LOX/LH2 J-2S engines is fired to perform a suborbital burn to achieve a 30 x 160 nmi orbit and then fired again to circularize at a 160 nmi circular orbit. The LSAM and EDS then wait for a smaller Crew Launch Vehicle (CLV or Ares 1) to launch the crew, crew capsule, and service module combination known as the Crew Exploration Vehicle (CEV). The CLV uses a 4-segment SRB and a single SSME upper stage to place the CEV in the 160 nmi circular orbit. The CEV and LSAM-EDS stacks then rendezvous in LEO and perform the Trans-Lunar Injection (TLI) using the LSAM's attached EDS.

This is the currently proposed launch infrastructure available in 2018. The remainder of this paper seeks to use this infrastructure as much as possible for Mars missions. Use of these vehicles or slight modifications only is desired.

II. Representative Mars Payload and Architecture[3]

In order to determine if the current architecture can be directly applied to the manned Mars problem, it is necessary to first define the necessary payload to Mars. It is recognized that the current ESAS transfer habitats (intended for transfers less than a week) and lunar surface payloads and habitats (designed for a 7 day surface stay) are insufficient for most proposed Mars missions (normally with transfers on the order of 180 days and surface stays often exceeding 500 days).[3] Therefore, to quantify if the current launch and TMI stages are sufficient for a Mars mission, it follows that a representative payload and concept of operations be provided as a baseline to gage the performance of current systems. The Mars Design Reference Mission v.3.0[3] (Mars DRM v.3.0) is used in this study as a representative Mars mission. Reference 3 outlines in detail the complete concept of operations of the architecture, but for the purpose of this study, it is sufficient to briefly mention the three payloads that need to be transported to Mars and to provide a brief description of the launch scheduling. These payloads are shown in Figure 2 as the top halves of each of the stacks and their masses are indicated by the red ovals. The first payload is the Earth Return Vehicle (ERV) (shown as the top half of the left stack in Figure 2), which serves as the return transfer vehicle after the surface mission is complete. This vehicle consists of a return habitat, aerobraking shell, Trans-Earth Injection Stage, and the systems to necessary to operate the vehicle. This is pre-deployed in Low Mars Orbit (LMO) approximately 26 months prior to the Crew Lander's launch. The ERV is the most massive of the three Mars DRM

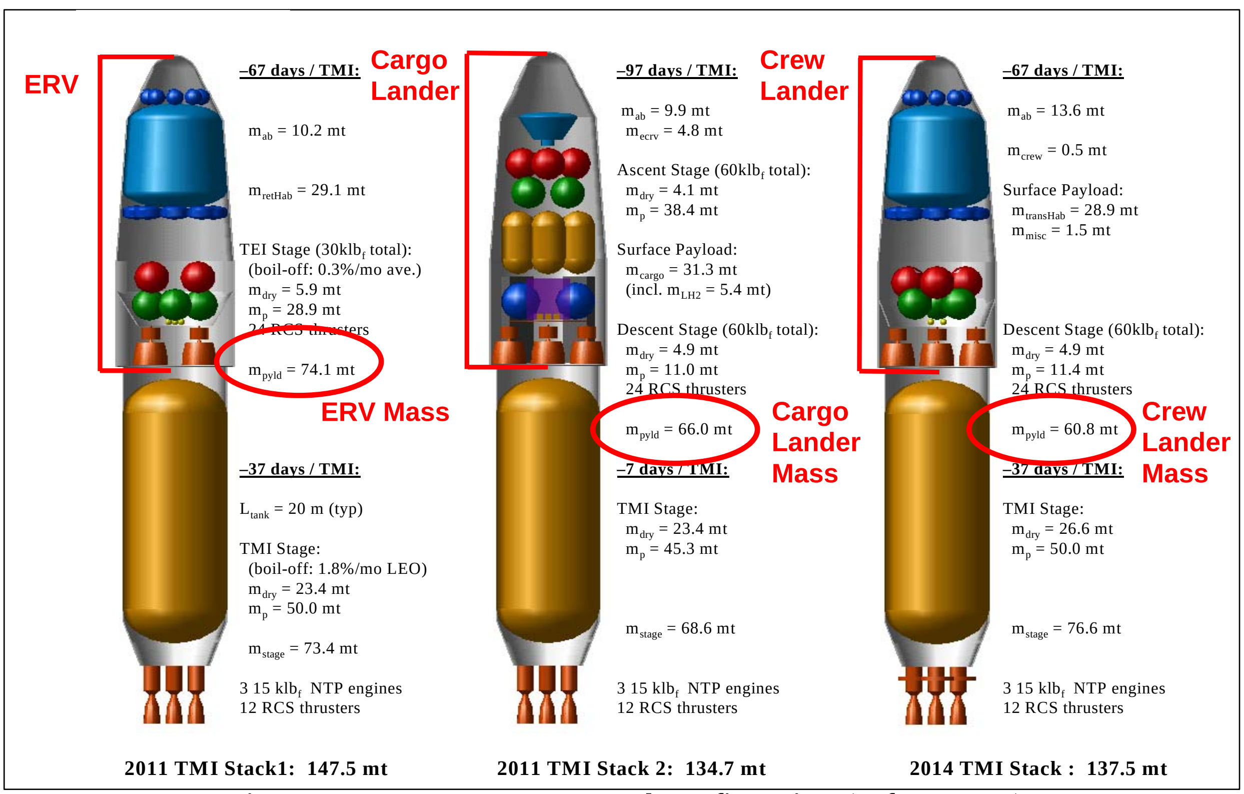

Figure 2. Mars DRM v.3.0 TMI Stack Configurations (Ref. 3 page 27)

v.3.0 payloads (74.1 mT). The second vehicle is the Cargo Lander (shown as the top half of the middle stack in Figure 2). This vehicle consists of an aeroshell, descent stage, nuclear surface power system, ISRU equipment, other cargo and an ascent stage with the Earth entry capsule used as the ascent habitat. It is pre-deployed to the Martian surface during the first Mars transfer opportunity with the ERV approximately 26 months before the crew leaves to go to Mars. On the surface it begins In-Situ Resource Utilization (ISRU) production of ascent stage propellant and prepositions surface power systems and other cargo. The Cargo Lander has a total mass of 66.0 mT. The third vehicle is the Crew Lander (shown as the top half of the right stack in Figure 2), which delivers the crew and surface habitat to the surface. This vehicle consists of an aeroshell, transfer habitat for the crew, the crew and a descent stage to land at Mars. This vehicle has a mass of 60.8 mT. In this study, these payloads and the general concept of operations of the Mars DRM v.3.0 are adopted to represent a Mars mission. They will be launched on the CaLV and the ESAS Earth Departure Stage (EDS) will provide the TMI burn instead of the Nuclear Thermal Rocket (NTR) used by Mars DRM v.3.0.

It is important to note the assumptions that this architecture employs to get payload masses like these. One of the major assumptions of Mars DRM v.3.0 is the use of a LOX / Methane propulsion system and the ability to use Martian atmosphere and hydrogen feedstock propellant to produce the ascent propellant in-situ. Use of the ISRU ascent propellant production technology has the impact of greatly decreasing the Cargo Lander size since launching, transporting and landing the ascent propellant necessary to leave Mars grows the necessary initial mass in low Earth orbit (IMLEO) significantly. ISRU is one of the major reasons for the 26 month transfer opportunity gap before crew arrival. This architecture also makes the assumption of aerocapture prior to Mars Orbit Insertion (MOI) and Mars entry. Aerocapture is when a spacecraft passes through the atmosphere of a planet to bleed of energy through drag to decrease the velocity entering either the orbit insertion or descent burns. Without this assumption, the incoming velocity would require more propulsive energy (i.e. more propellant mass) to reach the planet's surface or orbit. Another mass saving technology assumed by this architecture is the use of inflatable habitats known as TransHab. This technology, used on the ERV and Crew Lander, provides a much smaller packaging and lighter structure for these elements of the architecture than if conventional habitat materials are used. The assumption of an open loop consumables replacement of oxygen and water through ISRU at the surface of Mars saves a large amount of consumables mass which would have to be transported to the surface. An assumption of a developed nuclear surface power system also increases the power capability and, potentially, mass savings. The assumptions just mentioned are only some of the major assumptions which affect the representative mass of a manned Mars mission. They are reported to acknowledge the need of these technologies to achieve these payload masses. If these technologies are not used or replaced, it is expected that the mass of each of these payloads would increase.

III. Launch Vehicle Capability Analysis

In order to be able to investigate advantageous payload manifests and launch architectures, it is necessary to be able to quantify the performance of the current CaLV to put payloads into orbit. It is desired to know the maximum payload or propellant the CaLV can place in LEO. It is also desired to be able to specify the propellant remaining in an EDS for the TMI burn after propellant is expended for the sub-orbital burn to insert into the 30 x 160 nmi orbit and the subsequent circularization burn at 160 nmi. This requires a trajectory optimization to get the largest amount of payload into orbit for given ascent propellant. In order to accomplish this, a trade was conducted to characterize the propellant usage for each of the EDS burns to place varying amounts of payload to LEO. This is done using a trajectory optimization tool known as POST[4] (Program to Optimize Simulated Trajectories). "POST is a generalized point mass, discrete parameter targeting and optimization program. POST provides the capability to target and optimize point mass trajectories for multiple powered or unpowered vehicles near an arbitrary rotating, oblate planet. POST has been used successfully to solve a wide variety of atmospheric ascent and reentry problems, as well as exoatmospheric orbital transfer problems" (Reference 4). For this study, a POST simulation is used to maximize the amount of payload placed in LEO on the CaLV for a specified amount of the initially full EDS propellant to be used for the ascent burn. A gradient-based optimization routine is used to optimize the settings of selected dependent variables which define the ascent trajectory. This optimization is subject to discrete constraints on particular masses consumed and the final orbit achieved. POST, as mentioned, is simply a point mass trajectory tool. In POST, stage mass is specified only as jettisoned mass and there is no method of distinguishing fuel mass from structure from other masses.

In order to ensure that the POST simulation actually models the CaLV, an aerodynamics code and a mass management tool are used. The aerodynamics code, Aerodynamics Preliminary Analysis System or APAS[5], is used to compute lift and drag coefficient tables used as inputs to POST. These coefficients are modeled for an initial configuration of the CaLV, but are not modified during the analysis though the payload fairing may grow to accommodate reasonable payload densities. This makes the assumption of minimal drag increases with increasing fairing size.

A mass management tool is used to separate out the burnout mass returned by POST into TMI propellant remaining, payload carried by the EDS and the EDS dry weight. This allows for the determination of the payload and TMI propellant which get to LEO for a specified ascent propellant.

This collection of tools was used to run simulated optimized trajectories and yielded the following results shown in Figure 3. For an initially full EDS, ascent propellant masses (ranging from those corresponding to no payload to those yielding maximum payload) were used in the POST simulation to determine the amounts of payload and remaining propellant to be used as transfer propellant (TXI propellant) that can be placed in orbit. Figure 3 shows the resulting distribution of the propellants within the EDS between the ascent/circularization burn propellant and the remaining transfer propellant available for various payloads. The location where the ascent propellant required crosses the EDS full constraint indicates the location of maximum payload to LEO with a fully fueled EDS. This max payload of 157.9 mT is indicated in the figure.

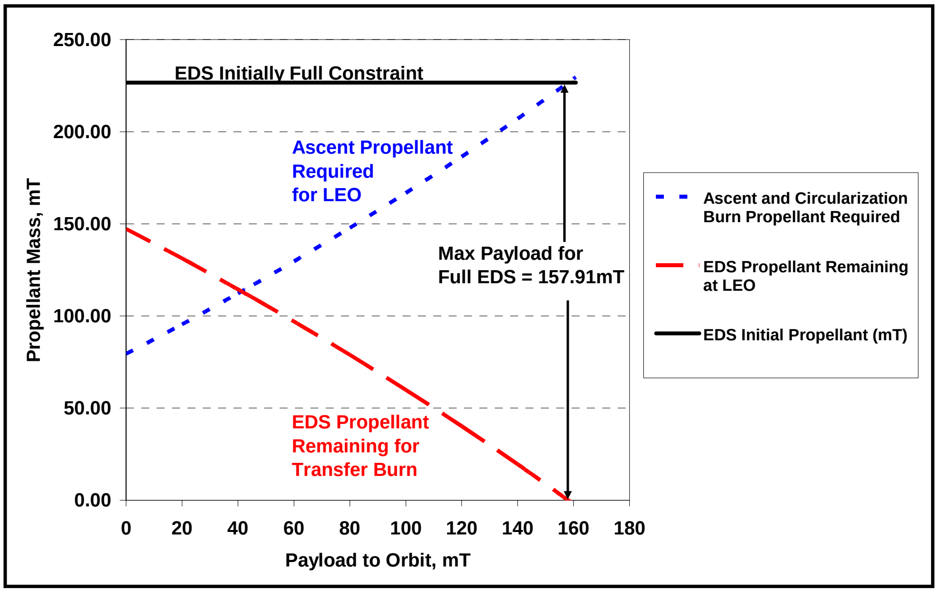

Figure 3. EDS Propellant Distribution for Varying Payload on CaLV

Through this trade the amount of propellant available for the transfer burn versus payload was characterized (Figure 3). An EDS launched with no payload delivers the maximum amount of propellant for the transfer burn to orbit (147.1 mT).

The next necessary step to measure the performance of the vehicle to send payloads to Mars involves using known Trans-Mars Injection delta-Vs, EDS specific impulses (I_{sp}), and the EDS empty mass to characterize the relationship between the payload to Mars and the propellant required to send it there. The rocket equation simplified for in-space maneuvers is as follows:

. $$\Delta V = g_0 I_{sp} \ln MR = g_0 I_{sp} \ln\left(\frac{m_P + m_S + m_{P/L}}{m_S + m_{P/L}}\right) \quad \textbf{(1)}$$

From this equation the following linear relationship between the payload and the propellant required to perform the TMI (or any other delta-V) can be derived:

. $$m_P = e^{\left(\frac{\Delta V}{g_0 I_{sp}}\right)} * \left(m_S + m_{P/L}\right) - \left(m_S + m_{P/L}\right) \quad \textbf{(2)}$$

The required performance of the EDS to perform the manned Mars TMI burn is shown in Figure 4. This diagram can be interpreted as follows. If a payload less than the value at which the required propellant and available propellant lines cross for a particular TXI, then there is more propellant available after launch than is required to perform the given delta-V, yielding a propellant surplus. Alternatively, if the payload is greater than the payload value corresponding to the crossing point, then there is not enough remaining propellant to perform the delta-V, hence a propellant deficit. If the payload is at the crossing point (53.47 mT for TMI) then there is exactly the right amount of propellant available to perform the burn.

This is a key chart for the measurement of Mars transportation performance. From this chart, launch and payload manifesting solutions for a crewed Mars mission can be determined. The basic procedure for creating these solutions is as follows.

For a given payload sent to orbit, Figure 4 can be used to determine the amount of available transfer propellant which arrives at LEO. This is done by finding the intersection of a vertical line drawn up from the payload axis and the solid curve representing this propellant available for TMI. By drawing a horizontal line from this intersection to the dashed curve representing required propellant for the transfer burn and then following a vertical line down from this second intersection to the payload axis, the total payload that the remaining propellant in the EDS is capable of sending to Mars may also be determined. If a propellant surplus remained after the first launch, performing this procedure could determine how much additional payload could be launched and sent with the first payload. Developing solutions involves using these basic procedures and other trades to determine the most advantageous distribution of a Mars mission mass.

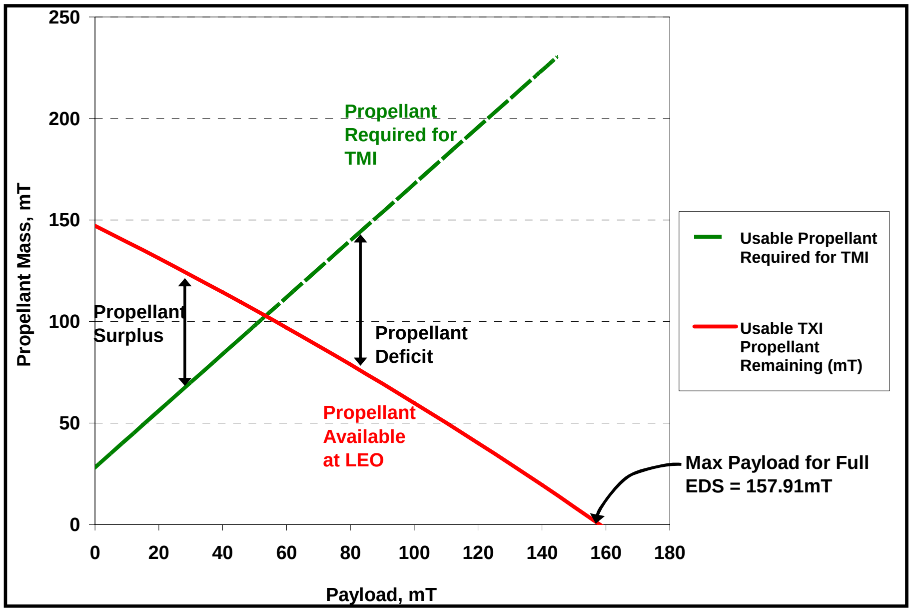

Figure 4. CaLV Available vs. Required Transfer Propellant

In the next section, this procedures and this chart will be used first to characterize various payload manifests and launch strategies and then to identify the advantages and disadvantages of each. It will also seek to explain the issues that complicate simply delivering a total amount of mass to Mars.

IV. Payload Manifesting and Launch Strategy Trades

Before discussing several different payload manifesting and launch strategy cases, it is necessary to clarify the Figures of Merit (FOMs) or desirable values used to characterize advantageous solutions. First, it is desirable to decrease the number of *necessary* launches. Less launches greatly decrease production and operations cost, decrease the probability of failure, and generally improve launch scheduling. It will be shown that a 6 launch solution is easily attainable using CaLV with the Mars DRM v.3.0 launch concept of operations. In fact, it will be shown that the ESAS CaLV is capable of providing much more payload to Mars than has been deemed necessary by this study. Thus for the sake of this study, the number of launches is used as a measure of the aggressiveness of the solution. Generally fewer launches propose less likely solutions. Secondly, it is desirable to increase Initial Mass to Low Earth Orbit (IMLEO) capability. Higher IMLEO provides the possibility of more science, equipment, or supplies to Mars. This provides flexibility, redundancy, and the possibility of increased Return on Investment (ROI). For a fixed number of launches, higher IMLEO provides margin to allow for either fewer mass-saving technologies in the payloads or for robustness in case a larger Mars payload is deemed necessary. Another desirable metric is reduced scheduling complexity. This could refer to either scheduling difficulty associated with cryogenic propellants boil-off in orbit due to launch delays or the necessary assignment of certain payloads to particular transfer opportunities from some architectural constraint. Because this second difficulty is a Mars reference architecture issue which has undetermined impact on the reference mass of the Mars mission, it is beyond the scope of this paper. This issue may still be mentioned for certain solutions to indicate advantages apart from mass savings. The importance of this concern should not be neglected in the specification of a total manned Mars architecture.

Some issues to consider when investigating solutions include the following. Aeroshells are required on a TMI stack if an aerocapture is assumed. This results in complications with payload manifests that break up and perform a TMI in separate pieces. The payload stacking necessary for multiple payload stacks has an effect upon the total vehicle height. If height exceeds current VAB[6] (Vehicle Assembly Building at Kennedy Space Center) capability, then both the assembly and launch infrastructure and facilities would have to be reworked. This generally yields unacceptable solutions. It is also important to ensure that payloads which must be transported or landed as a system not be separated. Payload mass cannot be separated from payload function. Finally, all solutions must have a transfer thrust-to-weight sufficient to avoid a spiraling low-thrust transfer trajectory for reasonable transfer times.

A. The Payload – Mars DRM v.3.0

The following tables shown in **Error! Reference source not found.** contain the mass breakdown of each of the Mars DRM v.3.0 elements.

Earth Return Vehicle (Version 3.0)	Mass (kg)
Habitat Element	26581
Life Support System	4661
Crew Accomodations and Consumables	12058
Health Care	0
EVA equipment	243
Communications/Information Management	320
30kw PVA power system	3249
Thermal Control System	550
Structure	5500
Science Equipment	600
Spares	1924
SUBTOTAL	29105
TEI stage drymass	4806
Propellant Mass	28866
EarthReturn RCS Propellant	1115
Aerobrake	10180
TOTAL MOI MASS	74072

Cargo Lander 1 (Version 3.0)	Mass (kg)
Earth Entry/Mars Ascent Capsule	4829
Ascent dry mass	4069
ASCENT MASS SUBTOTAL	
ISRU Plant	3941
Hydrogen Feedback	5420
PVA keep-alive power system	825
160 kW nuclear power plant	11425
1.0 km power cables, PMAD	837
Communication system	320
Pressurized rover	0
Inflatable Laboratory Module	3100
15 kwe DIPS cart	1500
Unpressurized rover	550
3 teleoperable rovers	1500
Water Storage Tank	150
Science Equipment	1770
TOTAL CARGO MASS	40236
Vehicle Structure	3186
Terminal Propulsion System	1018
TOTAL LANDED MASS	44440
Propellant	10985
Forward Aeroshell	9918
Parachutes and mechanisms	700
TOTAL ENTRY MASS	66043

Crew Lander (Version 3.0)	Mass (kg)
Habitat Element 2	28505
Life Support System	4661
Health Care	0
Crew Accomodations and Consumables	12058
EVA equipment	243
Communications/Information Management	320
Power	3249
Thermal	550
Structure	5500
Science Equipment	0
Spares	1924
Crew (6)	500
3 kw PVA keep-alive power	0
Unpressurized rover 3	550
EVA consumables	446
EVA suits	940
TOTAL Payload MASS	30941
Vehicle Structure	3186
Terminal Propulsion System	1018
TOTAL LANDED MASS	35145
Propellant	11381
Forward Aeroshell	13580
Parachutes and mechanisms	700
TOTAL ENTRY MASS	60806

Figure 5. Mars DRM v.3.0 Payload Mass Breakdowns (modified from Ref. 3 page 30-32)

These payloads are those which must be transported to Mars and have a total mass of 200.9 mT. In the following section, whenever an ERV, Cargo Lander, or Crew Lander is mentioned it is referring to the above systems and total masses (highlighted). Several solutions to launch and send these payloads were investigated and are presented in the following section. These were created using various strategies including payload manifest changes, dedicated TMI stage launches, and propellant transfer between EDSs.

B. Launch Solutions

The identified mass necessary for a crewed Mars mission was given in the previous section. This payload can be launched to orbit and sent to Mars in several different combinations, some more theoretical for a general Mars mission and some more practical to perform Mars DRM v.3.0 in particular. Several possible launch solutions were investigated. Figure 6 contains descriptions of launch solutions of interest, information about their capability, and a brief treatment of their concepts of operations, which are more fully developed in Figure 7. This section will discuss the importance of each of these solutions and some general trends discovered in the analysis.

The first solution is one of the simplest solutions investigated. This concept evenly distributes the Mars mission mass into payloads (less than 53.47 mT) such that each payload can launch and perform the TMI with the remaining propellant available. This allows for a 4-launch solution with no Earth rendezvous or propellant transfers to perform the TMI. There need be no waiting period between getting to LEO and performing the TMI, which reduces the amount of possible boil-off and eases launch scheduling pressures. This solution should be a major consideration for future Mars planning efforts in particular. If the Mars DRM v.3.0 payloads and mission are assumed, it would be difficult separating three highly integrated vehicles into four manageable pieces. It is likely that in order to achieve this at least one launch which transports both elements inserted into Mars orbit and elements landed on Mars. It

		General Capability of Method		Applied Capability						
Case Number	Description	Number of Launches	Maximum Payload Per Trip to Mars (mT)	Earth to Orbit Payload Manifest (mT)	Launch Payload Description	TMI Payload Manifest (mT)	Number of Launches Earth to Orbit	Number of TMI's	Total Payload Margin / Launch (mT)	Percent of Total Propellant Unburned
1	- No Payload Transfer - No Propellant Transfer - Idealized Noncontiguous Payload	1	53.5	50.2	Total Mars Payload / 4	50.2	4	4	3.2	7.0
		1	53.5	50.2	Total Mars Payload / 4	50.2				
		1	53.5	50.2	Total Mars Payload / 4	50.2				
		1	53.5	50.2	Total Mars Payload / 4	50.2				
2	- Payload Transfer - Propellant Transfer - Idealized Noncontiguous Payload	2	116.3	50.2	Total Mars Payload / 4	50.2	4	2	7.9	20.3
				50.2	Total Mars Payload / 4	50.2				
		2	116.3	50.2	Total Mars Payload / 4	50.2				
				50.2	Total Mars Payload / 4	50.2				
3	- No Payload Transfer - No propellant Transfer - Contiguous Payload	2	85.1	74.1	ERV	74.1	6	3	9.1	48.8
				No Payload						
		2	85.1	66.0	Cargo Lander	66.0				
				No Payload						
		2	85.1	60.8	Crew Lander	60.8				
				No Payload						
4	- Payload Transfer - Propellant Transfer - Contiguous Payload	3	182.6	74.1	ERV	74.1	4.5	3	9.8	17.0
				66.0	Cargo Lander	66.0				
				No Payload						
		1.5	62.5	60.8	Crew Lander	60.8				
				No Payload CLV						
5	- Payload Transfer - Propellant Transfer - Practical Noncontiguous Payload	3	182.6	39.3	ERV Payload and Aeroshell	39.3 + 34.8 = 74.1	4.5	3	9.8	17.6
				34.8 +15.9	ERV TEI Stage and Propellant					
					Cargo Lander Descent Stage and Propellant	50.2 + 15.9 = 66.0				
				50.2	Cargo Lander Payload and Aeroshell					
		1.5	62.5	60.8	Crew Lander	60.8				
				No Payload CLV						

Figure 6. Launch Solutions Descriptions and Performance

would probably require either the development of a third lander to carry down elements separated from the other two landers *or* the insertion and rendezvous of the payloads at Mars orbit to redistribute payload appropriately between 2 landers. This is probably the most likely solution for future Mars mission planning efforts, as it has the fewest launches and is the least technology development critical concept. Its major weakness is the lack of performance margin (3.2 mT per launch) to remain flexible for in-flight complications, unanticipated system growth during development, or the necessity of having non-separable payloads greater than 53.47 mT. Further complications involved in splitting the payloads will be discussed with a later concept.

The second concept uses the same payload manifesting as the first concept. This solution represents the best way that equally divided payloads can be sent to Mars. That is, it has the most payload margin (31.7 mT over 4 launches) and fewest launches. Maximizing this margin requires the use of propellant transfer between the EDSs and the transfer of payloads launched separately to combined TMI stacks. This concept of operations is clearly shown as Case 2 in Figure 7. The performance benefit over the first concept comes from the advantage gained by combining 2 payloads launched separately into one TMI. This key advantage was identified by noting the less than unity slope of the transfer propellant required curve in Figure 4 (dashed line). This gives that though the payload for a TMI might be doubled, the propellant necessary for the TMI burn does not double. Therefore, splitting the payload for launch and combining them for TMI affords more margin. This capability to perform a TMI for a larger mass is enabled by the use of propellant transfer between the EDSs to increase TMI propellant in one stack. Propellant transfer will be discussed in greater detail for another solution. In summary, the strength of this concept lies in its increased performance and few launches. It does increase at LEO complexity slightly over Case 1, but makes up for this with reduced TMIs. Its largest asset over Case 1 is the flexibility to launch and transport a single mass of up to 116.3 mT or two equal masses of 59.6mT.

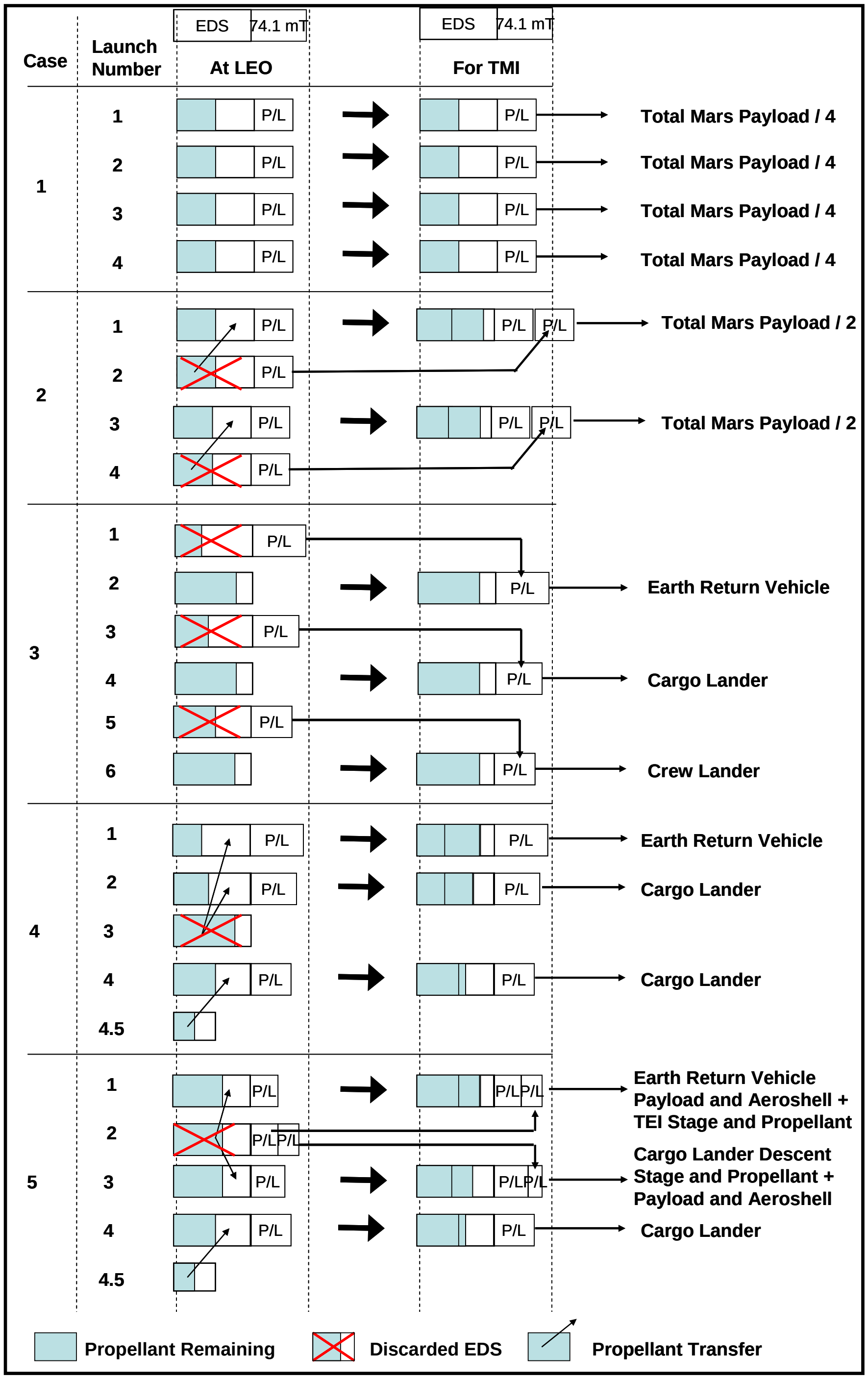

Figure 7. Concept of Operations for Launch Solutions

These two previous solutions use idealized payload splits to reduce launches. The third and fourth solutions focus upon transporting the Mars DRM v.3.0 vehicles unchanged to represent practical distribution of the payload mass to perform the mission. The concept of operations of the third solution is a slight modification from the Mars DRM v.3.0. The three vehicles are sent on dedicated launches as in Mars DRM v.3.0. For each vehicle, a launch is sent with no payload to place an EDS with maximum available propellant in LEO to perform the TMI. The available propellant in this EDS (147 mT) is more than the required propellant to transport any of the three Mars DRM v.3.0 payloads (131.6 mT for the ERV, 120.4 mT for the Cargo Lander, and 113.1 for the Crew Lander). This dedicated TMI stage requires no propellant transfer to send any of the payloads to Mars. In fact, the third solution highlights the margin available even if no propellant transfer is available (54.5 mT over the three payloads). This solution is robust as long as no single Mars payload element grows larger than 85.1 mT, at which point an EDS launched with no payload would not have enough remaining propellant to perform the TMI burn (i.e. no propellant margin). There are some disadvantages to this solution. First, this type of a solution wastes the remaining propellant from launching the Mars DRM v.3.0 TMI payload (48% of total propellant in orbit is wasted) that could have been used to send payload to Mars. It will be shown in a subsequent section that modifying this solution using propellant transfers provides significant advantages, particularly by making use of this lost propellant. Secondly, this solution requires 6 launches, which increases scheduling difficulties and costs due to the production and operation of several launch vehicles. The third solution is important because it definitively shows the CaLV can perform the Mars DRM mission with significant margin using chemical propulsion instead of NTR without the addition of any new technologies.

The fourth solution is important in that it shows how effective the third option can be made with the inclusion of just one technology: *propellant transfer*. Propellant transfer will generally provide advantages over the previous solutions by utilizing the previously wasted remaining propellant in jettisoned EDSs. The advantage of using propellant transfer can be visualized in Figure 8. This figure was created by first specifying an amount for Payload 1 to LEO and then using Figure 4 to determine the amount of Payload 2 that could be launched such that the amount of propellant available for the TMI could inject both payloads. This was done both with and without the availability of propellant transfer between the EDSs. The total amount of payload sent to Mars was also included in the figure for both options. Note that the maximum amount of payload that can be sent to Mars *without* propellant transfer (85.1 mT) corresponds to a complete separation of the payload and TMI EDS. Also note that the maximum amount of payload that can be sent to Mars *with* propellant transfer corresponds to an equal distribution between the two payloads.

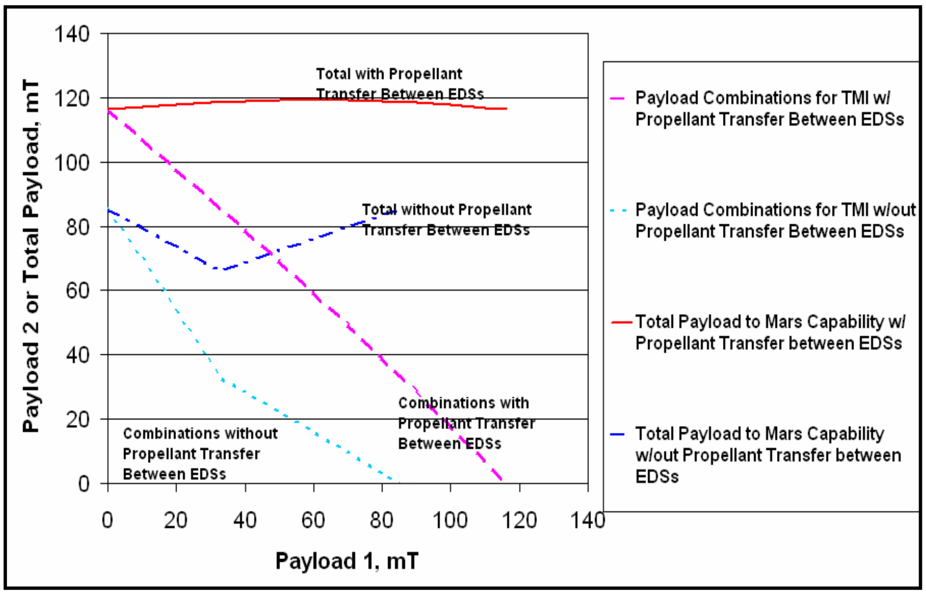

Figure 8. Advantage of Propellant Transfer Between EDSs Prior to TMI

It can be clearly seen that the advantage from a performance standpoint goes to the propellant transfer solutions. This is reflected in the decrease in launches necessary for these solutions. The fourth solution involves sending the Mars DRM v.3.0 payloads unchanged as in Case 3, but allowing for the transfer of propellant out of the previously jettisoned EDSs. In this solution the combined remaining propellant from the first three launches (323.0 mT) is much more than the propellant required to launch the ERV and Cargo Lander in two TMI burns (131.6 mT for the ERV and 120.4 mT for the Cargo Lander). The ERV and Cargo Lander must be sent on separate TMI stacks because the usable propellant constraints of an EDS limit the amount of usable propellant possible in an EDS (207.7 mT)[2] to less than is required for a combined TMI (223.9 mT). The Crew Lander has a propellant deficit of only 16.8 mT. This could be transported using the CLV, which has a payload capability of at least more than 22 mT[2]. This reduces the necessary launches from 5 to 4.5. This solution also has the largest payload margin per launch due to the

Earth Return Vehicle (Version 3.0)	Mass (kg)
Habitat Element	26581
Life Support System	4661
Crew Accomodations and Consumables	12058
Health Care	0
EVA equipment	243
Communications/Information Management	320
30kw PVA power system	3249
Thermal Control System	550
Structure	5500
Science Equipment	600
Spares	1924
SUBTOTAL	29105
TEI stage drymass	4806
Propellant Mass	28866
EarthReturn RCS Propellant	1115
Aerobrake	10180
TOTAL MOI MASS	74072

ERV Hab and Aeroshell
Total Mass = 39.285 mT

ERV TEI Stage and Propellant
Total Mass = 34.787 mT

Cargo Lander 1 (Version 3.0)	Mass (kg)
Earth Entry/Mars Ascent Capsule	4829
Ascent dry mass	4069
ISRU Plant	3941
Hydrogen Feedback	5420
PVA keep-alive power system	825
160 kW nuclear power plant	11425
1.0 km power cables, PMAD	837
Communication system	320
Pressurized rover	0
Inflatable Laboratory Module	3100
15 kwe DIPS cart	1500
Unpressurized rover	550
3 teleoperable rovers	1500
Water Storage Tank	150
Science Equipment	1770
TOTAL CARGO MASS	40236
Vehicle Structure	3186
Terminal Propulsion System	1018
TOTAL LANDED MASS	44440
Propellant	10985
Forward Aeroshell	9918
Parachutes and mechanisms	700
TOTAL ENTRY MASS	66043

Cargo Lander
Payload and Aeroshell
Total Mass = 50.154 mT

Cargo Lander Descent
Stage and Propellant
Total Mass = 15.889 mT

Crew Lander (Version 3.0)	Mass (kg)
Habitat Element 2	28505
Life Support System	4661
Health Care	0
Crew Accomodations and Consumables	12058
EVA equipment	243
Communications/Information Management	320
Power	3249
Thermal	550
Structure	5500
Science Equipment	0
Spares	1924
Crew (6)	500
3 kw PVA keep-alive power	0
Unpressurized rover 3	550
EVA consumables	446
EVA suits	940
TOTAL Payload MASS	30941
Vehicle Structure	3186
Terminal Propulsion System	1018
TOTAL LANDED MASS	35145
Propellant	11381
Forward Aeroshell	13580
Parachutes and mechanisms	700
TOTAL ENTRY MASS	60806

Crew Lander Habitat and
Aeroshell
Total Mass = 44.521 mT

Crew Lander Descent
Stage and Propellant
Total Mass = 16.285 mT

Figure 9. Advantage of Propellant Transfer Between EDSs Prior to TMI

use of propellant transfer. This method does require more rendezvous and the development of a efficient cryogenic propellant transfer system. The advantage of a lower number of launches would have to be weighed against the cost of developing such a system. The important conclusion is that the CaLV has significant potential to improve upon the third solution with investment in only one technology.

The purpose of the last investigated solution is to point out the practical difficulties of splitting up the Mars DRM v.3.0 payloads. The first and second solutions appear very advantageous, but investigation of the Mars DRM v.3.0 concept of operations prevents the splitting of Mars DRM v.3.0 into 4 equal masses. The systems which must be launched together and the transfer opportunity gap between lander launches allow for little separation or rearrangement of the payloads. For example, removing Cargo Lander pieces like ISRU equipment or the nuclear surface power system away from the payload portion of the lander could result in complex rendezvous before landing to fit those parts into the aeroshell. Therefore the purpose of the fifth solution is to provide the best anticipated performance with a practical payload splitting. The most natural method of separating the Mars DRM v.3.0 payloads is to launch the propulsive stages separately from the payloads and aeroshell combinations, since these are somewhat separated and would be easy to rendezvous. This means separating the Trans-Earth Injection (TEI) stage and associated propellants from the ERV payload and aeroshell and separating the descent stages and propellants from the each of the lander payloads and aeroshells. This separation is shown in Figure 9. Utilizing propellant transfer between EDSs and payload transfers as shown in Figure 7 and taking advantage of the use of the CLV in the same manner as the last solution, yields the possibility of performing the mission with in 4.5 launches as shown in Figure 6 and Figure 7. After launching the aeroshell and habitat portion of the ERV, the propellant deficit to perform the TMI burn for the assembled ERV is 11.4 mT. After launching the payload and aeroshell portion of the Cargo Lander, the propellant deficit to perform the TMI burn for an assembled Cargo Lander is 14.7 mT. The amount of propellant remaining in the EDS used to launch the ERV TEI stage and Cargo Lander descent stage (105.3 mT) is more than enough to meet the total propellant deficit in the other two launches (25.8mT). After launching the payload and aeroshell portions of the Crew Lander, the propellant deficit to perform the TMI burn for the assembled Crew Lander is 2.4 mT. The remaining 16.3 mT can be launched on the CLV with enough remaining propellant to meet the propellant deficit. This solution is not desirable over the simpler methods 1 and 2, but would be necessary if the Mars DRM v.3.0 concept of operations is required. This option offers similar performance to the fourth method at the cost of complexity in the concept of operations.

V. Conclusion

Several observances can be made from the above proposed solutions. The CaLV proves effective at performing the Mars mission. It can perform the Mars DRM v.3.0 mission with more margin and no new technologies despite the replacement of the NTR with a chemical propulsion system. To further reduce the number of launches assuming the Mars DRM v.3.0 payloads requires the implementation of propellant transfer between the EDSs. This technology greatly increases the capability of the CaLV to perform the Mars mission. This technology allows for the substitution of the 5th CaLV launch with a CLV to provide extra propellant for the Crew Lander TMI. To further reduce launches to 4-launch solutions, either new Mars payloads which can be launched and sent to Mars in one shot are required, or something must be done about the transfer opportunity gap in the Mars DRM v.3.0 concept of operations. The most likely solution is to develop some means of eliminating boil-off so that propellant surplus from the early launches can be used to meet the propellant deficit of the Crew Lander. Further reduction of launches requires propellant transfer technology development, development of NTR, elimination of the VAB height constraint, and pushing the CaLV to its payload capability limit.

If the primary goal is to get the most mass to Mars as possible, the number of launches can be increased on any of the propellant transfer or resupply options to achieve a significant enough margin to handle most Mars payloads in a reasonable number of launches even if several of the previously assumed Mars DRM v.3.0 technologies are neglected. Two major restrictions to such an approach exist. First, the complexity of the Mars transportation architecture has been shown to have a large impact on masses through a constraint on architectural flexibility. This could be anticipated to restrict performance to comply with the architecture. Secondly, it may be necessary to limit the entry mass at Mars for safe Mars entry.

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