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LUNAR MISSION AEROBRAKE PERFORMANCE STUDY

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13. ABSTRACT *(Maximum 200 words)*

Nine lunar mission scenarios were developed to show the transfer vehicle performance benefits of aerobraking into low-Earth orbit (LEO) upon Earth return as opposed to an all-propulsive maneuver. The initial mass in LEO (IMLEO) of the lunar transfer vehicle is considered the measure of vehicle performance. Four types of mission profiles in conjunction with two vehicle concepts were used to construct the scenarios. These nine scenarios were designed to represent a broad range of possible lunar missions so that a general knowledge base of aerobraking and lunar transfer vehicle performance levels could be obtained. Also discussed in this study are the mass sensitivities of each transfer vehicle to changes in the selected design parameters: Isp, crew module mass, payload to surface, and aerobrake mass fraction.

A parametric study was performed on two of the mission scenarios to help quantify the performance benefits by adding a set of drop tanks to the vehicle. The parametric study also provides partial derivatives which show the sensitivities of IMLEO to the four design parameters listed above. The last section of this report is a ranking of the mission scenarios based on vehicle performance.

The intent of this report is to present vehicle performance levels only. No consideration is given to the Earth-to-orbit vehicle, cost, or operational complexities such as rendezvous, aerobrake guidance, or contingencies.

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LUNAR MISSION AEROBRAKE PERFORMANCE STUDY

INTRODUCTION

This report describes the analyses and results of a general lunar transfer vehicle aerobrake performance study. The study was conducted in anticipation of questions concerning the potential performance benefits of aerobrake applications for lunar missions in the Space Exploration Initiative (SEI). In addition, it was desired to obtain a general comparison of various lunar mission scenarios. To accomplish this, nine mission scenarios were developed which represent a broad range of vehicle and mission options. The mission scenarios were analyzed using two combinations of vehicle design parameters which resulted in a minimum and maximum value of initial mass in low-Earth orbit (IMLEO) for each scenario. The design parameters included the engine specific impulse (Isp), lunar surface payload, crew module mass, and the aerobrake mass fraction. The nine mission scenarios that were analyzed provided the largest range of performance trades with a moderate number of computer simulation runs.

The nine mission scenarios are comprised of direct lunar transfer, low lunar orbit (LLO) rendezvous, and L1 Lagrange point rendezvous mission profiles. Included among these scenarios are the 90-Day Study steady-state piloted mission[1] and the Stafford Synthesis Group[2] ballistic Earth return mission.

The Taguchi method was investigated in the early stages of this study as a means to account for all possible lunar mission scenarios. This method, although valuable in other applications, proved unsuccessful because of the interactions between the vehicle parameters and their dependence on the mission scenario.

Variations of two vehicle concepts were investigated: the 90-Day Study lunar transfer vehicle/lunar excursion vehicle (LTV/LEV) and the single propulsion/avionics (P/A) module LTV.[3] The single-P/A concept was developed in 1990 by the Preliminary Design Office at Marshall Space Flight Center (MSFC) following the 90-Day Study. It is currently baselined as a two-stage vehicle (core stage + drop tanks) in which the aerobrake is parked in LLO.

Two specific issues were addressed concerning the single-P/A module: (1) the performance loss in taking the aerobrake to the lunar surface as opposed to parking it in LLO, and (2) the performance benefits of adding another tank stage (dropped in LLO after propellant transfer to the core stage prior to trans-Earth injection). The first issue is addressed in the lunar transfer system analysis section of this report. The second issue is addressed in the parametric analysis. This section shows parametric performance data for the two- and three-stage single-P/A module LTV.

The sensitivity of vehicle mass to changes in the system parameters (Isp, crew module mass, payload to the lunar surface, and aerobrake mass fraction) is presented for both for aerobraked and all-propulsive Earth returns.

To provide a performance range for each mission scenario, the values of system parameters used for the performance analysis were combined in such a way as to yield a low and high IMLEO for both an aerobraked and an all-propulsive Earth return. This range from low to high IMLEO displays the sensitivity of each mission scenario to changes in vehicle design parameters.

All results are in metric units with the symbol (t) representing a metric tonne (1,000 kg).

STUDY DEFINITIONS

The following section provides brief definitions and examples of terms used in this report.

Mission Scenario

As stated in the introduction, the mission scenarios were designed to represent a large number of possible lunar missions. There are many ways to go to the Moon when one considers the number of vehicle options and the various orbital nodes through which that vehicle may travel. In addition, the sequence in which the stages are used and the possible transfer of propellant from one stage to another adds to the problem of defining a mission scenario.

Mission scenario is a combination of one mission profile, one vehicle concept, and one set of operational assumptions (fig. 1).

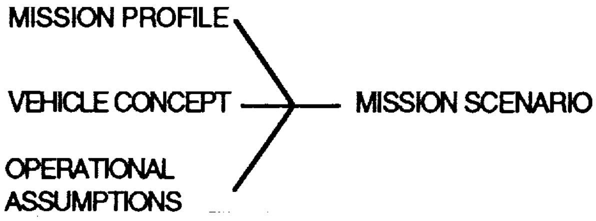


Figure 1. Mission scenario definition.

Mission Profile

Mission profile is the series of orbital nodes through which the lunar transfer vehicle travels. This study included four types of mission profiles: direct, LLO, LLO with a ballistic reentry to the Earth's surface, and the L1 mission profile. Figures 2 through 5 show the four mission profiles and their corresponding delta velocity (ΔV) budgets. The ΔV budgets shown in these figures are for an aerobraked Earth return, however, each mission scenario was also analyzed with an all-propulsive return so that the performance benefits of aerobraking could be obtained. The appendix gives the definition of maneuver acronyms. The ΔV budgets were

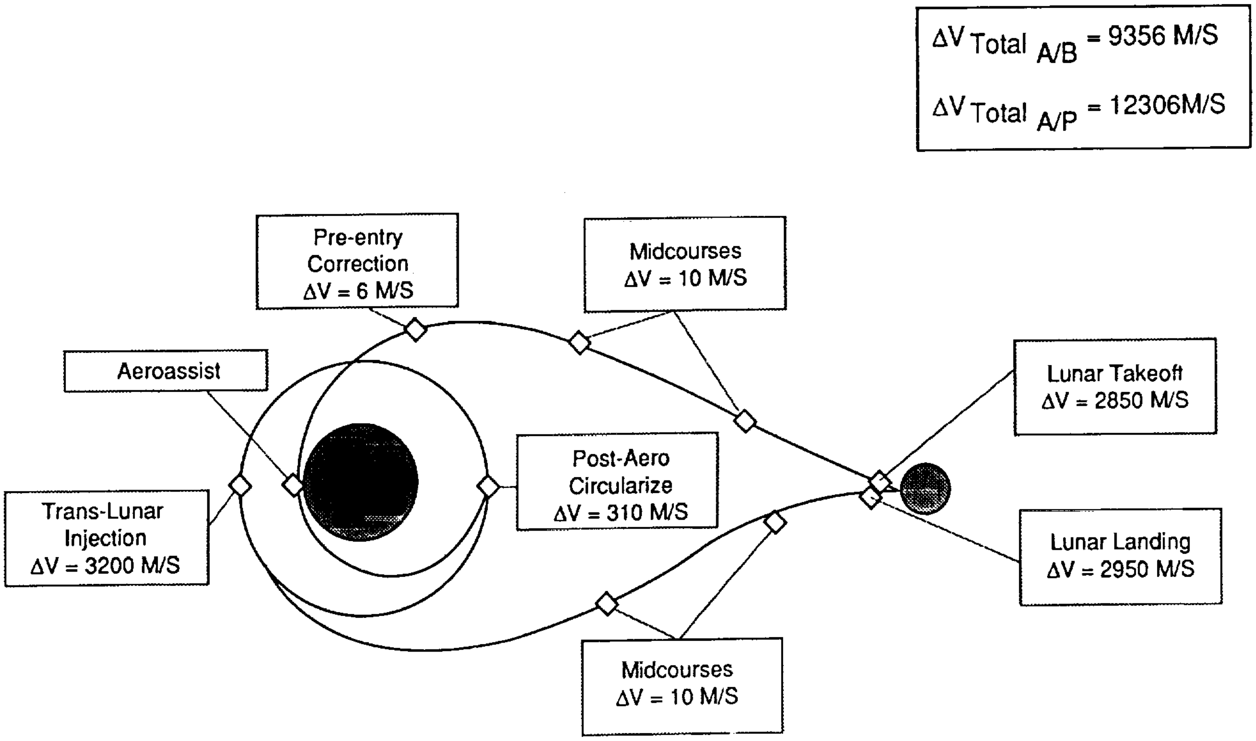


Figure 2. Delta-V budget: direct mission profile.

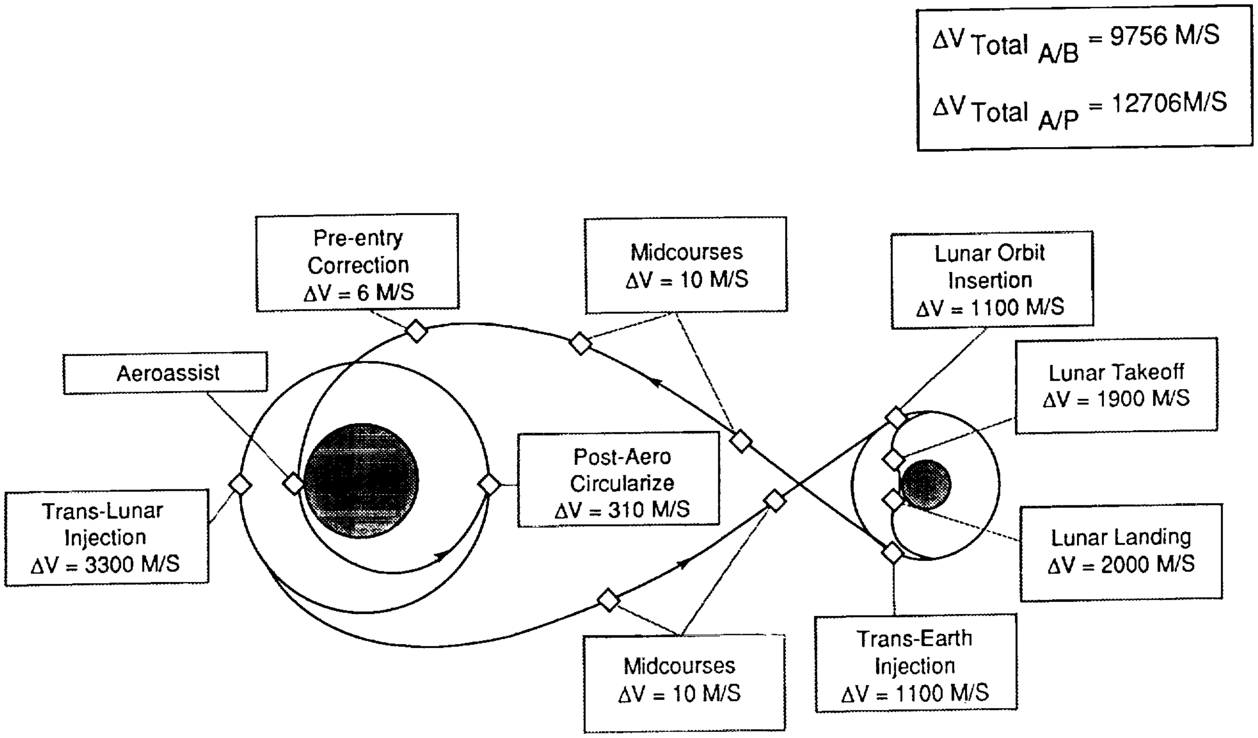


Figure 3. Delta-V budget: LLO mission profile.

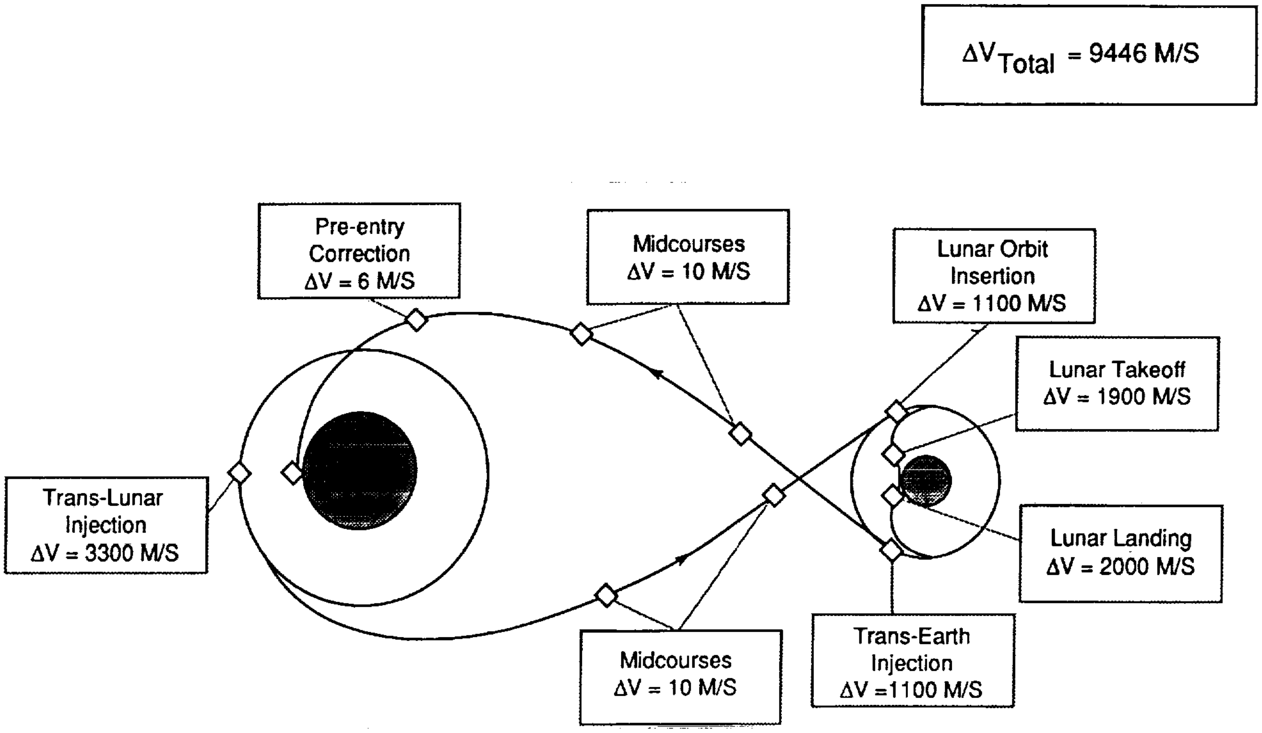


Figure 4. Delta-V budget: LLO/ballistic reentry mission profile.

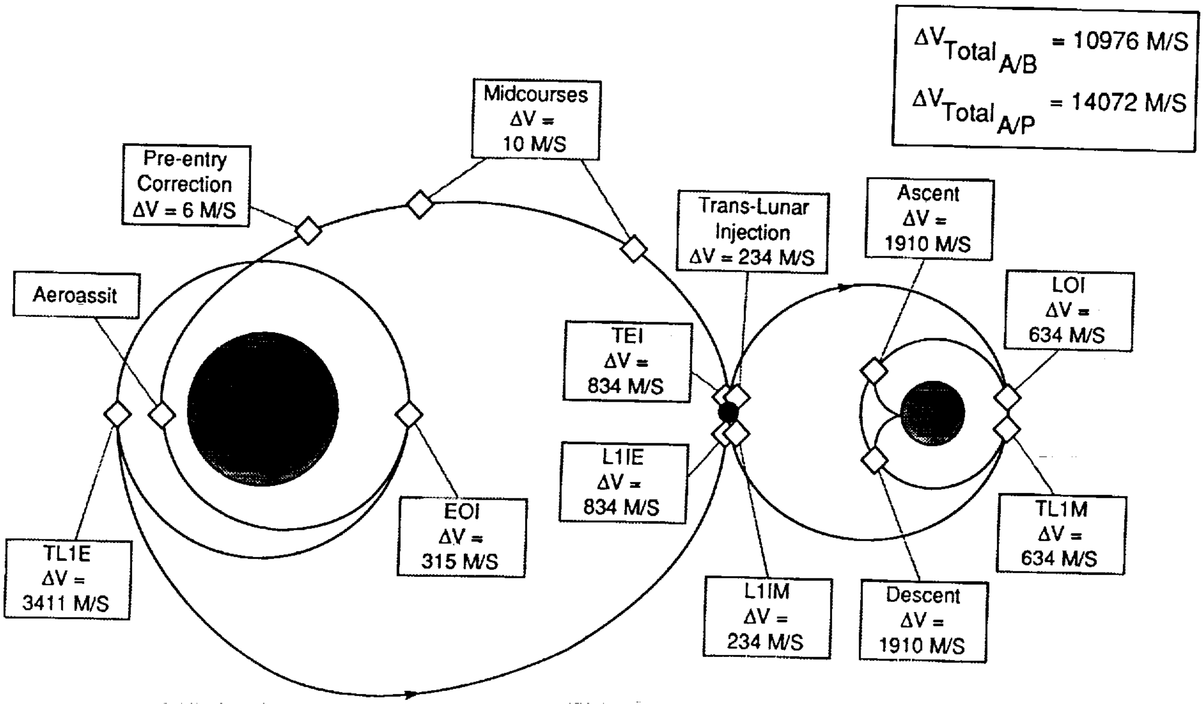


Figure 5. Delta-V budget: L1 mission profile.

obtained from the Lunar/Mars Exploration Program Office at Johnson Space Center (JSC) except for the direct mission which is from reference 1.

Direct mission profile: The vehicle departs LEO and descends to the lunar surface without inserting into a lunar parking orbit. The vehicle then ascends into the return trajectory and enters an Earth parking orbit using aerobraking or an all-propulsive maneuver as shown in figure 2.

LLO mission profile: The vehicle inserts into a lunar parking orbit prior to descent and after ascent (fig. 3). The LLO profile provides the opportunity to park components in lunar orbit which are not needed on the surface, such as the aerobrake, radiation shield, and the Earth return stage or propellant.

LLO/ballistic reentry mission profile: Similar to the LLO profile except the Earth return method is a ballistic reentry to the Earth's surface (fig. 4). This profile is the same as the Apollo mission profile and was included in this study in response to the recommendation for a ballistic return in the 1991 Synthesis Group Report.[2]

L1 mission profile: The vehicle leaves Earth orbit and brakes at the L1 Lagrange point. Vehicle components which are not needed on the Moon may be parked at the Lagrange point. After the vehicle leaves L1, it is inserted into a lunar orbit. The descent and ascent maneuvers are performed between the lunar parking orbit and the surface. The vehicle returns to Earth through the same nodes. This profile, shown in figure 5, was included in response to the recent interest in using the Lagrange points as staging nodes.

Vehicle Concept

Figure 6 shows the two vehicle concepts that were investigated in this study.

The single-P/A module: A lunar transfer vehicle designed by the Preliminary Design Office at MSFC in 1990 following the 90-Day Study. As the name implies, it has one propulsion system that performs all mission maneuvers and only one crew module.

Dual vehicle: Based on the 90-Day Study LTV/LEV. The LTV is used for transfers between LEO and either LLO or L1, depending on the mission profile. The LEV is based at either LLO or L1 and is used for transfers between its base and the lunar surface. Propellant and cargo are transferred from the LTV to the LEV at the LEV orbital base.

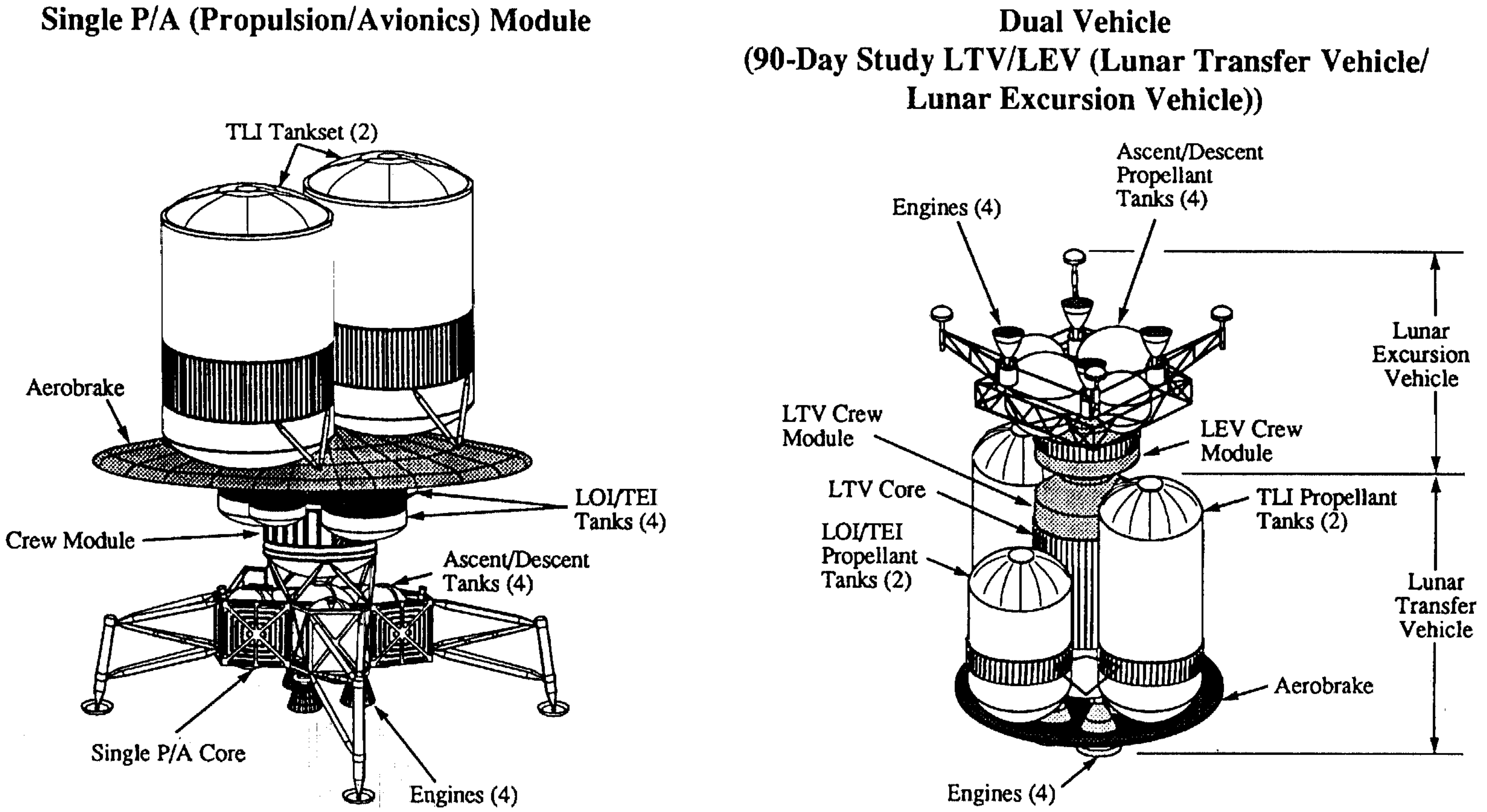
Vehicle variations included two- and three-stage configurations, with and without an aerobrake (aerobrake or all-propulsive Earth return).

Operational Assumptions

Various operational assumptions were required to fully define the lunar mission scenarios. These assumptions included the following information for each mission scenario:

Number of stages

Staging sequence



Single P/A (Propulsion/Avionics) Module

Dual Vehicle (90-Day Study LTV/LEV (Lunar Transfer Vehicle/ Lunar Excursion Vehicle))

Options: 2 Stage
3 Stage
Aerobraked Earth Return
All Propulsive Return

Figure 6. Vehicle concepts.

Tank stage sizing

Propellant transfers

Components (aerobrake, return prop., etc.) parked in LLO or L1

Rendezvous in LLO or L1.

These assumptions varied for each scenario, however in most, the trans-lunar injection (TLI) tanks were sized to hold all the propellant needed for the mission. Because the vehicles in this study were assumed to be based in LEO and the TLI tanks were ejected in all scenarios, replacement TLI tanks would be required for the next mission. All the mission propellant could be delivered in the replacement TLI tanks, then transferred to other tanks and the core stage prior to LEO departure.

Stage

Propulsive stage: A stage which includes a propulsion system and propellant tanks; may be referred to as the core stage.

Tank stage: A stage consisting of a pair of propellant tank sets that are dropped at some point in the mission. Each tank set has one liquid hydrogen tank and one liquid oxygen tank.

Aerobrake

Integral aerobrake: This type of aerobrake is taken to the lunar surface. It is a permanent component of the transfer vehicle. It has no subsystems (reaction control system (RCS), power, communications, etc.) and its mass includes only the structure and the thermal protection system (TPS).

Freeflying aerobrake: This aerobrake is a separate component of the transfer vehicle. It can remain in orbit as an autonomous spacecraft, and then upon rendezvous, be reattached to the transfer vehicle. In addition to the structure and the TPS, the aerobrake mass includes subsystems such as attitude control, power, and communications.

Aerobrake efficiency factor: (η) is a measure of the percent savings in IMLEO for a transfer vehicle employing an aerobrake upon Earth (or other) return, as opposed to an all-propulsive return.

$$\eta = \frac{\mathrm{IMLEO}_{A/P} - \mathrm{IMLEO}_{A/B}}{\mathrm{IMLEO}_{A/P}} .$$

Aerobrake mass fraction: A system parameter for this study. It represents the ratio of aerobrake mass to the total vehicle mass at atmospheric reentry.

SELECTED MISSION SCENARIOS

Table 1 lists and describes the nine mission scenarios as defined by one mission profile, one vehicle concept, and a set of operational assumptions. Note that scenario No. 6 is the mission scenario recommended by the Stafford Synthesis Group,[2] and scenario No. 7 is the profile used for the 90-Day Study steady-state piloted mission.[1]

Table 1. Selection mission scenarios.

Mission Profile	Vehicle Concept	Operational Assumptions
1. Direct	Single P/A, 2-stage	Tank set 1 (TS1) sized for all propellant Transfer propellant to core stage before TLI TS1 performs TLI Drop TS1 after TLI
2. Direct	Single P/A, 3-stage	TS1 sized for TLI, TEI, and EOI propellant Transfer TEI, EOI propellant to core stage before TLI TS2 performs LOI, descent Drop TS2 on lunar surface
3. LLO	Single P/A, 2-Stage	TS1 sized for all propellant Transfer propellant to core stage before TLI TS1 performs TLI Drop TS1 after TLI Aerobrake, rad. shield, return prop. parked in LLO (in storage tanks) Core stage performs LOI, descent, ascent; Return propellant transferred to core before TEI
4. LLO	Single P/A, 3-Stage	TS1 sized for TLI descent, ascent propellant Transfer des., asc. propellant to core stage before TLI Drop TS1 after TLI TS2 sized for LOI, TEI, EOI; performs LOI Aerobrake, rad. shield, TS1 parked in LLO Core stage performs descent, ascent; rendezvous in LLO, TS1 transfers propellant for TEI, EOI Drop TS2 in LLO
5. LLO; All to surface	Single P/A, 3-Stage	TS1 sized for TLI, ascent, TEI, EOI propellant Transfer asc., TEI, EOI prop. to core stage before TLI Drop TS1 after TLI TS2 performs LOI, descent Aerobrake, rad. shield taken to lunar surface Drop TS2 on lunar surface
6. LLO; Ballistic Reentry (Stafford Synthesis Recommendation)	Single P/A, 3-Stage	TS1 sized for TLI descent, ascent propellant Transfer des., asc. propellant to core stage before TLI Drop TS1 after TLI TS2 sized for LOI, TEI, EOI; performs LOI Rad. shielf, TS2 parked in LLO Core stage performs descent, ascent; rendezvous in LLO TS2 transfers propellant for TEI, EOI Drop TS2 in LLO Ballistic Reentry

Table 1. Selection mission scenarios (continued)

Mission Profile	Vehicle Concept	Operational Assumptions
7. LLO	Dual Vehicle (90-Day Study)	Steady-state piloted mission TS1 sized for TLI, TEI, EOI propellant Transfers propellant to core stage before TLI TS1 performs TLI; Drop TS1 after TLI TS2 sized for LOI, desc., asc.; performs LOI TS2 transfers desc., asc. prop. to LEV after rendezvous in LLO LTV drops TS2 in LLO; LEV descends LEV crew module = 3,769 kg LTV core performs TEI, EOI TS1 sized for desc., asc., TEI, EOI
8. L1	Single P/A, 3-Stage	TS2 sized for L1IE, TLI, LOI, TL1M, L1IM Des., asc. prop. transferred to core and TEI, EOI prop. transferred to storage tank before TL1E TS1 dropped after TL1E; A/B parked at L1 TEI, EOI prop. parked at L1 in storate tanks TS2 performs L1IE, TLI, LOI TS2 parked in LLO Core sized for des., asc. TL1M, L1IM prop. transferred to core; TS2 dropped in LLO TEI, EOI, prop. tranfserred to core at L1
9. L1	Dual Vehicle	TS1 sized fo TL1E, TEI, EOI propellant TEI, EOI propellant transferred to core stage before TL1 TS1 performs TLI; Drops TS1 after TL1E TS2 sized for L1IE, TLI, LOI, desc., asc., TL1M, L1IM, performs L1IE LEV based at L1 TS2 transfers TLI, LOI, desc., asc., TL1M, L1IM prop. to LEV after rendezvous at L1 LTV drops TS2 at L1; LEV descends LEV crew module = 3,769 kg LTV core performs TEI, EOI

SCALING EQUATIONS

The software used for the mission scenario simulations required scaling equations for the tank and core stages. Scaling equations, shown below for both vehicle concepts, define the burnout mass of the stage as a function of its propellant capacity. Note that the tank stage scaling equation was used for both vehicle concepts.

Single P/A Core Stage

$0 < Mp < 40{,}000$ kg $Mbo = 5{,}038 + 5.78959\text{E-}02*Mp$ (kg)
$Mp > 40{,}000$ kg $Mbo = 0.1628*Mp$ (kg) (mass fraction = 0.86)

Dual Vehicle LTV Core Stage

$0 < Mp < 40{,}000$ kg $Mbo = 4{,}397 + 5.78959\text{E-}02*Mp$ (kg)
$Mp > 40{,}000$ kg $Mbo = 0.1494*Mp$ (kg) (mass fraction = 0.87)

Drop Tank Stage (both vehicles)

$11{,}000 < Mp < 160{,}000$ kg $Mbo = 469 + 0.041461*Mp - 4.9689\text{E-}08*Mp\text{^}2$ (kg)
$Mp > 160{,}000$ kg $Mbo = 0.0363*Mp$ (kg) (mass fraction = 0.965)

For each stage there were two scaling equations used, each valid for a given propellant loading. The equations for the lower range were developed in previous lunar vehicle studies at MSFC.[4,5] They follow the form:

$$M_{bo} = A + BM_p + CM_p^2$$

The coefficients were determined using a second or third order curve fit of data which defined the stage burnout mass over a range of propellant loadings. These scaling equations were extrapolated beyond the given range of propellant loading by assuming a constant stage mass fraction (λ) for large propellant loadings. This is a valid assumption since the value of λ tends to reach a limiting value as the propellant loading increases. The value of the constant mass fraction was determined by substituting the scaling equation into the formula which defines the stage mass fraction and calculating λ at a propellant loading slightly higher than the maximum propellant loading of the original scaling equation. This substitution is shown below.

$$\lambda = M_p/(M_p + M_{bo}) = M_p/(A+(B+1)M_p+CM_p^2)$$

The calculated value of λ was then used to define the scaling equations used for the higher propellant loadings using the following transformation.

$$M_{bo} = [(1-\lambda)/\lambda]M_p \quad \text{(i.e. } B = (1-\lambda)/\lambda\text{)}$$

SYSTEM PARAMETERS

Four system parameters were used to define the transfer vehicle performance as indicated by the IMLEO:

Payload to the lunar surface

Vehicle Isp

Aerobrake mass fraction

Crew module mass.

To obtain an understanding of the range of potential performance levels for the nine mission scenarios, these input system parameters were given values such that they would yield a low-transfer vehicle IMLEO (low IMLEO inputs) and a high-transfer vehicle IMLEO (high IMLEO inputs). In this manner, the initial mass of the transfer vehicle is bounded and one has a range of performance levels for that scenario. The low and high IMLEO inputs (table 2) were selected based on results of current SEI studies and projected technological advances.

Table 2. System parameter IMLEO inputs.

	High IMLEO Inputs	Low IMLEO Inputs
PAYLOAD TO SURFACE (kg)	15000	5000
VEHICLE Isp (s)	450	481/465 *
AEROBRAKE MASS FRACTION (Free-Flying/Integral)	30% 25%	20% 15%
CREW MODULE MASS (kg) (LEO/Ballistic Return)	6000 9500	4000 7500

* Low value of Isp used for lunar ascent and descent

In addition to the low and high IMLEO inputs, each mission scenario was simulated using an aerobraked return and an all-propulsive return (except mission scenario No. 6, which used a ballistic Earth return). In this manner, the performance benefits of aerobraking could be assessed.

RUN MATRIX

There were four runs for each mission scenario: high and low IMLEO inputs for both aerobraked and all-propulsive Earth return as described above. Table 3 shows the study run matrix. Listed in the matrix are the input values: Isp, crew module mass, A/B mass fraction, payload to lunar surface, and Earth return method. For reference, the number of stages, mission profile, vehicle concept and the mission scenario number are listed as well.

Table 3. Run matrix.

RUN #	Vehicle Concept Mission Profile	NO. STAGES	MISSION SCENARIO #	Isp (s)	CREW MODULE MASS (t)	A/B MASS FRACTION	PAYLOAD TO SURFACE (t)	EARTH RETURN METHOD
1	Single P/A Direct	2	1	450	6	.25	15	Aerobrake (Integral)
2	Single P/A Direct	2	1	481/ 465	4	15	5	Aerobrake (Integral)
3	Single P/A Direct	2	1	450	6		15	All-Propulsive
4	Single P/A Direct	2	1	481/ 465	4		5	All-Propulsive
5	Single P/A Direct	3	2	450	6	25	15	Aerobrake (Integral)
6	Single P/A Direct	3	2	481/ 465	4	15	5	Aerobrake (Integral)
7	Single P/A Direct	3	2	450	6		15	All-Propulsive
8	Single P/A Direct	3	2	481/ 465	4		5	All-Propulsive

Table 3. Run matrix (continued).

RUN #	Vehicle Concept Mission Profile	NO. STAGES	MISSION SCENARIO #	Isp (s)	CREW MODULE MASS (t)	A/B MASS FRACTION	PAYLOAD TO SURFACE (t)	EARTH RETURN METHOD
9	Single P/A LLO	2	3	450	6	.30	15	Aerobrake (Free-Flying)
10	Single P/A LLO	2	3	481/ 465	4	.20	5	Aerobrake (Free-Flying)
11	Single P/A LLO	2	3	450	6		15	All-Propulsive
12	Single P/A LLO	2	3	481/ 465	4		5	All-Propulsive
13	Single P/A LLO	3	4	450	6	.30	15	Aerobrake (Free-Flying)
14	Single P/A LLO	3	4	481/ 465	4	.20	5	Aerobrake (Free-Flying)
15	Single P/A LLO	3	4	450	6		15	All-Propulsive
16	Single P/A LLO	3	4	481/ 465	4		5	All-Propulsive

Table 3. Run matrix (continued).

RUN #	Vehicle Concept Mission Profile	NO. STAGES	MISSION SCENARIO #	Isp (s)	LTV CREW MODULE MASS (t)	A/B MASS FRACTION	PAYLOAD TO SURFACE (t)	EARTH RETURN METHOD
17	Single P/A LLO All to surface	3	5	450	6	.25	15	Aerobrake (Integral)
18	Single P/A LLO All to surface	3	5	481/ 465	4	.15	5	Aerobrake (Integral)
19	Single P/A LLO All to surface	3	5	450	6		15	All-Propulsive
20	Single P/A LLO All to surface	3	5	481/ 465	4		5	All-Propulsive
21	Single P/A LLO Ballistic Re-entry	3	6	450	9.5		15	Ballistic
22	Single P/A LLO Ballistic Re-entry	3	6	481/ 465	7.5		5	Ballistic

Table 3. Run matrix (continued).

RUN #	Vehicle Concept Mission Profile	NO. STAGES	MISSION SCENARIO #	Isp (s)	LTV CREW MODULE MASS (t)	A/B MASS FRACTION	PAYLOAD TO SURFACE (t)	EARTH RETURN METHOD
23	DUAL VEHICLE LLO	3	7	450	6	.25	15	Aerobrake (Integral)
24	DUAL VEHICLE LLO	3	7	481/ 465	4	.15	5	Aerobrake (Integral)
25	DUAL VEHICLE LLO	3	7	450	6		15	All-Propulsive
26	DUAL VEHICLE LLO	3	7	481/ 465	4		5	All-Propulsive
27	Single P/A L1	3	8	450	6	.30	15	Aerobrake (Free-Flying)
28	Single P/A L1	3	8	481/ 465	4	.20	5	Aerobrake (Free-Flying)
29	Single P/A L1	3	8	450	6		15	All-Propulsive
30	Single P/A L1	3	8	481/ 465	4		5	All-Propulsive
31-34	DUAL VEHICLE L1	3	9	SAME AS RUNS 23-26				

RESULTS

Lunar Transfer System Performance

Table 4 lists the results for the first portion of the study. Included in this table are the run number, Earth return method, and the IMLEO input level; (H)igh or (L)ow. The forth column lists the IMLEO, which was the measure of performance for this study. The next two columns give the vehicle atmospheric entry mass (M_{entry}) and the aerobrake mass ($M_{A/B}$, aerobrake cases only). The remaining columns list the propellant capacity and mass fraction for each stage. The propellant capacities shown include the propellant that is used for propulsive maneuvers by the stage and any propellant that may be transferred to other stages. Figure 6 is a graphical representation of the performance which show the IMLEO values for each mission scenario. The Y-axis shows the transfer vehicle IMLEO value in metric tonnes and the X-axis lists the nine mission scenarios investigated. There are two bars for each mission scenario: the left bar represents the aerobraked return while the right bar represents the all-propulsive return. The shaded region for each bar displays the range of IMLEO values obtained from the low and high IMLEO input values described earlier. For example, mission scenario No. 4 (three-stage single P/A performing a LLO mission profile) will have a mass of approximately 125 to 215 tonnes in LEO when aerobraking is employed as the Earth return method and will have a mass of approximately 150 to 235 tonnes when an all-propulsive Earth return is used.

The following observations can be made about the selected mission scenario performance levels:

For the direct mission profile, the two-stage, single-P/A Module LTV is 31.7 to 217.0 t (21.8 to 86.8 percent) greater in IMLEO than the three-stage single P/A for an aerobraked (A/B) return and 110.4 to 424.5 t (48.8 to 123.0 percent) greater for an A/P return.

For the LLO mission profile, the two-stage single P/A is 8.5 to 26.8 t (6.9 to 12.4 percent) greater in IMLEO than the three-stage single P/A for A/B return and 22.7 to 53.7 t (15.2 to 22.0 percent) greater for A/P return.

A two-stage single P/A performing a direct-mission profile is 45.5 to 223.9 t (34.6 to 92.2 percent) greater in IMLEO than the two-stage single P/A performing an LLO mission profile for A/B return and 165.0 to 472.5 t (96.2 to 159.0 percent) greater for A/P return.

A three-stage single P/A performing a direct-mission profile is 22.3 to 33.7 t (15.5 to 18.1 percent) greater in IMLEO than the three-stage single P/A performing an LLO mission profile for A/B return and 77.3 to 101.8 t (41.7 to 51.9 percent) greater for A/P return.

A three-stage single P/A that carries all the components to the lunar surface is 33.5 to 57.3 t (26.5 to 27.2 percent) greater in IMLEO than the three-stage single P/A which parks the Earth return components in lunar orbit for A/B return and 95.3 to 147.7 t (60.6 to 64.0 percent) greater for A/P return.

A three-stage single P/A performing the ballistic-reentry mission profile is 0.86 t (0.4 percent) less to 12.9 t (10.5 percent) greater in IMLEO than the three-stage single P/A-LLO for A/B return. The crew module for the ballistic reentry mission scenario was assumed to be greater due to the ablative heat shielding. This shield is taken to the

Table 4. Lunar transfer system results.

						Propellant Capacity/Mass Fraction		
Run *	Earth Return	IMLEO Input Level	IMLEO	M_{entry}	$M_{A/B}$	Stage 1	Stage 2	Stage 3
Single P/A 2 stg. Direct:						(tank)	(core)	
1	A/B	H	466918.9	46921.8	11730.4	392579.6/0.965	151771.2/0.860	-
2	A/B	L	177117.9	19175.5	2876.3	147313.6/0.964	60070.6/0.860	-
3	A/P	H	770157.8	-	-	689093.6/0.965	291893.1/0.90**	-
4	A/P	L	336591.7	-	-	299263.4/0.965	133468.3/0.90**	-
Single P/A 3 stg. Direct:						(tank)	(tank)	(core)
5	A/B	H	249851.6	19897.0	4974.2	150189.6/0.964	56535.4/0.955	21331.4/0.772
6	A/B	L	145434.4	14254.5	2138.2	86692.0/0.959	33550.6/0.949	15055.3/0.718
7	A/P	H	345745.3	-	-	224927.4/0.965	78013.4/0.958	46613.0/0.860
8	A/P	L	226242.1	-	-	147178.6/0.964	52309.8/0.954	35738.4/0.834

* All results in Kg's.

** Lowest Mass Fraction that would yield a convergence

Table 4. Lunar transfer system results (continued).

Run *	Earth Return	IMLEO Input Level	IMLEO	M_{entry}	$M_{A/B}$	Propellant Capacity/Mass Fraction Stage 1	 Stage 2	 Stage 3
Single P/A 2 stg. LLO:						(tank)	(core)	(storage tank)
9	A/B	H	242961.5	27370.4	8211.1	194081.5/0.965	55775.7/0.860	10364.9/0.92
10	A/B	L	131649.3	17669.4	3533.9	104585.4/0 961	31870.6/0.822	6467.0/0.90
11	A/P	H	297650.1	-	-	252817.4/0.965	62702.3/0.860	33375.8/0.949
12	A/P	L	171565.4	-	-	145910.9/0.964	36142.7/0.835	23434.0/0.943
Single P/A 3 stg. LLO:						(tank)	(tank)	(core)
13	A/B	H	216220.4	22131.9	6639.6	142006.5/0.964	30225.3/0.947	28147.1/0.808
14	A/B	L	123133.7	15463.0	3092.6	79813.8/0.958	17851.0/0.937	17851.1/0.746
15	A/P	H	243918.2	-	-	156591.8/0.965	48888.6/0.954	28147.1/0.808
16	A/P	L	148915.0	-	-	92787.3/0.960	32744.6/0.949	17851.1/0.746

* All results in Kg's.

Table 4. Lunar transfer system results (continued).

Run #	Earth Return	IMLEO Input Level	IMLEO	M_{entry}	$M_{A/B}$	Propellant Capacity/Mass Fraction		
						Stage 1	Stage 2	Stage 3
Single P/A 3 stg. LLO All To Surface:								
						(tank)	(tank)	(core)
17	A/B	H	273469.3	20065.5	5016.4	166957.2/0.965	62550.4/0.956	22951.2/0.783
18	A/B	L	156580.8	14334.1	2150.1	94684.2/0.960	36281.4/0.950	15890.5/0.727
19	A/P	H	391589.9	-	-	257279.9/0.965	89233.0/0.959	51072.9/0.860
20	A/P	L	244153.3	-	-	160083.7/0.965	56732.6/0.955	37222.1/0.838
Single P/A 3 stg. LLO Ballistic Reentry:								
						(tank)	(tank)	(core)
21	B.R.	H	215361.2	-	-	146913.7/0.964	27303.7/0.946	33506.8/0.828
22	B.R.	L	136027.9	-	-	91426.8/0.960	18043.9/0.938	22975.6/0.783

* All results in Kg's.

Table 4. Lunar transfer system results (continued).

Run #	Earth Return	IMLEO Input Level	IMLEO	M_{entry}	$M_{A/B}$	Propellant Capacity/Mass Fraction Stage 1	Stage 2	Stage 3	Prop. Trnsfr. to LEV**
Dual Vehicle **LLO:** 90-Day Study S.S Piloted						(tank)	(tank)	(core)	
23	A/B	H	190747.7	17760.8	4440.2	107355.4/0.961	43962.2/0.952	6909.7/0.590	24695.4
24	A/B	L	113134.1	12695.1	1904.3	61659.4/0.956	28791.5/0.947	4728.7/0.503	17512.2
25	A/P	H	226508.9	-	-	141938.2/0.964	47531.6/0.953	22661.1/0.799	24695.4
26	A/P	L	143182.2	-	-	88910.5/0.959	31750.8/0.948	16859.1/0.758	17512.2
Single P/A 3 stg. **L1:**						(tank)	(tank)	(core)	(strge tank at L1)
27	A/B	H	251048.9	23223.4	6967.0	169120.3/0.965	35921.9/0.950	26986.9/0.803	6981.6
28	A/B	L	144306.2	16311.5	3262.3	96158.3/0.960	21217.5/0.941	17200.2/0.740	4673.8
29	A/P	H	282235.6	-	-	202990.0/0.965	38208.3/0.951	26986.9/0.803	24062.1
30	A/P	L	171915.9	-	-	123530.8/0.962	23269.4/0.943	17200.2/0.740	17833.7

* All results in Kg's.

** Previously Determined

Table 4. Lunar transfer system results (continued).

Dual Vehicle
L1:

Run #	Earth Return	IMLEO Input Level	IMLEO	M_{entry}	$M_{A/B}$	Propellant Capacity/Mass Fraction			Prop. Trnsfr. to LEV**
						Stage 1	Stage 2	Stage 3	
						(tank)	(tank)	(core)	
31	A/B	H	232328.4	17631.9	4408.0	130466.9/0.963	61240.3/0.956	5393.3/0.534	43254.6
32	A/B	L	144465.8	12619.1	1892.9	78063.1/0.958	42697.3/0.952	3696.7/0.445	31652.1
33	A/P	H	267942.0	-	-	165755.6/0.965	63959.8/0.956	21509.4/0.792	43254.6
34	A/P	L	173993.3	-	-	105573.3/0.961	44922.7/.953	16007.0/0.750	31652.1

* All results in Kg's.
** Previously Determined

lunar surface which causes lower performance compared to the LLO mission scenario in which the aerobrake is left in low lunar orbit. However, the ballistic reentry mission scenario was found to be 12.9 to 28.5 t (8.7 to 11.7 percent) less in IMLEO than the three-stage single P/A performing the LLO mission profile with A/P return.

A three-stage single P/A performing an LLO mission profile is 10 to 25.5 t (8.8 to 13.4 percent) greater in IMLEO than the three-stage dual vehicle (90-Day Study steady-state piloted mission scenario) for A/B return and 5.7 to 17.4 t (3.9 to 7.7 percent) greater for A/P return.

A three-stage single P/A and the three-stage dual vehicle, both performing an L1 mission profile, display almost identical performance. However, the chart shows that as the input performance parameters (Isp, payload to surface, crew module mass, and A/B mass fraction) are changed to cause a higher IMLEO, the dual vehicle concept performs increasingly better.

A three-stage single P/A performing a L1 mission profile is 21.2 to 34.8 t (16.1 to 17.2 percent) greater in IMLEO than the three-stage single P/A performing an LLO mission profile for A/B return and 23.0 to 38.3 t (9.4 to 15.7 percent) greater for A/P return.

A three-stage dual vehicle performing a L1 mission profile is 31.4 to 41.6 t (21.8 to 27.8 percent) greater in IMLEO than the three-stage dual vehicle performing an LLO mission profile for A/B return and 30.7 to 41.4 t (18.3 to 21.5 percent) greater for A/P return.

Aerobrake Performance

Table 5 lists the aerobrake efficiency factors for each of the mission scenarios. The aerobrake efficiency factor was defined earlier in the study as the percent savings in IMLEO for a transfer vehicle that uses an aerobrake maneuver as opposed to an all-propulsive maneuver. The chart can be read as follows: A two-stage single-P/A vehicle performing a direct mission profile (mission scenario No. 1), using the high IMLEO inputs will be 39.0 percent less in IMLEO when using an aerobrake maneuver as opposed to an all-propulsive maneuver upon Earth return.

Figure 7 graphically illustrates the aerobrake efficiency data. The bottom of the shaded region of each mission scenario is the aerobrake efficiency for the high IMLEO inputs while the top of each shaded region displays the aerobrake efficiency for the low IMLEO inputs. Using this format, one can determine the range of IMLEO savings for each mission scenario when aerobraking is employed as opposed to an all propulsive Earth return. The following observations are made concerning the aerobrake performance:

The selected mission scenarios show that for the highest IMLEO input cases (upper limit for that scenario), the transfer vehicle is 11.0 to 39.0 percent less in IMLEO when using an aerobraked Earth return as opposed to an all-propulsive return, and the lowest IMLEO input cases yields a transfer vehicle with 16.1 to 47.4 percent less mass.

The two-stage single P/A performing a direct mission profile (mission scenario No. 1) shows greatest savings (39.0 to 47.4 percent) in IMLEO while the three-stage, single P/A performing an L1 mission profile (mission scenario No. 7) shows the least savings (11.0 to 16.1 percent).

Table 5. Aerobrake performance results.

Mission Scenario #	Aerobrake Efficiency Factor		
	$\eta_{\text{High IMLEO Inputs}}$	$\eta_{\text{Low IMLEO Inputs}}$	Δ
1	.390	.474	.084
2	.277	.357	.080
3	.184	.233	.049
4	114	.173	.059
5	.302	.358	.056
6	-	-	-
7	.168	.210	.042
8	.110	.161	.051
9	.133	.170	.037

In most cases, a mission scenario with a higher IMLEO displayed a higher aerobrake efficiency factor. Also, the aerobrake becomes more efficient with decreasing Isp or increasing crew module mass or surface payload mass. The reason for an increase in aerobraking efficiency is that aerobraking in effect, saves more propellant at the lower vehicle performance levels than at the high performance levels.

Normally, the aerobrake is more efficient (saves more percentage of IMLEO) for low Isp and high crew module mass as is the case for the high IMLEO inputs. However, in this study, to achieve the highest IMLEO for a mission scenario, the payload to the lunar surface was also increased. As a result, some of the trends normally displayed by the aerobrake efficiency factor are not visible.

Sensitivity Analysis

Figure 8 shows the magnitude of the range of IMLEO for each mission scenario and Earth return method. The range of IMLEO's gives an indication of the sensitivity of each mission scenario to the vehicle parameters that were varied. The mission scenarios with smaller ranges are less sensitive to variations in the vehicle design parameters. This characteristic is often referred to as robustness. It is interesting to note that the mission scenarios with the lowest IMLEO, as shown previously, also have the smallest range of variation. This indicates that the mission scenarios which yield the lowest IMLEO's are also the most robust. The data also shows that aerobraking decreases the range of IMLEO variation by 2 to 33 percent over all-propulsive Earth returns. Therefore, it could be concluded that aerobraking may improve the robustness of a lunar transportation system. The benefits of aerobraking in reducing the sensitivity of IMLEO to each vehicle design parameter will be shown in the next section.

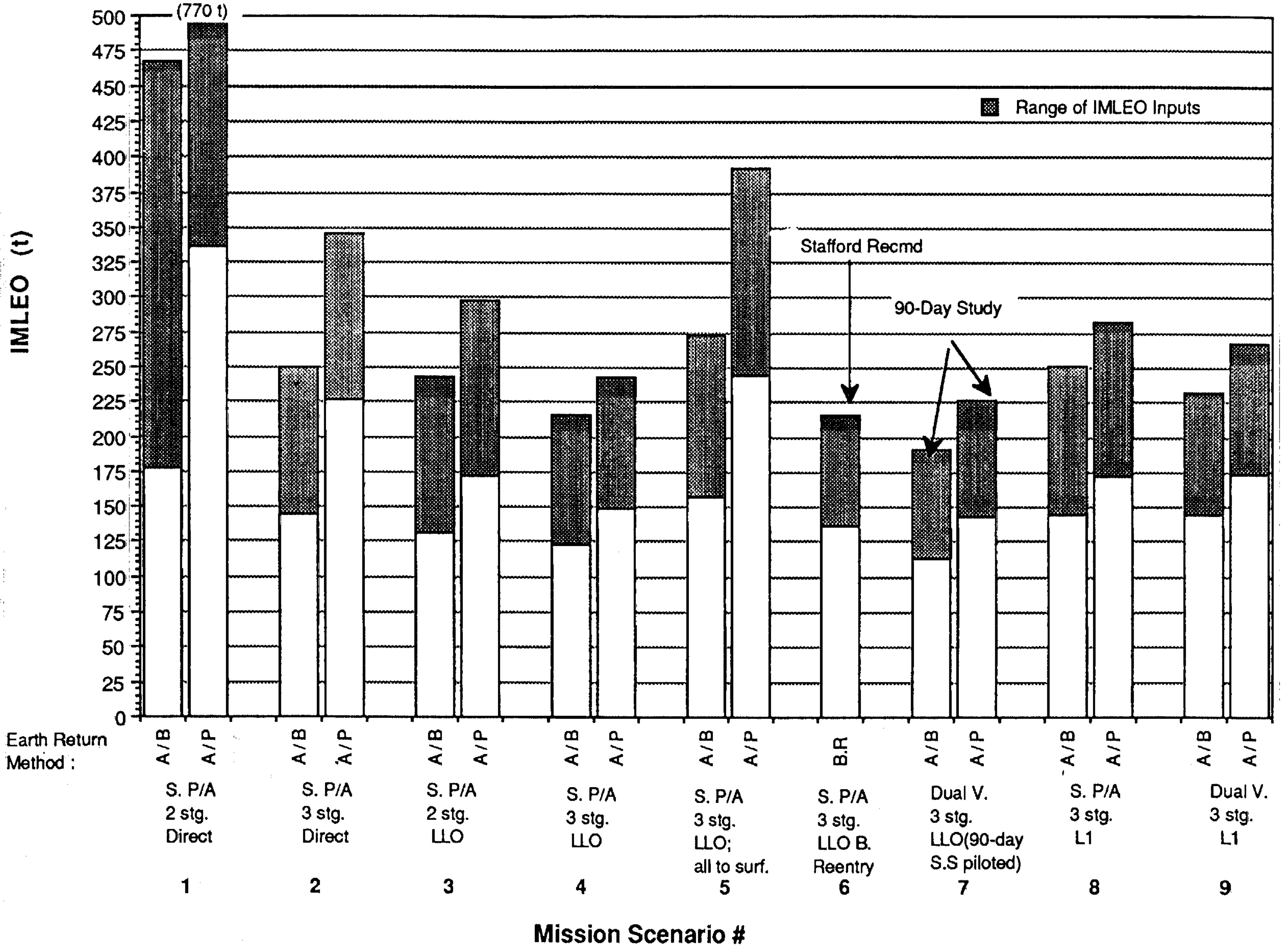


Figure 7. Lunar transfer system performance results: mission scenario IMLEO comparison.

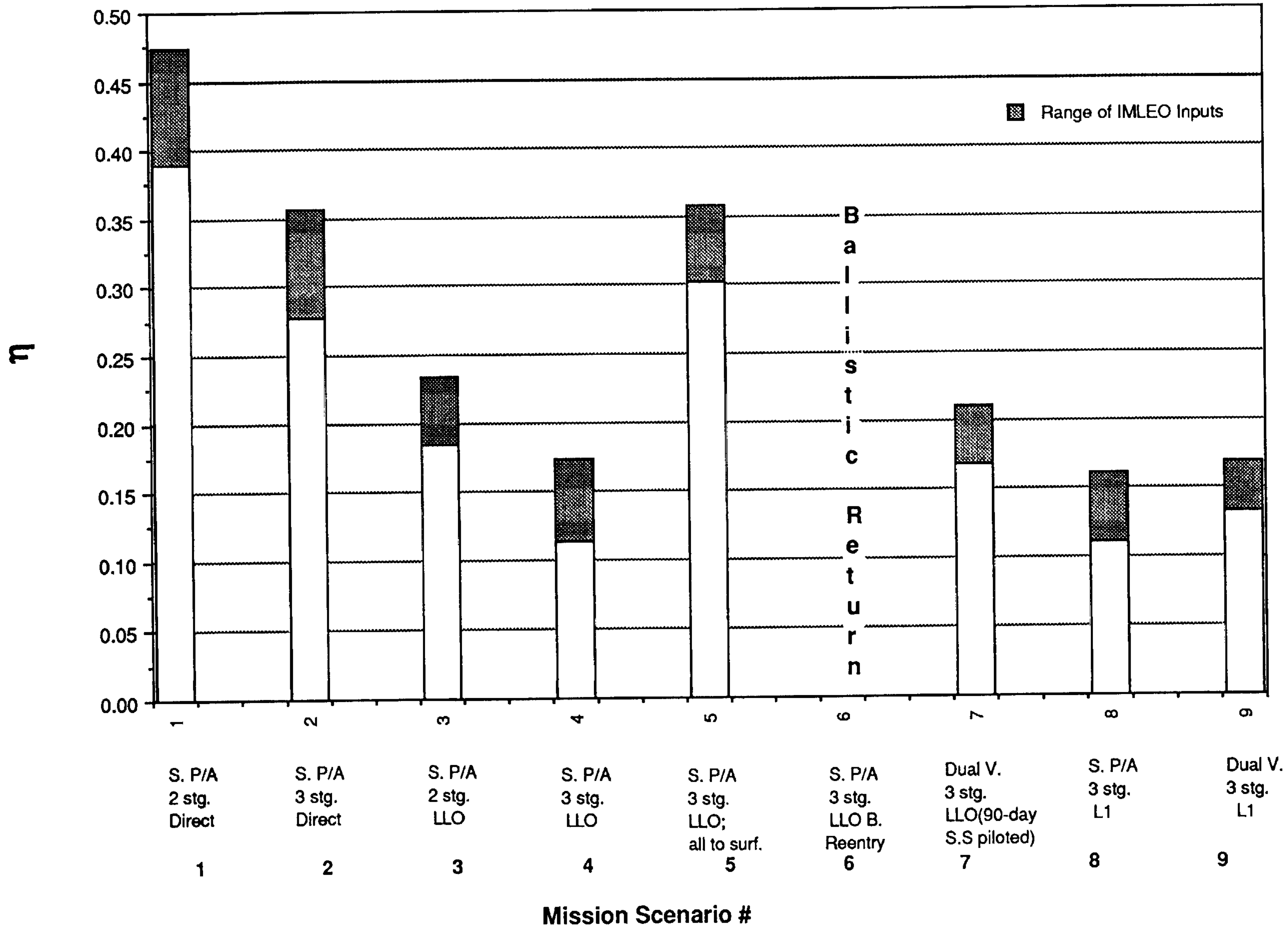


Figure 8. Aerobrake performance results: mission scenario aerobrake efficiency factor comparison.

Parametric Analysis

Two mission scenarios were chosen for a parametric study; the two- and three-stage single-P/A module performing an LLO mission profile (mission scenarios 3 and 4). As stated in the introduction, the current single-P/A baseline is a two-stage (core stage + TLI drop tank set) vehicle in which the aerobrake is parked in LLO. Parametric analysis will show the performance benefits of an additional drop tank set.

The parametric study was modeled as follows: baseline values and ranges for the four system parameters were chosen for both mission scenarios. Three system parameters were kept constant at the baseline values while the fourth parameter was varied for both the aerobrake and all-propulsive return. This was repeated for each parameter. The parameter values are listed below in table 6. The baseline values are listed in the middle column.

Table. 6. Parametric analysis parameters.

			Baseline		
Payload to Surface (kg)	5,000	10,000	15,000	20,000	25,000
Isp (s)	450	465	481/465*	-	-
A/B Mass Fraction (%)	10	15	22	25	30
Crew Module Mass (kg)	3,000	4,000	5,000	6,000	7,000

* Low value of Isp used for ascent and descent

Figures 9 and 10 are the graphical results of the parametric study for the two and three-stage, single-P/A vehicles, respectively. Tables 7 and 8 are results extracted from the parametric graphs. The baseline mission inputs are listed again for reference. The partial derivatives are based on a linear approximation of the data. In this manner, one can predict the impact on IMLEO to changes in design parameters. For example, the two-stage single P/A performing an LLO mission profile has a baseline IMLEO of 186 t when employing an aerobraked Earth return (table 7). If the payload requirement increases from 5,000 kg to 6,200 kg (an increase of 1,200 kg); the resulting IMLEO would increase by approximately

$$(1{,}200 \text{ kg}) \times (5.30 \text{ kg/kg}) = 6{,}300 \text{ kg}.$$

Therefore, the adjusted IMLEO is 186 t + 6.3 t = 192.3 t.

The following are observations concerning the two- and three-stage single-P/A parametric study:

The baseline three-stage single P/A in an LLO mission profile is approximately 8 t less in IMLEO than the two-stage single P/A for an aerobraked (A/B) return and approximately 26 t less for an A/P return.

The IMLEO for the two-stage single P/A performing an LLO mission profile is 19.1 percent more sensitive to changes in payload to the lunar surface compared to the three-stage single P/A for A/B return and 36.0 percent more sensitive for A/P return.

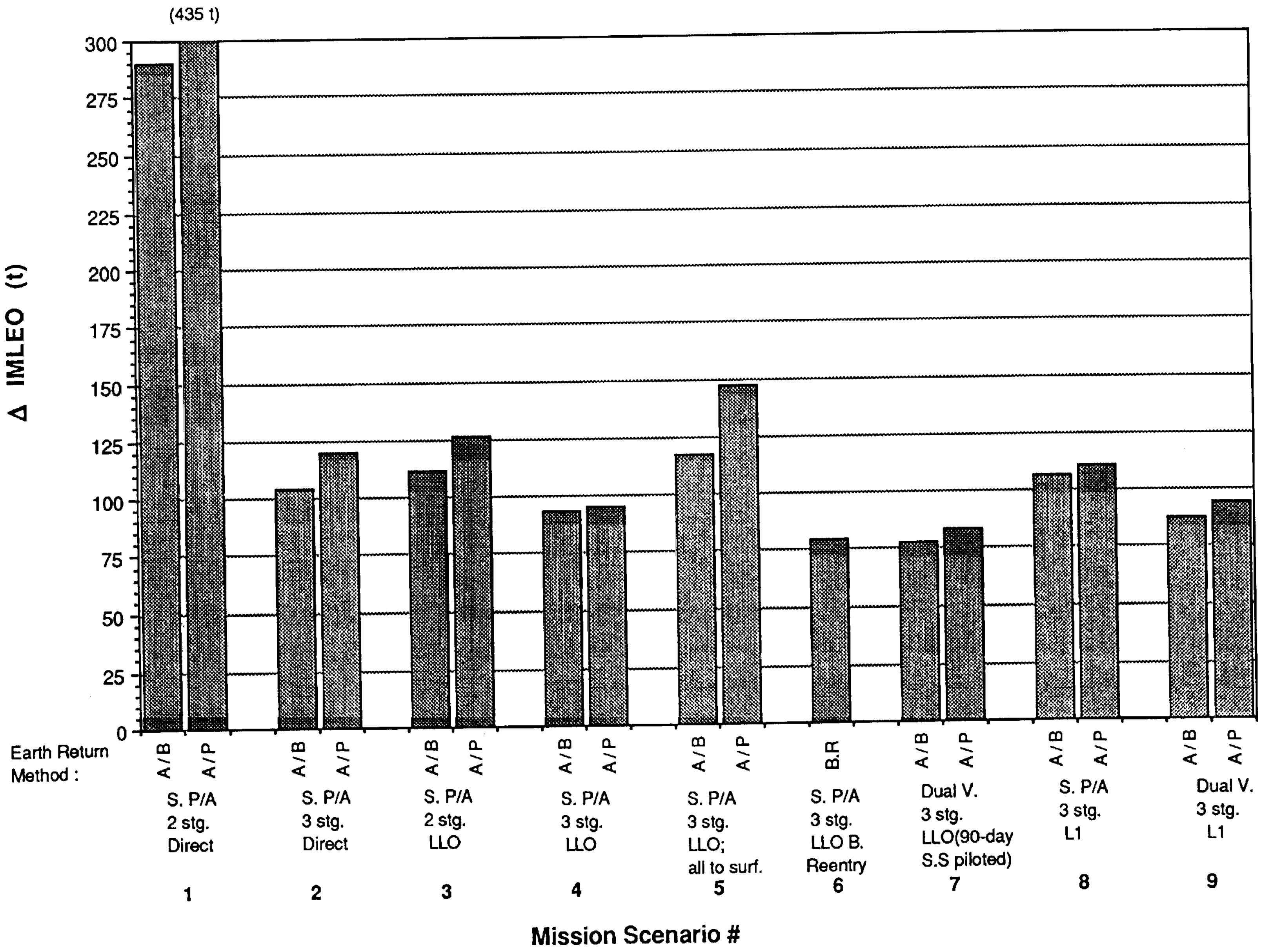


Figure 9. Sensitivity analysis of mission scenarios.

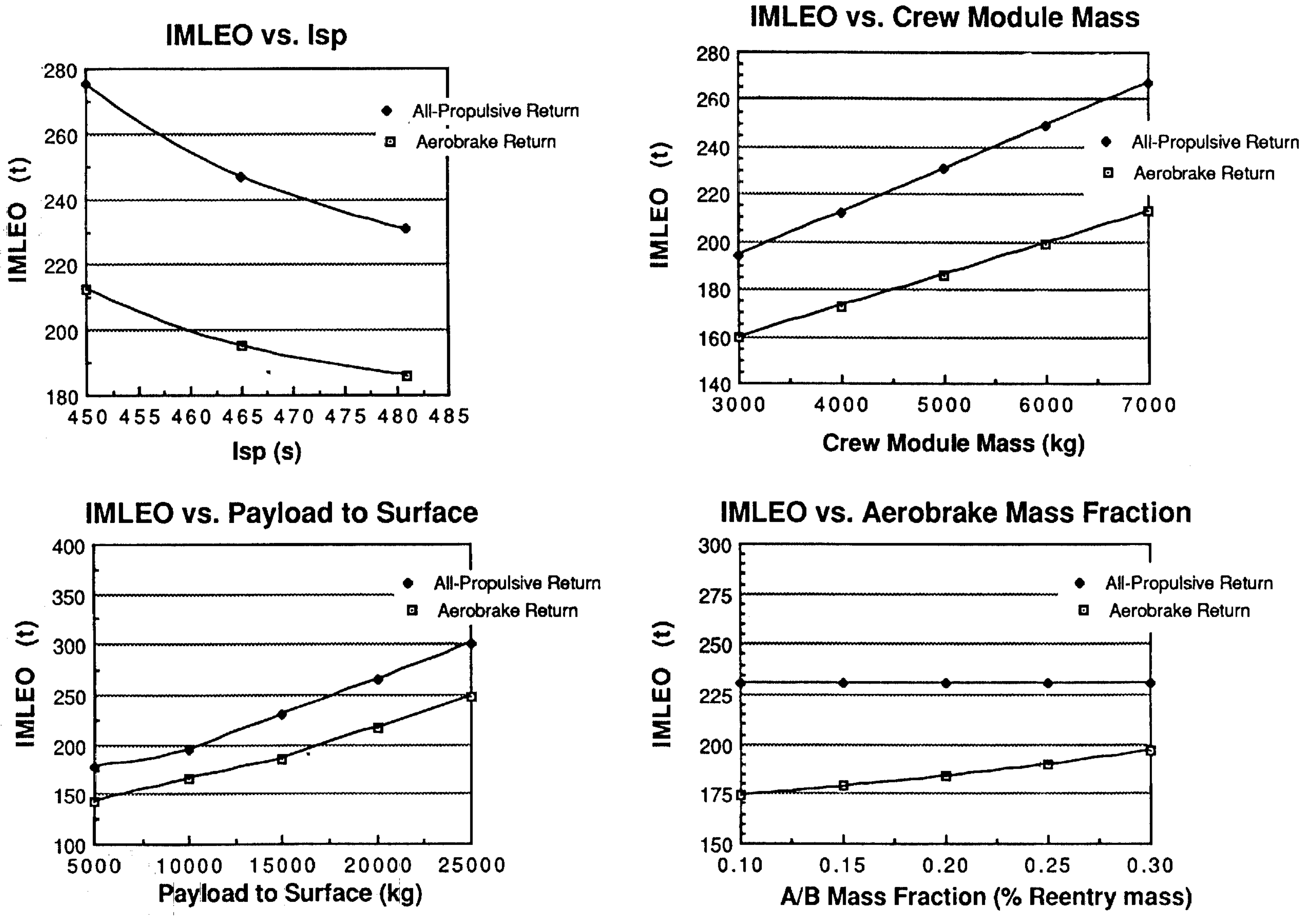


Figure 10. Parametric results: LLO two-stage single P/A.

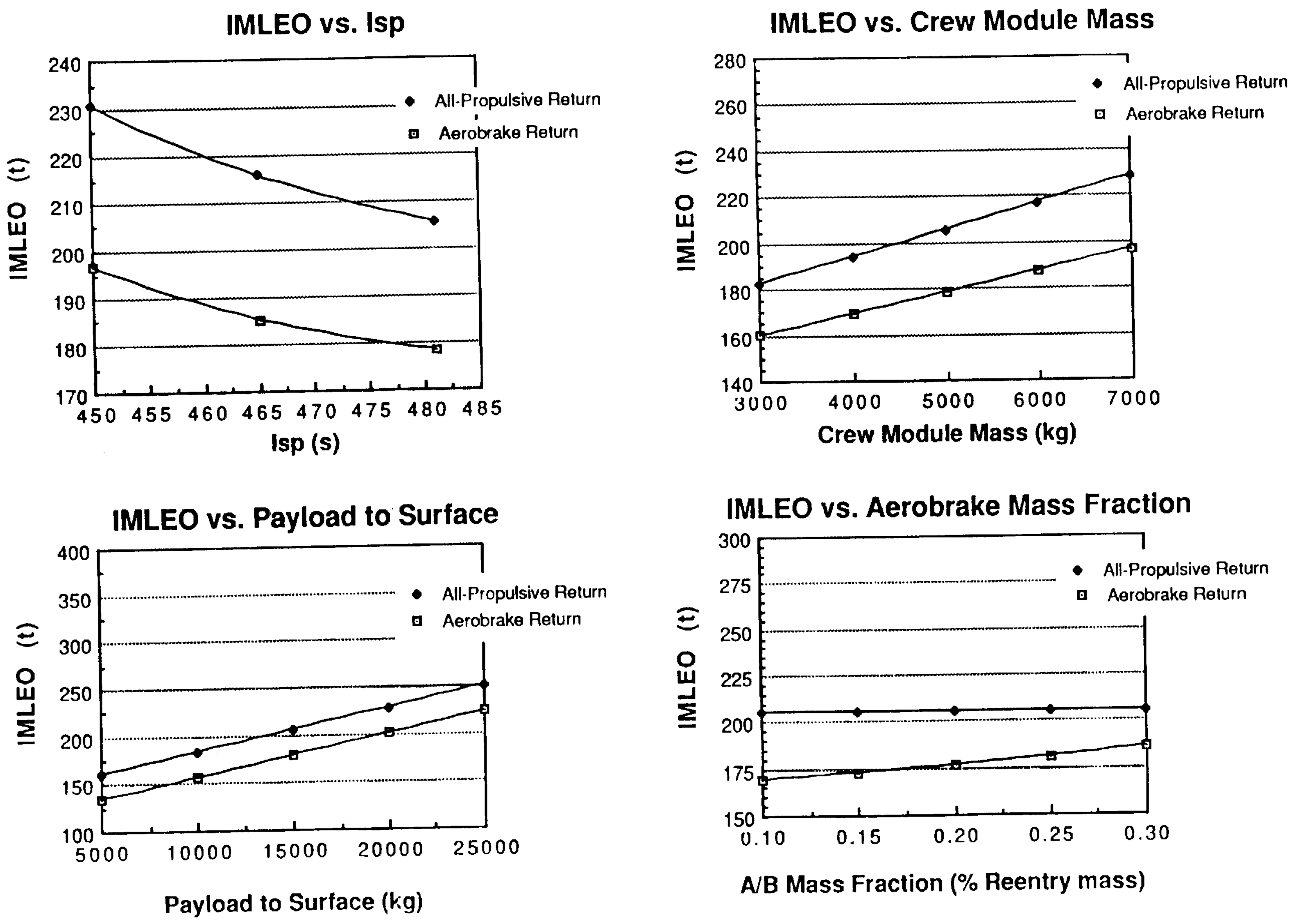


Figure 11. Parametric results: LLO three-stage single P/A.

Table 7. Parametric results: two-stage single P/A.

Baseline Mission:

2 stage, Single P/A, LLO Mission Profile (2 stg. S. P/A;LLO)

Isp = 481 s (465 s for ascent/descent)
Payload to Surface = 15000 kg.
Crew Module = 5000 kg.
A/B Mass Fraction = 22%

Results*:	IMLEO$_{\text{A/B return}}$ = 186 t	IMLEO$_{\text{A/P return}}$ = 231 t
	A/B Return:	A/P Return:
	$\frac{\delta M_0}{\delta I_{sp}} = -870.0\ \frac{KG}{s}$	$\frac{\delta M_0}{\delta I_{sp}} = -1460.0\ \frac{KG}{s}$
	$\frac{\delta M_0}{\delta \text{ Payload}} = 5.30$	$\frac{\delta M_0}{\delta \text{ Payload}} = 6.13$
	$\frac{\delta M_0}{\delta \text{ Crew Module}} = 13.2$	$\frac{\delta M_0}{\delta \text{ Crew Module}} = 18.3$
	$\frac{\delta M_0}{\delta \text{ A/B Mass Fraction}} = 1126.85\ \frac{KG}{\%}$	$\frac{\delta M_0}{\delta \text{ A/B Mass Fraction}} =$ -

* Ratios based on linear approximation of data over given parameter ranges

Table 8. Parametric results: three-stage single P/A.

Baseline Mission:

3 stage, Single P/A, LLO Mission Profile (3 stg. S. P/A;LLO)

Isp = 481 s (465 s for ascent/descent)
Payload to Surface = 15000 kg.
Crew Module = 5000 kg.
A/B Mass Fraction = 22 %

Results*:	IMLEO$_{\text{A/B return}}$ = 178 t	IMLEO$_{\text{A/P return}}$ = 205 t
	A/B Return:	A/P Return:
	$\frac{\delta M_0}{\delta I_{sp}} = -598.7\ \frac{KG}{s}$	$\frac{\delta M_0}{\delta I_{sp}} = -844.7\ \frac{KG}{s}$
	$\frac{\delta M_0}{\delta \text{ Payload}} = 4.45$	$\frac{\delta M_0}{\delta \text{ Payload}} = 4.51$
	$\frac{\delta M_0}{\delta \text{ Crew Module}} = 9.18$	$\frac{\delta M_0}{\delta \text{ Crew Module}} = 11.45$
	$\frac{\delta M_0}{\delta \text{ A/B Mass Fraction}} = 823.05\ \frac{KG}{\%}$	$\frac{\delta M_0}{\delta \text{ A/B Mass Fraction}} =$ -

* Ratios based on linear approximation of data over given parameter ranges

The IMLEO for the two-stage single P/A is 43.8 percent more sensitive to changes in crew module mass compared to the three-stage single P/A for A/B return and 59.8 percent more sensitive for A/P return.

The IMLEO for the two-stage single P/A is 36.9 percent more sensitive to changes in aerobrake mass fraction compared to the three-stage single P/A for A/B return.

The IMLEO for the two-stage single P/A is 45.3 percent more sensitive to changes in Isp compared to the three-stage single P/A for A/B return and 72.8 percent more sensitive for A/P return.

Mission Scenario Rankings

Table 9 is a listing of the best mission scenarios based on IMLEO for three criteria. As the chart indicates, the top two mission scenarios use aerobraking for return to Earth orbit. The third uses aerobraking (ballistic reentry) for return to Earth's surface. This demonstrates the obvious benefits of aerobraking for lunar missions. These rankings are based solely on the values of IMLEO. Cost and operational considerations could alter these rankings. It should be noted that the mission sequences used in this study were not optimized. If the staging sequences were optimized, IMLEO would be reduced further. It should also be noted that the scenarios listed on this chart are among the most robust mission scenarios as shown in the parametric analysis. Based on the relatively narrow perspective of this study it is not possible to select the optimum mission scenario, however, the scenarios listed on this chart appear to be the most promising for further investigation.

Table 9. Mission scenario rankings.

BEST AEROBRAKED SCENARIOS	BEST ALL PROPULSIVE SCENARIOS	BEST OVERALL SCENARIOS
#7	#6	#7, A/B RETURN
#4	#7	#4, A/B RETURN
#3	#4	#6
THESE RANKINGS ARE BASED ON VEHICLE PERFORMANCE ONLY		

KEY: #3 : LLO; 2 STAGE SINGLE P/A, RETURN TO LEO
#4 : LLO; 3 STAGE SINGLE P/A, RETURN TO LEO
#6 : LLO; 3 STAGE SINGLR P/A, BALLISTIC RETURN TO EARTH (STAFFORD)
#7 : LLO; 3 STAGE DUAL VEHICLE, RETURN TO LEO (90 DAY STUDY)

STUDY CONCLUSIONS

The selected mission scenarios show an 11- to 49-percent decrease in IMLEO when aerobraking is employed as an Earth return method as opposed to an all-propulsive maneuver.

A three-stage, single-P/A for which the aerobrake and return propellant is parked in LLO, is 33.5 to 57.3 t less in IMLEO compared to the same vehicle if all components are taken to the lunar surface.

The 90-Day Study steady-state piloted LTV is 10 to 25.5 t less in IMLEO than the three-stage single P/A for the same mission profile.

Both the three-stage single P/A and the dual vehicle LTV are significantly greater in IM LEO when performing an L1 mission profile compared to an LLO mission profile.

The two-stage single P/A is 8.5 to 26.8 t greater in IMLEO than the three-stage single P/A, if an aerobraked Earth return is assumed.

The parametric study shows the IMLEO for the two-stage single P/A performing an LLO mission profile is more sensitive to changes in all system parameters (Isp, crew module mass, payload to lunar surface, and aerobrake mass fraction) than the three-stage single P/A.

The sensitivity analysis indicates aerobraking may improve the robustness of every mission scenario, i.e., aerobraking not only reduces IMLEO (compared to all-propulsive) but also may decrease IMLEO's sensitivity to changes in system parameters.

STUDY RECOMMENDATIONS

The results and conclusions of this study were based entirely on the vehicle performance as indicated by IMLEO. Further analysis should include Earth-to-orbit transportation, mission operations, and program cost analyses.

APPENDIX
SYMBOLS AND ACRONYMS

A/B	aerobrake
A/P	all-propulsive
ASC	ascent (from lunar surface)
BR	ballistic return
DES	descent (to lunar surface)
EOI	Earth orbit insertion
IMLEO	initial mass in low-Earth orbit
JSC	Johnson Space Center
kg	kilogram
LEO	low-Earth orbit
LEV	lunar excursion vehicle
LLO	low lunar orbit
LOI	lunar orbit insertion
LTV	lunar transfer vehicle
L1IE	L1 insertion from Earth
L1IM	L1 insertion from Moon
Mbo	burnout mass
Mp	mass of propellant
MSFC	Marshall Space Flight Center
P/A	propulsion/avionics
PD	Program Development Office/Preliminary Design Branch
RCS	reaction control system
SEI	Space Exploration Initiative

t	metric tonne (1,000 kg)
TEI	trans-Earth injection
TLI	trans-lunar injection
TL1E	trans-L1 from Earth
TL1M	trans-L1 from Moon
TPS	thermal protection system
TS	tank stage
η	aerobrake efficiency factor
ΔV	vehicle velocity increment for mission maneuver
λ	stage mass fraction

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APPROVAL

LUNAR MISSION AEROBRAKE PERFORMANCE STUDY

By J. Mulqueen and D. Coughlin

The information in this report has been reviewed for technical content. Review of any information concerning Department of Defense or nuclear energy activities or programs has been made by the MSFC Security Classification Officer. This report, in its entirety, has been determined to be unclassified.

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