# CONCEPTUAL ANALYSIS OF A LUNAR BASE TRANSPORTATION SYSTEM

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## INTRODUCTION

The Report of the National Commission on Space (*National Commission on Space,* 1986) and the NASA/National Academy of Science Symposium on Lunar Bases and Space Activities of the 21st Century (*Mendell,* 1985) demonstrated that a return to the Moon would be a logical and feasible extension of NASA's goal to expand the human presence in space. Development of a permanently manned lunar base would provide an outpost for scientific research, economic exploitation of the Moon's resources, and the eventual colonization of the Moon.

Important to the planning for such a lunar base is the development of transportation requirements for the establishment and maintenance of that base. This was accomplished as part of a lunar base systems assessment study conducted by the NASA Langley Research Center in conjunction with the NASA Johnson Space Center. Lunar base parameters are presented using a baseline lunar facility concept and timeline of developmental phases. Masses for habitation and scientific modules, power systems, life support systems, and thermal control systems were generated, assuming space station technology as a starting point. The masses were manifested by grouping various systems into cargo missions and interspersing manned flights consistent with construction and base maintenance timelines.

A computer program that sizes the orbital transfer vehicles (OTVs), lunar landers, lunar ascenders, and the manned capsules was developed. This program consists of an iterative technique to solve the rocket equation successively for each velocity correction ($\Delta V$) in a mission. The $\Delta V$ values reflect integrated trajectory values and include gravity losses. As the program computed fuel masses, it matched structural masses from General Dynamics' modular space-based OTV design (*Ketchum,* 1986a).

Variables in the study included the operational mode (i.e., expendable vs. reusable and single-stage vs. two-stage OTVs), cryogenic specific impulse, reflecting different levels of engine technology, and aerobraking vs. all-propulsive return to Earth orbit. The use of lunar-derived oxygen was also examined for its general impact. For each combination of factors, the low-Earth-orbit (LEO) stack masses and Earth-to-orbit (ETO) lift requirements are summarized by individual mission and totaled for the developmental phase. In addition to these discrete data, trends in the variation of study parameters are presented.

## METHODOLOGY

The methodology for the lunar base transportation study is shown in Fig. 1. Requirements for the baseline lunar base mission model, derived by NASA Johnson Space Center, produced a set of functional requirements for the lunar base that included habitability, manufacturing, commercial applications, science, and exploration. System concepts were developed and analysis and technology option trade studies were conducted to define the mass, volume, power, and resupply requirements of the lunar base system. A manifest was prepared based on the priority requirements of equipment and hardware for the lunar base and the

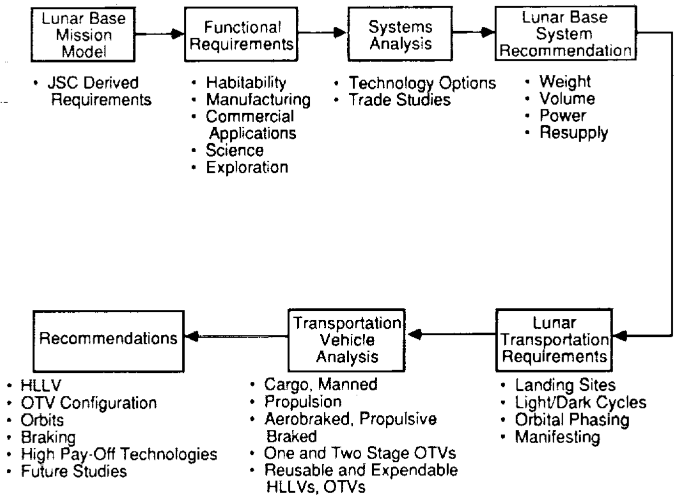

**Fig. 1.** Lunar base studies methodology.

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volume and mass requirements of the transportation system. The manifest information was then input into the analysis of transportation vehicle options. This analysis considered such factors as (1) separate manned and cargo missions; (2) reusable vs. expendable OTVs; (3) one- vs. two-stage OTVs; (4) aerobraking vs. propulsive braking on return to LEO; (5) specific impulse of cryogenic engines; and (6) impact of using lunar-derived oxygen in lunar vicinity.

## MISSION DESCRIPTION

Development of a lunar base will probably progress in steps and phases as shown in Table 1 (*Roberts,* 1986). The first phase will incorporate unmanned reconnaissance or global mapping missions to expand the scientific database of the Moon (including lunar resource research). In the Phase II scenario, a temporary manned facility would be established on the lunar surface to provide limited research capability for science, materials processing, and lunar surface operations. Follow-on phases would establish permanent occupancy and self-sufficient bases, leading to colonization of the Moon. This study addresses the transportation requirements and system for the Phase II temporary facility.

The Phase II lunar base required a total mass of 207,865 lbm delivered to the lunar surface. A breakdown of the facility and equipment masses is given in Table 2. Manifesting the lunar base

TABLE 1. Lunar base phases.

| Phase | Mission | Time Period | Crew Size | Power (kW) | Function | Facilities |
|---|---|---|---|---|---|---|
| I | Lunar surface mapping | 1995-2000 | — | — | • Preliminary site selection | • Unmanned lunar orbiter satellite |
| II | Lunar sorties to establish a small space port | 2000-2008 | 0-5 | 100 | • Final site selection<br>• Site preparation<br>• Exploration to 10 km<br>• Core samples to 5 m<br>• Materials processing | • Habitability module<br>• Soil mover/crane<br>• Pilot LOX plant<br>• Core sampler<br>• Surface transporter |
| III | Expand space port to increase functional capabilities | 2008-2018 | 5-11 | 300 | • Permanently manned<br>• Expanded crew<br>• Materials research<br>• Closed loop research<br>• LOX utilization | • 2 habitability modules<br>• Science/astronomy<br>• Expanded LOX plant |
| IV | Establish lunar base with minimum support from Earth for survival | 2018-2028 | 11-30 | 1000 | • Full LOX production<br>• Habitat growth<br>• Locally derived products/consumables | • 6 habitability modules<br>• 2 science/astronomy modules<br>• 1000 metric ton per year LOX plant<br>• Closed ECLSS<br>• LOX storage and servicing modules |

TABLE 2. Lunar base facility and equipment masses.

| | Lunar Base | | 90-day Resupply | | |
|---|---|---|---|---|---|
| Facility | Mass (lbm) | Volume (ft$^3$) | Mass (lbm) | Volume (ft$^3$) | Power (kW) |
| Habitation Module 1 | 36,108 | 6,532 | 5,162 | 289 | 4.72 |
| Node 1 | 16,983 | 2,860 | 325 | 32 | 4.68 |
| Node 2 | 16,972 | 2,860 | 695 | 40 | 3.35 |
| Node 3 LOX | 17,627 | 2,860 | 226 | 35 | 73.41 |
| Air Lock 1 | 5,879 | 1,006 | 70 | 7 | 1.16 |
| Air Lock 2 | 5,879 | 1,006 | 68 | 7 | 1.16 |
| Air Lock 3 | 5,671 | 1,006 | 40 | 5 | 0.99 |
| Transporter 1 | 4,469 | 2,219 | 195 | 110 | 0 |
| Crane/Regolith Mover 1 | 14,239 | 4,269 | 620 | 210 | 0 |
| Launch/Lander Pad 1 | 27,600 | 15,150 | 50 | 2 | 0.05 |
| Maintenance Shed 1 | 8,090 | 3,500 | 46 | 1 | 1.00 |
| External Equipment | 48,348 | 3,576 | 2,854 | 207 | 117.00 |
| Total | 207,865 | 46,844 | 10,351 | 945 | 207.50 |

material/components resulted in a requirement for 16 missions, 9 manned and 7 unmanned. A sample manifest for missions 1 and 2 (a manned and cargo mission) is presented in Table 3. The lunar base masses and manifest were developed in the NASA Langley assessment study from the NASA Johnson requirements.

To establish the Phase II lunar base, a transportation system capable of transporting manned capsules with a mass of about 13,000 lbm to and from the lunar surface and ferrying a cargo of 35,000 to 40,000 lbm to the lunar surface is required. For this study, the total mass (including payloads, modules, fuel, and crew) to be delivered to Earth orbit is approximately 3.0 million lbm to 4.5 million lbm, depending on the operational mode, engine efficiency, and reentry braking system.

## TRANSPORTATION SYSTEM DESCRIPTION AND WEIGHT SUMMARY

The transportation system required for buildup and maintenance of a lunar base assumed Earth launch of a heavy-lift launch vehicle (HLLV) to a staging area (space station) in LEO and OTVs for transfer of all material to the Moon. The HLLV is capable of delivering approximately 150,000 lbm into LEO.

The space-based OTV concept that was used as the baseline for this study is the General Dynamics S-4C modular tank concept (*Ketchum,* 1986b). Figure 2 shows line drawings of the one-stage manned (with lunar ascent and descent vehicle) and two-stage cargo (with hab module payload) configurations.

TABLE 3. Sample mission manifest.

| Mission 1 (manned) | | Mission 2 (unmanned) | |
|---|---|---|---|
| Manned capsule | 13,200 lbm | Regolith mover/crane | 14,239 lbm |
| Core sampler | 40 lbm | 50% external power equipment | 11,601 lbm |
| Stay time extension module (18-day supply) | 3,300 lbm | Maintenance shelter | 8,069 lbm |
| Lunar rover | 4,469 lbm | | |
| Crew and supplies | 1,500 lbm | | |
| Subtotal | 22,509 lbm | Subtotal | 33,390 lbm |
| Package (10%) | 2,251 lbm | Package (10%) | 3,393 lbm |
| Total mass approx. | 24,800 lbm | Total mass approx. | 36,800 lbm |

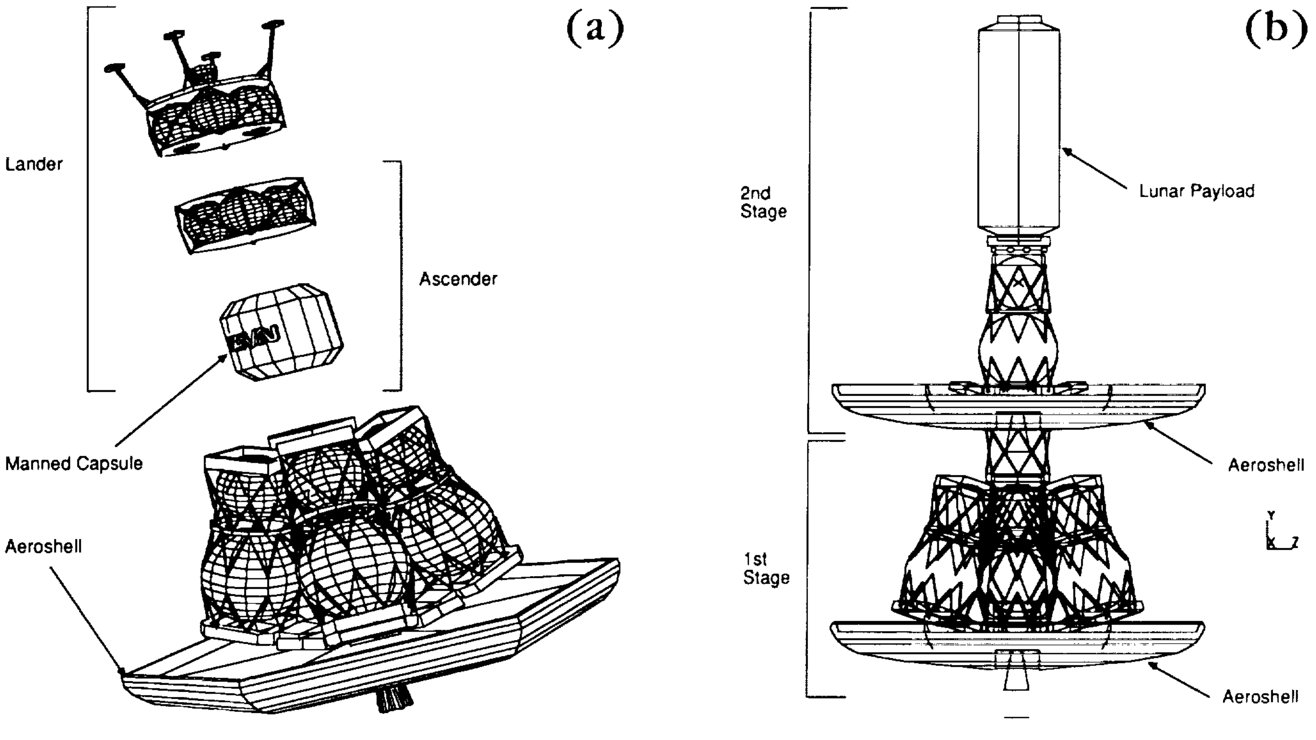

**Fig. 2.** Orbital transfer vehicle (OTV) line drawings: (a) one-stage manned and (b) two-stage cargo.

The S-4C OTV is composed of the following components: (1) twin engines; (2) geotruss aerobrake; (3) propellant tank sets (hydrogen and oxygen); (4) avionics package; and (5) payload.

In order to accommodate different payloads (masses), up to seven propellant tank sets can be accommodated on a single stage. The propellant capacity and the associated mass breakdown of the OTV for practicable numbers of tank sets are given in Table 4.

## LUNAR MISSIONS TRANSPORTATION MODE SCENARIOS

Transportation mode scenarios for one-stage and two-stage lunar missions are shown in Fig. 3. Both manned and cargo, as well as expendable and reusable, missions are presented.

The mission scenario begins with the lunar transportation system (one- or two-stage) in LEO. For the manned missions, the transportation system consists of the OTV, a manned capsule, a lunar lander, and a lunar ascender. The cargo mission transportation system consists only of the OTV, the lunar lander, and the lunar payload. The OTV performs the translunar injection (TLI) burn and the lunar orbit insertion (LOI) burn. The OTV is discarded in lunar orbit, and the descender is discarded on the lunar surface. For the manned missions, the lunar ascender returns the manned capsule to lunar orbit to rendezvous with the OTV and is discarded. The OTV for all return missions (all manned and the reusable cargo missions) performs a trans-Earth injection (TEI) burn. Earth orbit insertion (EOI) is performed either propulsively or by aerobraking in the upper atmosphere along with a small $\Delta V$ burn. Once in LEO, the OTV and manned capsule will be refitted for reuse (reusable missions). For the expendable missions, a new OTV must be delivered by the HLLV for follow-on missions.

In the case of the two-stage OTV in Figs. 3c,d, stage one separates after TLI and is either discarded (expendable) or performs an Earth-orbit aerobraking in the upper atmosphere, along with a small $\Delta V$ burn to rendezvous with the space station for subsequent reuse. The second stage performs the LOI, and the OTV remains in lunar orbit while the lunar lander performs a powered descent carrying the payload (manned or cargo) to the lunar surface. For the expendable cargo missions, the lunar lander is discarded on the lunar surface and the OTV is discarded in lunar orbit.

## COMPUTER PROGRAM DESCRIPTION

A FORTRAN program based on an iterative solution to the rocket equation was written to solve for the mass required to be delivered to LEO. The general form of the rocket equation is

$$\Delta V = g_c I_{sp} \, ln(M_o/M_f) \qquad (1)$$

where $\Delta V$ is the change in velocity required for a specific maneuver (ft/sec), $g_c$ is Earth gravity (32.174 ft/sec$^2$), $I_{sp}$ is the specific impulse of the fuel (sec), $M_o$ is the initial mass before the maneuver (lbm), and $M_f$ is the final mass after the manuever (lbm).

Solving for the mass of fuel required for each manuever, the rocket equation takes the form of

$$M_{fuel} = M_f(e^{\Delta V/g_c I_{sp}} - 1) \qquad (2)$$

where $M_{fuel}$ is the mass of fuel required for the maneuver (lbm).

TABLE 4. Vehicle mass summary.

| | Number of Fuel Tank Sets | | | | |
|---|---|---|---|---|---|
| | 1 | 3 | 4 | 5 | 7 |
| Structure | 2,732 | 3,514 | 3,905 | 4,296 | 5,078 |
| Tanks | 292 | 1,381 | 1,926 | 2,470 | 3,559 |
| Propulsion system | 1,178 | 1,828 | 2,153 | 2,478 | 3,128 |
| Thermal control system | 125 | 261 | 329 | 397 | 533 |
| GN&C | 150 | 150 | 150 | 150 | 150 |
| Electrical systems | 555 | 555 | 555 | 555 | 555 |
| Aerobrake (reusable) | 1,341 | 2,298 | 2,298 | 2,298 | 2,298 |
| Propellant | 40,843 | 122,529 | 163,372 | 204,215 | 285,901 |
| Residual propellant | 529 | 1,526 | 1,995 | 2,463 | 3,401 |
| Pressurant | 9 | 27 | 36 | 45 | 63 |
| *Reusable OTV* | | | | | |
| Dry mass | 6,374 | 9,987 | 11,316 | 12,644 | 15,301 |
| Wet mass | 47,217 | 132,516 | 174,688 | 216,859 | 301,202 |
| Mass after maneuver | 6,912 | 11,540 | 13,347 | 15,152 | 18,765 |
| *Expendable OTV* | | | | | |
| Dry mass | 5,033 | 7,689 | 9,018 | 10,646 | 13,003 |
| Wet mass | 45,217 | 130,218 | 172,390 | 214,561 | 298,904 |
| Mass after maneuver | 5,571 | 9,242 | 11,049 | 12,854 | 16,467 |

| | Lunar lander | Lunar ascender |
|---|---|---|
| Structure | 8,360 | 5,720 |
| Propellant | 29,920 | 11,000 |

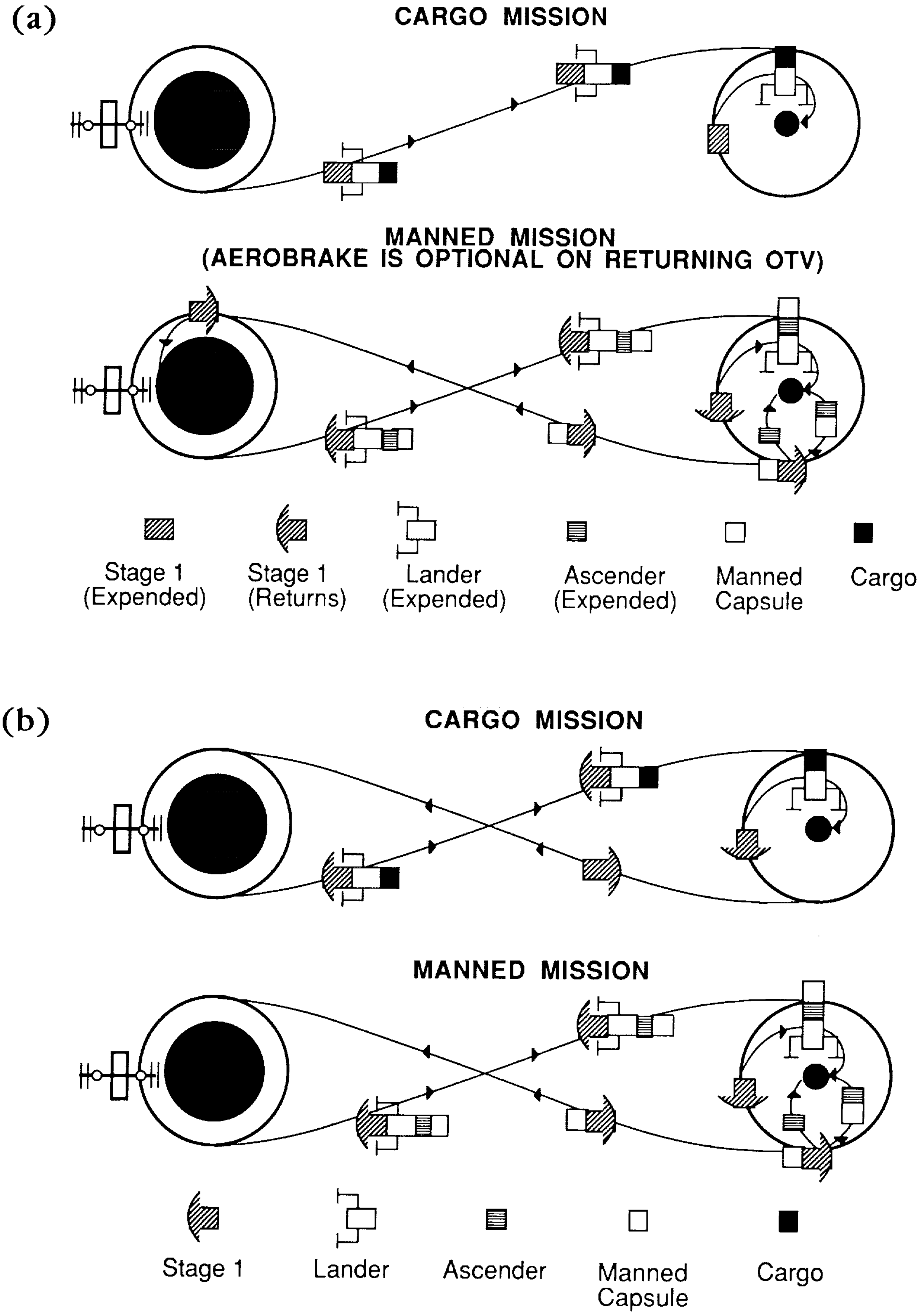

**Fig. 3.** Lunar mission scenarios: **(a)** one-stage, expendable OTV; **(b)** one-stage, reusable OTV.

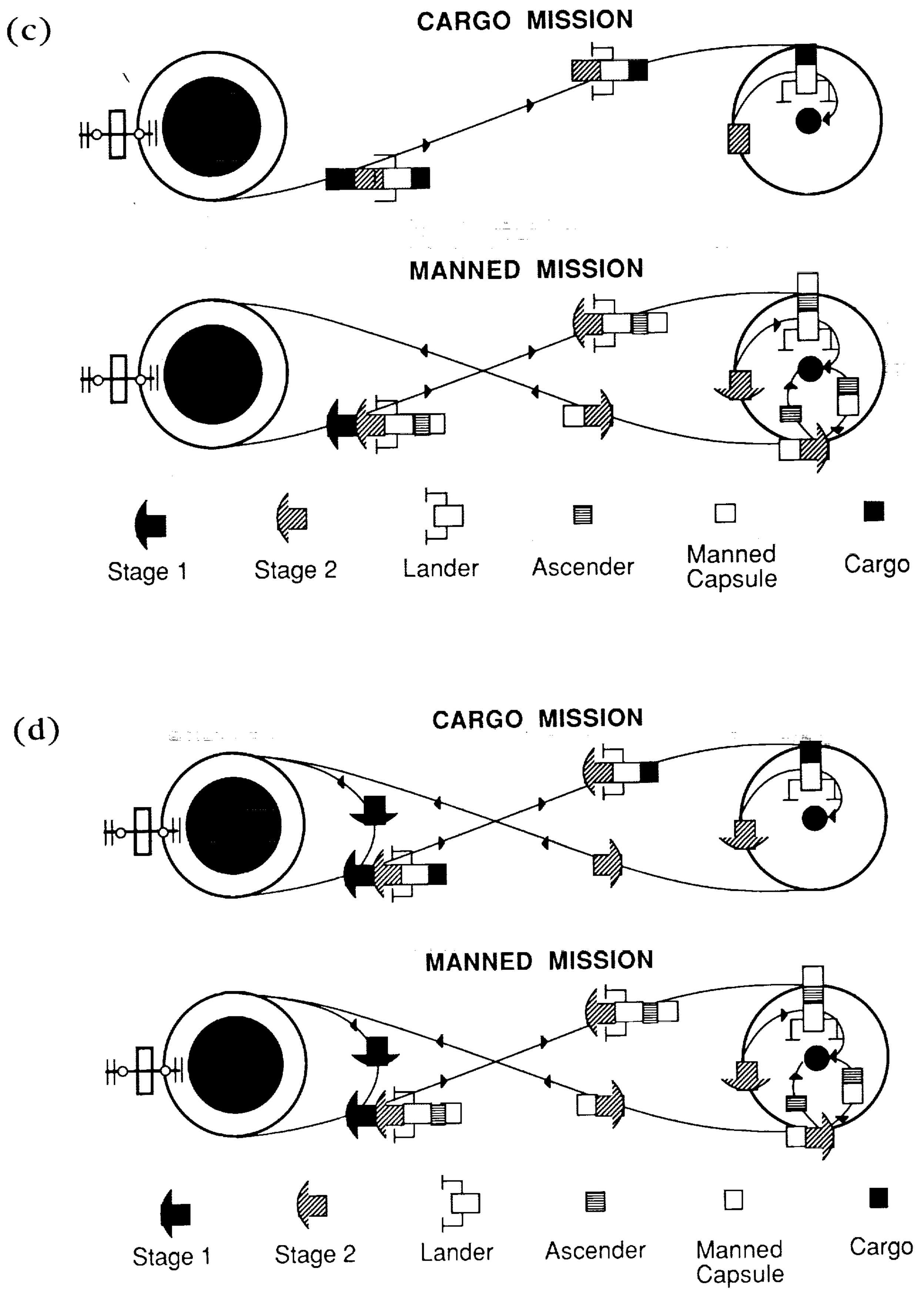

**Fig. 3.** (continued) (c) Two-stage, expendable OTV; (d) two-stage, reusable OTV.

The ΔV values shown in Fig. 4 are comparable to actual flight values from Apollo. The program starts with the manned module's ascent from the lunar surface and iterates backward from the lunar surface to determine the mass that must be delivered to LEO for the mission. This mass is the sum of the structure and fuel masses for all maneuvers plus the mass of the lunar payload (personnel, cargo, and supplies).

## ETO MASS SUMMARY

The ETO masses were determined for all 16 missions in each transportation scenario. For manned missions, the initial delivery of the reusable manned capsule was not considered in the ETO mass. Also, the initial delivery of the OTV was not considered in the ETO mass for reusable missions. A sample 16-mission ETO mass summary for a one-stage, reusable, aerobraked OTV with a specific impulse of 460 sec is shown in Table 5.

Tables 6 and 7 provide the total mass to be delivered to LEO for the 16-mission lunar base buildup and the number of HLLV launches required for each scenario. Twelve scenarios covering all the trade-off options are shown. Mass to LEO varied from 3.03 million lbm to 4.91 million lbm, and the number of HLLV launches varied from 20 to 33. These total mission numbers and the ETO vs. lunar payload mass trend charts (to be discussed in the next section) were used to define the optimum lunar base transportation system.

## TRADE-OFFS

A series of trade-off studies were conducted on key design parameters to determine the optimum transportation system for the manned and the cargo missions. Parameters affecting the design of the transportation system included (1) manned vs. cargo (unmanned); (2) reusable vs. expendable OTV; (3) one- vs. two-stage OTV; (4) aerobraking vs. propulsive braking on return to LEO; and (5) specific impulse of the cryogenic engines. Because of the large number of charts involved using the nine different variables, only sample trend charts for each set of variables are presented.

Trend charts of ETO mass required for varying manned capsule and lunar payload masses are presented in Figs. 5 to 9. Note that the step increases in ETO masses in the figures are due to the modular design of the OTV. As the deliverable lunar payload mass increases, the propellant requirement increases. When the propellant requirement exceeds the capability of the propellant tank set in the design, the computer program increases the number of tank sets to accommodate the new requirement, which, in turn, increases the structural mass of the OTV by a discrete amount.

### Reusable vs. Expendable

The question of employing reusable as opposed to expendable OTV systems is very complex. Not only is the added mass (fuel) needed to transport and return the system to LEO a consideration,

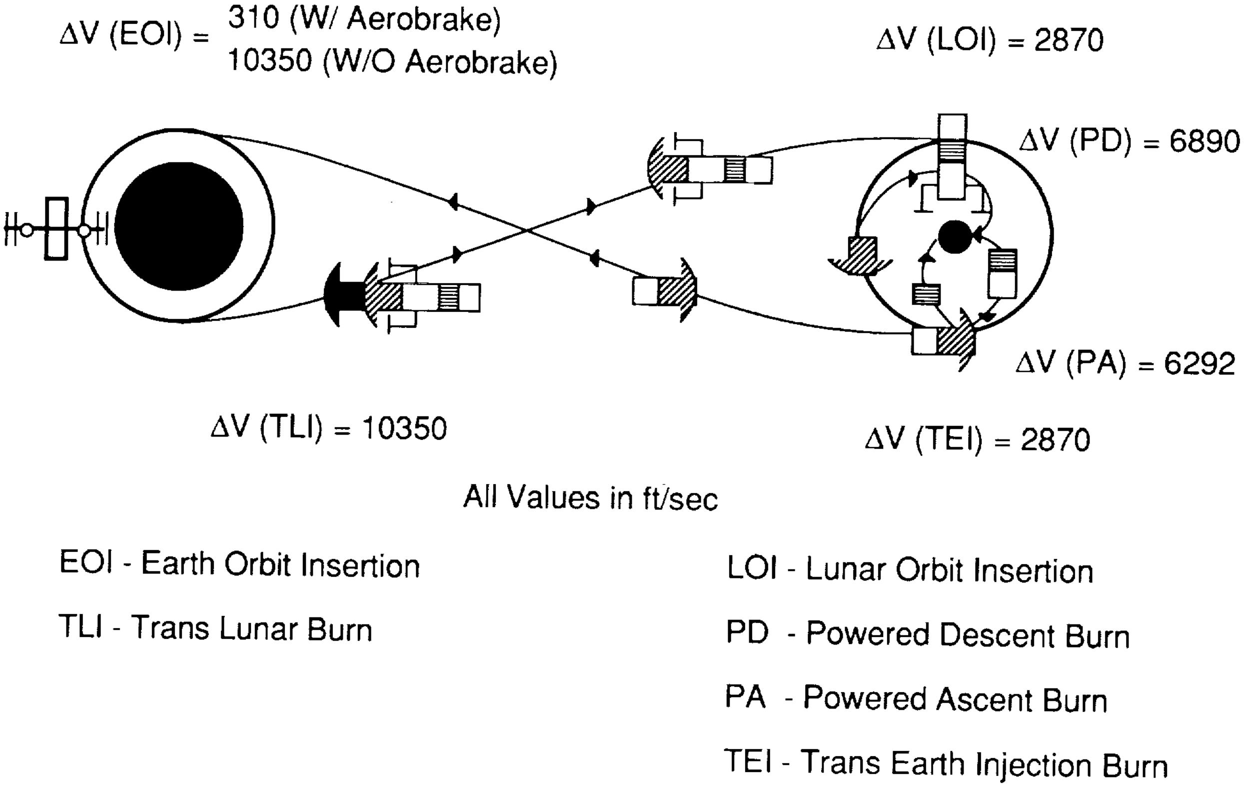

**Fig. 4.** Propulsive ΔV summary.

TABLE 5. Sample ETO mass summary.

| Mission # | Mass (in lbm) | Mission # | Mass (in lbm) |
|---|---|---|---|
| 1 | 260,595 | 9 | 228,525 |
| 2 | 202,814 | 10 | 228,525 |
| 3 | 228,525 | 11 | 228,525 |
| 4 | 204,370 | 12 | 143,111 |
| 5 | 228,525 | 13 | 217,084 |
| 6 | 214,488 | 14 | 196,587 |
| 7 | 154,007 | 15 | 217,084 |
| 8 | 154,007 | 16 | 217,084 |

One-stage, reusable OTV, aerobrake used; $I_{sp} = 460$ sec. Total mass to low Earth orbit = 3,323,856 lbm. Requires 22 launches of an HLLV (150,000 lbm payload capability).

TABLE 6. Transportation summary for a one-stage OTV.

| $I_{sp}$ (sec) | Mission Designation | Case No. | First Stage Aero | First Stage Nonaero | Weight to LEO, lbm $\times 10^6$ | No. of HLLV Launches Req'd. (150 k lbm) |
|---|---|---|---|---|---|---|
| 440 | Reusable | 1 | X | | 3.61 | 24 |
| | Expendable | 2 | X* | | 3.74 | 25 |
| | Reusable | 3 | | X | 4.83 | 32 |
| | Expendable | 4 | | X* | 4.70 | 32 |
| 460 | Reusable | 5 | X | | 3.32 | 22 |
| | Expendable | 6 | X* | | 3.43 | 23 |
| | Reusable | 7 | | X | 4.41 | 30 |
| | Expendable | 8 | | X* | 4.33 | 29 |
| 485 | Reusable | 9 | X | | 3.03 | 20 |
| | Expendable | 10 | X* | | 3.16 | 21 |
| | Reusable | 11 | | X | 3.98 | 27 |
| | Expendable | 12 | | X* | 3.96 | 27 |

*For manned missions, stage 1 returns to LEO; for cargo missions, stage 1 is expended.

Phase II (16 missions: 9 manned, 7 unmanned).

TABLE 7. Transportation summary for a two-stage OTV.

| $I_{sp}$ (sec) | Mission Designation | Case No. | First Stage Aero | First Stage Nonaero | Second Stage Aero | Second Stage Nonaero | Weight to LEO, lbm $\times 10^6$ | No. of HLLV Launches Req'd. (150 k lbm) |
|---|---|---|---|---|---|---|---|---|
| 440 | Reusable | 1 | X | | X | | 3.57 | 24 |
| | Expendable | 2 | | | X* | | 3.75 | 25 |
| | Reusable | 3 | | X | | X | 4.91 | 33 |
| | Expendable | 4 | | | | X* | 4.57 | 31 |
| 460 | Reusable | 5 | X | | X | | 3.32 | 22 |
| | Expendable | 6 | | | X* | | 3.49 | 23 |
| | Reusable | 7 | | X | | X | 4.44 | 30 |
| | Expendable | 8 | | | | X* | 4.22 | 28 |
| 485 | Reusable | 9 | X | | X | | 3.03 | 20 |
| | Expendable | 10 | | | X* | | 3.21 | 22 |
| | Reusable | 11 | | X | | X | 4.02 | 27 |
| | Expendable | 12 | | | | X* | 3.85 | 26 |

*For manned missions, stage 2 returns to LEO; for cargo missions, stage 2 is expended.

Phase II (16 missions: 9 manned, 7 unmanned).

but the structural and developmental cost of the reusable system, as well as the replacement cost of expendable systems for resupply and follow-on missions, must also be considered. An accurate cost comparison of these two types of vehicles is beyond the scope of this study. This study was concerned only with the ETO masses involved and did not consider any cost factors. The developmental cost of a reusable system could possibly offset its operating cost advantage over an expendable system.

Calculation of the total ETO mass for the reusable and expendable missions considered the added fuel to return the reusable system to Earth orbit for refit, whereas the expendable missions required a completely new OTV structure for each mission. Comparison of the ETO mass vs. lunar payload mass for both manned and cargo missions in the reusable and expendable configurations is shown in Fig. 5. The ETO mass of the reusable vehicle is consistently lower than that of the expendable vehicle

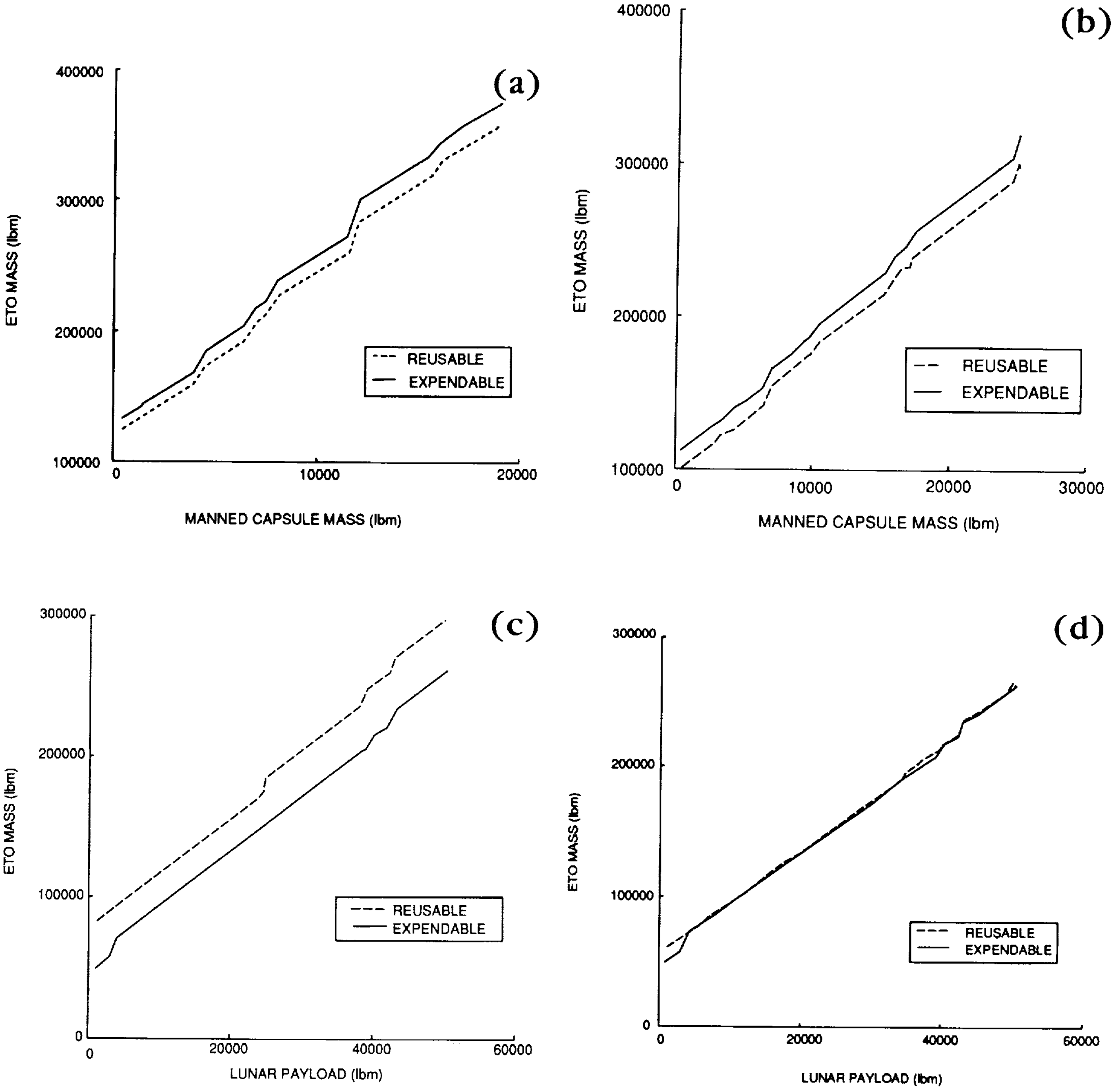

**Fig. 5.** ETO mass comparison of reusable and expendable OTVs: (a) one-stage, nonaerobraked, manned; (b) one-stage, aerobraked, manned; (c) one-stage, nonaerobraked, cargo; and (d) one-stage, aerobraked, cargo.

for the manned missions. The ETO mass for the reusable aerobraked cargo mission (Fig. 5d) is higher than that of the expendable mission. This is due to the large quantity of fuel required to return the reusable aerobraked cargo OTV to Earth orbit.

Over the 16-mission buildup of the lunar base, a saving of one HLLV ETO flight is achieved using aerobraking and reusable instead of expendable systems, regardless of staging (Tables 6 and 7). Without aerobraking, the expendable system is equal to or less costly (in terms of HLLV launches) than the reusable system, even though a new OTV is required for each mission.

### One vs. Two Stages

The trend in ETO mass vs. manned capsule mass is almost identical for the one-stage and two-stage systems (Fig. 6). The same trend was noted in the cargo missions. This becomes more obvious when the total number of HLLV launches for the Phase II buildup is considered (Tables 6 and 7). In only three scenarios did the total mass to LEO using one vs. two stages vary by more than 80,000 lbm, thereby requiring one less HLLV for the two-stage missions. Each of these three scenarios involved expendable, nonaerobraked missions. Logistically, then, it is not necessary to consider a two-stage system in the lunar base transportation scenario. (Note that these results differ from the classical one-stage vs. two-stage comparison. In this study, the expended propulsive stages were not discarded; however, as indicated in Table 6, the one-stage OTV returns to LEO for manned missions and, for the two-stage manned OTV case, stage 2 returns to LEO. These returning stages require the addition of aerobrakes and other recapture components, thereby complicating the classical staging trade.)

### Aerobraking vs. Propulsive Braking

The trends for both manned and cargo aerobraked vs. propulsive-braked systems are shown in Fig. 7. Using aerobraking for the cargo missions means a saving of 20,000 lbm to 30,000 lbm. The manned missions show a more drastic decrease in ETO mass with aerobraking. Here, the savings vary from 30,000 lbm for a 5000-lbm manned capsule to 100,000 lbm for a 20,000-lbm manned capsule. This translates into a savings of 8

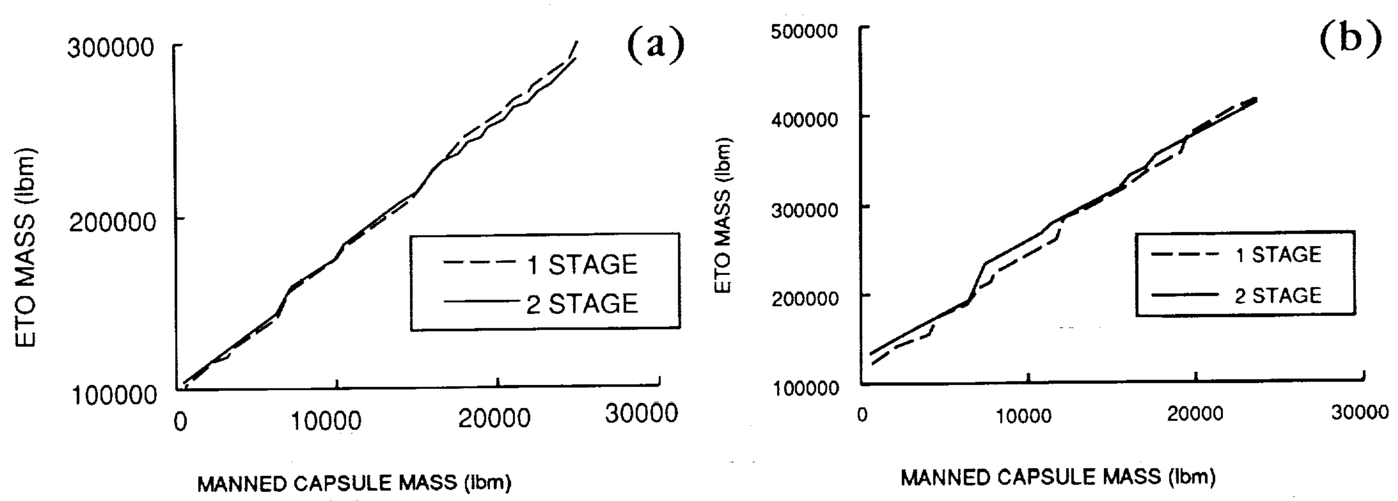

**Fig. 6.** ETO mass comparison of one-stage and two-stage OTVs: **(a)** reusable, manned, aerobraked and **(b)** reusable, manned nonaerobraked.

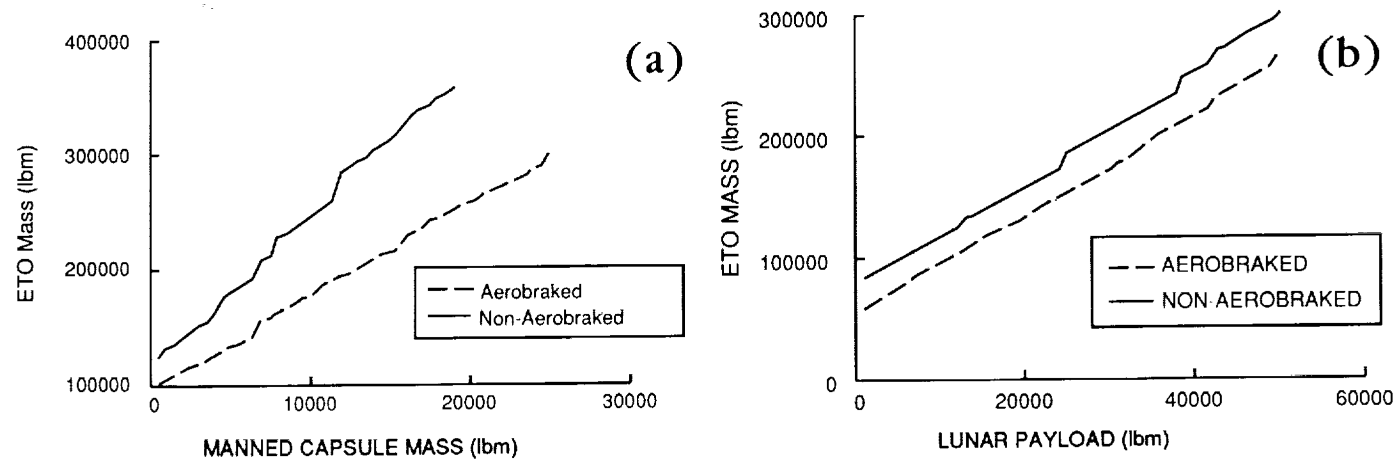

**Fig. 7.** ETO mass comparison of aerobraking and nonaerobraking ($I_{sp}$ = 460 sec): **(a)** reusable, manned, one-stage and **(b)** reusable, cargo, one-stage.

HLLV launches over the 16-mission buildup of the lunar base (Tables 6 and 7). The savings in HLLV launches (ETO mass) when using the aerobraked system is due to the reduced amount of fuel necessary for Earth-orbit insertion. The much larger savings in mass in the manned mission case results from the larger mass that is being returned to low Earth orbit. The development and use of an aerobraking system becomes a distinct enhancing technology for lunar base missions.

### Specific Impulse of the Cryogenic Engine

The trade study concerning the effect of varying specific impulse assumed only engines using cryogenic propellants, liquid oxygen, and liquid hydrogen. Three $I_{sp}$ values (440, 460, and 485 sec) were considered, relative to state-of-the-art engine technology. An $I_{sp}$ of 440 sec corresponds to current RL-10 engine technology, 460 sec considers a modified RL-10 engine using a large expansion ratio, and 485 sec corresponds to an engine based on advanced technology.

Trends in the $I_{sp}$ effect on ETO mass are presented in Fig. 8. As expected, in all cases the higher the $I_{sp}$, the lower the ETO mass for a given manned capsule or lunar payload mass. The effect of the aerobrake in reducing the number of HLLV launches for the 16 missions is less dramatic for higher $I_{sp}$ values. For a reusable OTV with an $I_{sp}$ of 440 sec, use of the aerobrake saves eight or nine HLLV launches, while the same OTV with a 485-sec $I_{sp}$ saves only seven HLLV launches (Tables 6 and 7).

## LUNAR LOX IMPACT

The lunar surface is rich in minerals from which oxygen can be derived. *Roberts* (1986) showed that a transportation system using lunar-derived oxygen offers substantial ETO mass savings over a totally Earth-based system. For the present study, the use of lunar oxygen was only considered for lunar descent and ascent, trans-Earth injection, and Earth circularization maneuvers of reusable missions. Comparisons of ETO masses for variations in lunar payload mass for reusable cargo and manned missions are shown in Figs. 9a-d.

For a reusable cargo mission (one stage with an $I_{sp}$ of 460 sec) with a 30,000-lbm lunar payload (Figs. 9a,b), the ETO mass for the nonaerobraked transportation system using Earth-derived LOX is 3.3 times that of the lunar-derived LOX system (204,000 lbm vs. 62,000 lbm). The addition of aerobraking reduces the ETO mass to 172,000 lbm for the Earth-derived LOX system with no appreciable change in the lunar-derived system ETO mass (the Earth-derived LOX system is still a factor of 2.8 higher).

The effect of using lunar-derived LOX is even more dramatic for the manned missions (Figs. 9c,d). Assuming a 19,000-lbm manned module (one-stage system with an $I_{sp}$ of 460 sec), the ETO mass is 100,000 lbm for a lunar-derived LOX nonaerobraked transportation system as opposed to 355,000 lbm (a factor of 3.5 higher) for an Earth-derived LOX system. With aerobraking, the same manned capsule requires an ETO mass of 88,000 lbm for a lunar-derived LOX system and an ETO mass of 266,000 lbm for an Earth-derived system (3 times higher than the lunar-derived system).

With lunar LOX, the ETO mass of cargo missions can be reduced to 25-50% of that required with Earth-derived LOX. For manned missions using lunar LOX, the ETO mass can be reduced to 16-25%. For the 16-mission buildup, the total ETO mass can be reduced from 3.32 million lbm to 1.10 million lbm with the use of lunar-derived LOX (Fig. 10). Those mass savings are due

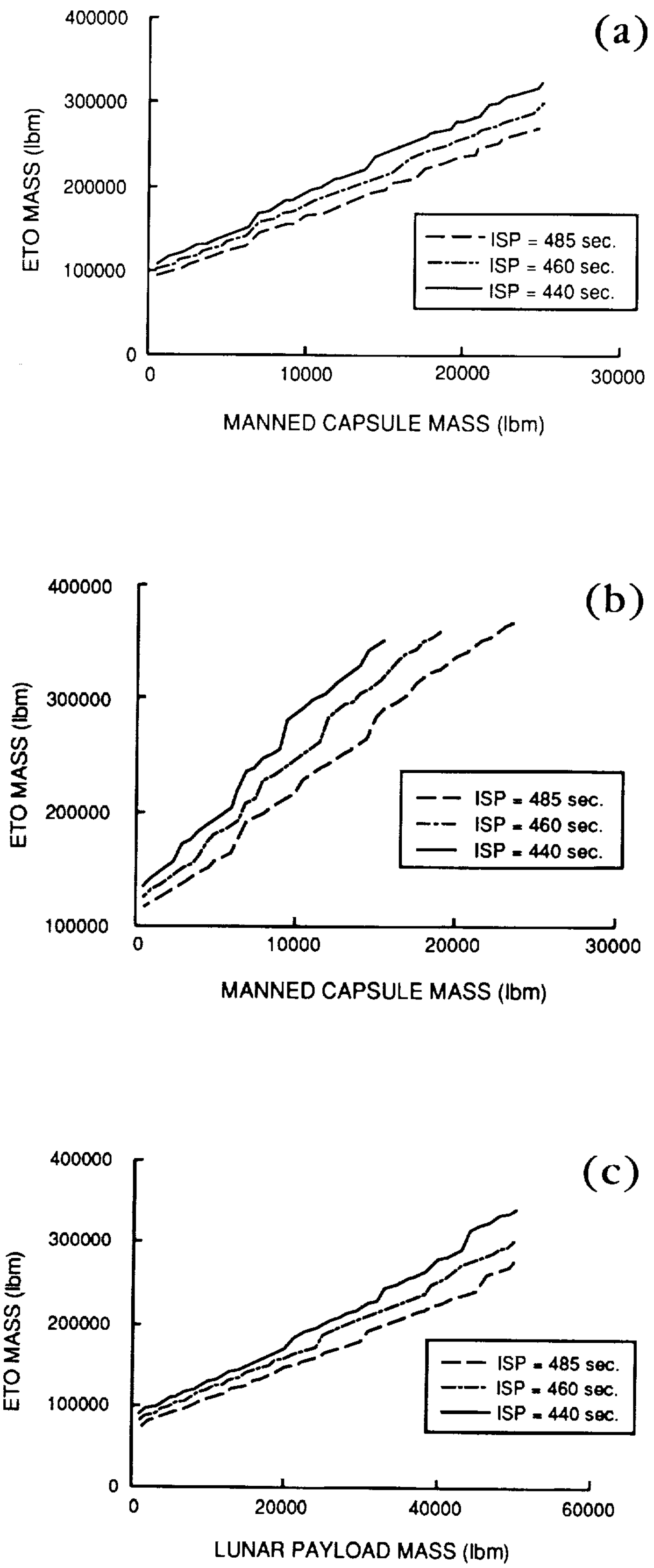

**Fig. 8.** ETO mass comparison of effect of specific impulse ($I_{sp}$): **(a)** reusable, manned, one-stage, aerobraked; **(b)** reusable, manned, one-stage, nonaerobraked; and **(c)** reusable, cargo, one-stage, aerobraked.

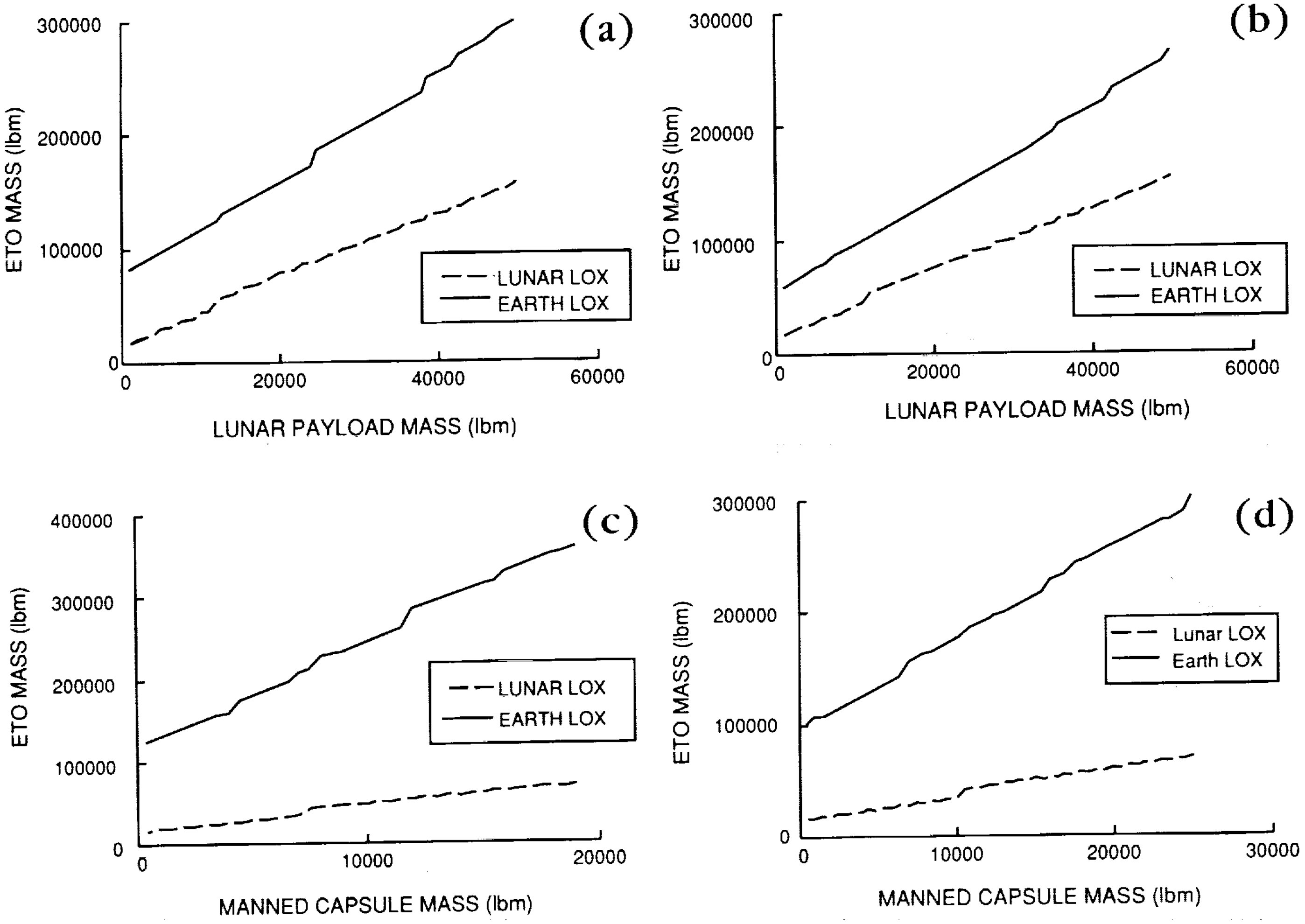

**Fig. 9.** Impact of lunar-derived LOX: **(a)** reusable, cargo, one-stage, aerobraked; **(b)** reusable, cargo, one-stage, nonaerobraked; **(c)** reusable, manned, one-stage, aerobraked; and **(d)** reusable, manned, one-stage, nonaerobraked.

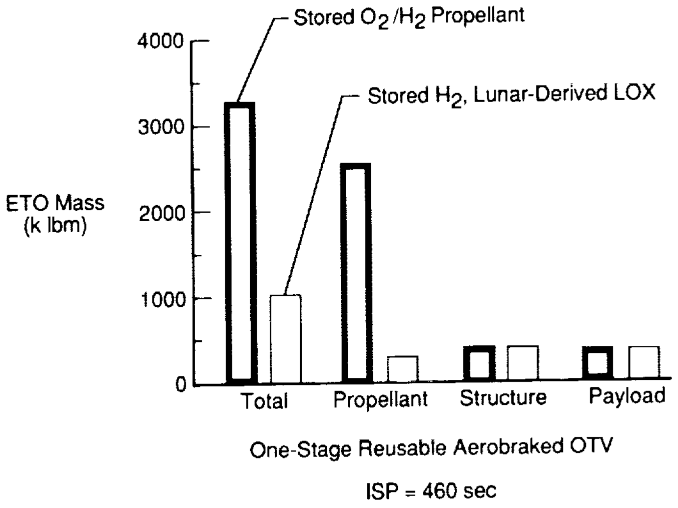

**Fig. 10.** Impact of lunar-derived LOX on total ETO mass.

primarily to the propellant mass reduction from 2.5 million lbm (Earth-derived LOX) to 0.35 million lbm (lunar-derived LOX). The estimated mass of a pilot LOX plant is included in the lunar base facility and equipment mass (Table 3), but a LOX production plant with an estimated mass of 8400 lbm (*Williams et al.,* 1979) is needed to derive the benefits shown here.

## CONCLUSIONS

A systems analysis and assessment has been conducted on the transportation requirements to support a Phase II lunar base mission. The objectives of the study were to assess the relative impact of lunar base support requirements on a LEO-based transportation system and to identify key and/or enabling technologies.

It is immediately evident from the analysis that construction and support of a Phase II lunar base will place a tremendous burden on any space transportation system. The development of the Phase II lunar base will require 3 million lbm to 4 million lbm total weight in LEO over the course of some 20-30 launches of a 150,000-lbm HLLV. Considering trajectory limitations for specific Earth-to-Moon missions, coupled with even the most optimistic ETO and LEO turnaround scenarios (not addressed in this report), this translates into a commitment of several years of dedicated lunar missions.

From an ETO mass standpoint, only small differences were noted between the use of reusable or expendable systems. However, the cost of expendable modules and vehicles must be considered relative to the developmental cost of the reusable system. It is possible that the developmental cost of a reusable system may offset its operating cost advantage over an expendable system. It appears that using a two-stage OTV yields no significant advantage in mass savings. In terms of operational logistics, then, a one-stage OTV makes the most sense. Aerobraking stands out as a critical, if not enabling technology. Over the course of 16 lunar missions, aerobraking can reduce LEO masses and corresponding ETO lift requirements on the order of 1.5 million lbm to 2 million lbm. Aerobraking is also critical in making a reusable OTV advantageous. As expected, the higher the $I_{sp}$ of the engine, the lower the fuel needs and ETO masses. The ETO masses were also observed to be more sensitive to $I_{sp}$ in reusable and all-propulsive modes. The use of aerobraking reduced the impact of increasing $I_{sp}$. An engine with an $I_{sp}$ of 485 sec is probably beyond the near-future state of the art, but an $I_{sp}$ of 460 sec appears definitely achievable. Utilizing lunar-derived oxygen for lunar landing, ascent from the lunar surface, and return to Earth orbit can reduce mission start mass to 16-50% of that required with Earth-derived LOX.

Overall, the trend analysis of this study indicates that the optimum transportation system would be a one-stage, aerobraked, reusable vehicle with the highest engine efficiency attainable. The use of lunar oxygen is advisable.

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