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Lunar Landing Craft for the Reusable Launch Vehicle and Shuttle Vehicles

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Introduction

THE objective of the study was to configure a set of lunar transfer vehicles for personnel and cargo delivery to the lunar surface. These vehicles would be delivered to orbit via the reusable launch vehicle (RLV) or Shuttle and then mated together, allowing only propellant transfer between stages but not allowing on-orbit assembly. An RLV or Shuttle capable of delivering about 25,000 lb to the International Space Station orbit was assumed. If launched from the Kennedy Space Center due east to a 86 n mile orbit, the same vehicle (assuming a single stage to orbit) could launch approximately 40,000 lb. Of this amount, about 10% would include airborne support equipment for payload support within the launch vehicle payload bay. Thus only about 36,400 lb would be usable payload. Because it was a goal of the study to eliminate on-orbit assembly, the largest payload and vehicle stage size would by definition be no larger or heavier than that amount capable of being delivered by the RLV or Shuttle to low Earth orbit. Propellant transfer from a dedicated tank in the Earth-to-orbit (ETO) payload bay to purposely off-loaded lunar vehicle propellant tanks was necessary. Both the lunar direct mode (LDM) and the Apollo-style lunar orbit rendezvous (LOR) trajectory modes were analyzed. Six vehicle sets and two mission types were evaluated. These types are briefly explained next.

Split Delivery

Separate crew transfer vehicles and unmanned cargo vehicles are utilized. The cargo vehicle lands a habitat or other large payload, and the crew follows in a separate descent/ascent stage, landing within walking distance to the quiescent surface module. Two such split-delivery pairs were analyzed. What is to be determined for the piloted case is the weight of the single transfer/re-entry capsule that the crew occupies while in transit to and from the moon.

All-Up Delivery

In this scenario, the crew capsule and surface cargo module are carried together on the same vehicle. The smaller crew cab serves as a secondary backup pressure vessel for the crew while they are living out of the larger habitat module on the surface. What is to be determined for the all-up case is the weight of the surface payload that the crew occupies while on the moon, given predetermined values for the re-entry and ascent capsule.

Both modes require docking of stages on orbit but are configured so as not to require on-orbit assembly. Once the stages are connected, off-loaded (partially empty) tanks are filled to capacity with LO2 carried from a tank located in the RLV or Shuttle. These tanks are reused on subsequent propellant transfer flights. Adequate cryogenic insulation and some additional LH2 must be carried in the lunar vehicle tanks to prevent excessive hydrogen boiloff while the craft waits in orbit for the fluid transfer flights.

Assumptions

The assumptions used in the vehicle sizing analysis are as follows. All vehicles were sized to fit in the 15-ft-diam by 60-ft-long Shuttle cargo bay. A launch vehicle payload bay associated support equipment of 10% of payload weight was used. RL-10 type hydrogen/oxygen engines with a vacuum specific impulse of 468 s were utilized for main propulsion. Liquid oxygen tanks were of Al-Li construction, and liquid hydrogen tanks of composite materials, as were the external strut-to-ring-frame structure, thrust structure, and landing legs structure. A 15% inert weight growth factor was applied against all vehicle inert weight. For all scenarios the lunar transfer and landing craft was expended, with crew return via

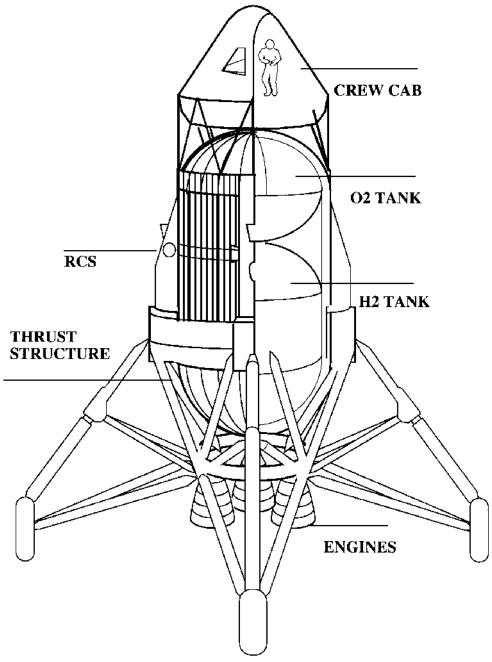

Fig. 1 Crew delivery landing craft.

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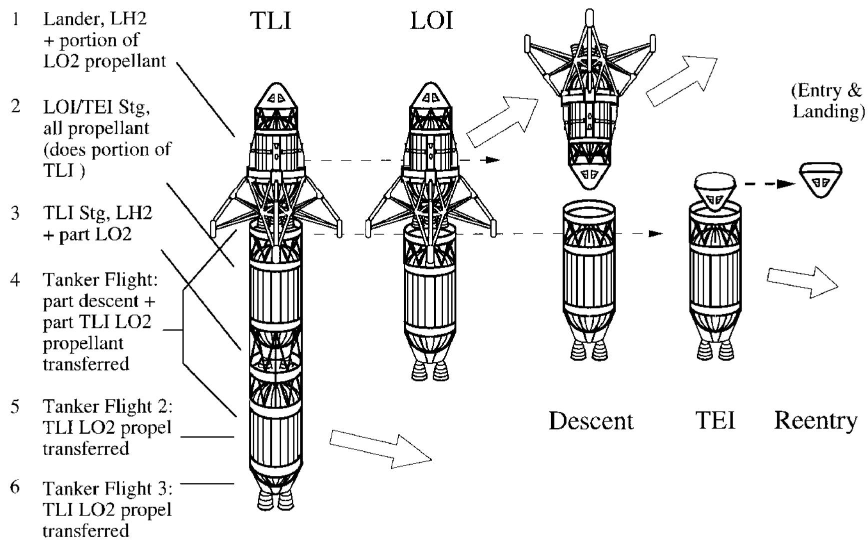

Fig. 2 Split-delivery set: crew delivery three-stage LOR mode.

LOR: CREW ONLY		LDM: CARGO ONLY	
1	2	3	4
TRANSFER-ASCENT-REENTRY CAB 11.4 klb	14.5 klb	SURFACE MODULE 18.4 klb	23.6 klb
Lander with all LH2 & crew cab & portion of LO2 36.4 klb	36.4 klb	Lander with all LH2 & cargo portion of LO2 36.4 klb	36.4 klb
LOI / TEI stage, all LH2 & LO2 36.4 klb	36.4 klb	TLI stage, all LH2 & portion of LO2 36.4 klb	36.4 klb
TLI stage, all LH2 & portion of LO2 36.4 klb	36.4 klb	Tanker 1: TLI & lander remaining LO2 36.1 klb	36.3 klb
Tanker 1: TLI LO2 & desc LO2 only 36.4 klb	36.4 klb	Tanker 2: TLI remaining LO2 36.1 klb	36.3 klb
Tanker 2: TLI Remaining LO2 36.4 klb	36.4 klb	Tanker 3: TLI remaining LO2	36.3 klb
Tanker 3: TLI Remaining O2	36.4 klb		

Split delivery (separate crew, cargo) lander

LOR: CREW + CARGO	LOR: CREW + CARGO	
5	6	Column
ASC CAB 5.5 klb; REENTRY CAB 12.1 klb; SURF MOD 18.1 klb	ASC CAB 5.5 klb; REENTRY CAB 12.1 klb; SURF MOD 24.5 klb	Pay-Load
		ETO Flights
Lander, ascent cab, all LH2 & surface module 36.4 klb	Lander, ascent cab, all LH2, portion of LO2 36.4 klb	1
LOI / TEI stage, reentry cab, all LH2 & portion of LO2 36.4 klb	LOI/TEI stage, reentry cab, all LH2, portion of LO2 36.4 klb	2
TLI stage with all LH2 & portion of LO2 36.4 klb	TLI stage with all LH2 36.4 klb	3
Tanker 1: remaining lander LO2 & LOI / TEI LO2 36.2 klb	Surface module & tank for additional landerLO2 36.4 klb	4
Tanker 2: portion of TLI LO2 36.3 klb	Tanker 1: remaining lander LO2 & portion LOI / TEI LO2 33.4 klb	5
Tanker 3: portion of TLI LO2 36.3 klb	Tanker 2: portion TEI & TLI LO2 33.4 klb	6
Tanker 4: portion of TLI LO2 36.3 klb	Tanker 3: portion of TLI LO2 32.1 klb	7
Tanker 5: remaining TLI LO2 36.3 klb	Tanker 4: portion TLI LO2 32.1 klb	8
	Tanker 5: remaining TLI LO2 32.1 klb	9

All-up (combination crew plus cargo) lander

Fig. 3 RLV or Shuttle ETO flights and lunar payload delivery; fluid transfer flights are circled.

a small Apollo-style crew capsule. Single-stage descent/ascent landers were utilized, with landings legs left on the surface as a weight saving measure. No liquid hydrogen propellant transfer would take place. Figure 1 shows a cutaway view of a representative landing craft. Figure 2 shows the various stages joined together in orbit. For an in-depth analysis of lunar landing craft configurations, see Ref. 1.

Results are presented in Table 1 and in Fig. 3, in which six vehicle sets are listed one in each column. Most of the following discussion will reference Fig. 3.

Split-Delivery Missions

Four split-delivery vehicle sets are set forth according to the number and type of ETO flights necessary to deliver the specified payloads, which are listed at the top of each column in Fig. 3. In the first two columns, under the heading LOR: CREW ONLY, a single, combination transfer, ascent, and re-entry capsule is utilized by the crew. The joint lunar orbit insertion (LOI) and trans-Earth insertion (TEI) stage remains in lunar orbit during the surface activity and then boosts only the transfer/re-entry capsule back to Earth for direct entry. The spent lander stage is jettisoned before the TEI

Table 1 Payload capabilities

Mission Type	Flight mode	Flights	Re-entry capsule, lb	Ascent capsule, lb	Surface cargo, lb
1) Split delivery	LOR	5	11,400	n/a	n/a
2) Split delivery	LOR	6	14,500	n/a	n/a
3) Split delivery	LDM	4	n/a	n/a	18,400
4) Split delivery	LDM	5	n/a	n/a	23,600
5) All-up delivery	LOR	8	12,100	5,500	18,100
6) All-up delivery	LOR	9	12,100	5,500	24,500

Table 2 Mission delta velocities

Mission mode	LDM, ft/s	LOR, ft/s
TLI impulsive ($C3 = -2$)	10,500	10,500
Midcourse outbound	65	65
Direct to surface impulsive	9,679	n/a
LOI	n/a	2,953
Descent	n/a	6,890
Hover	328	328
Direct to Earth ascent	9,351	n/a
Ascent to low lunar orbit	n/a	6,890
Trans-Earth injection	n/a	3,002
Midcourse inbound	65	65

burn. Results indicate that for five ETO flights of 36,400 lb each, a combination capsule of 11,400 lb can be delivered. Two of these ETO flights are propellant-transfer-only flights. (In Fig. 3, the circled numbers represent fluid transfer flights.) For six ETO flights of 36,400 lb, the payload (capsule) weight comes to 14,500 lb, and three fluid transfer flights are required.

In columns 3 and 4 of Fig. 3, under the heading LDM: CARGO ONLY, flight manifests are given for two unmanned, cargo delivery vehicles. For these missions the lander does not enter a lunar parking orbit but descends directly to the lunar surface (LDM). For four ETO flights, 18,400 lb of cargo can be delivered one way to the lunar surface. Five flights properly configured can deliver a 23,600-lb payload. These two missions utilize two stages, a translunar injection (TLI) stage and a direct to surface landing stage. In this later case (column 4) the TLI stage does a portion of the lunar deceleration burn so that the combined weight of the lander (inert), surface payload, and descent LH2 is less than the 36,400-lb launch vehicle limit. Summing up the two parts of the split-delivery approach (the crew and cargo vehicle sets), nine ETO flights are required for the two payloads of 11,400 lb (capsule) and 18,400 lb (surface module). (This is the cumulative total of columns 1 and 3.) For 11 ETO flights, a larger 14,500-lb capsule and a larger 23,600-lb surface module can be delivered (columns 2 and 4). These payload weights are also listed in Table 1, where the columns of Fig. 3 are listed as rows 1–6.

All-Up Combined Crew and Cargo

Columns 5 and 6 of Fig. 3 list the manifest for two all-up (joint crew/cargo) vehicle sets. In these cases three separate habitats are taken: a re-entry/transfer cab, a separate lander descent/ascent cab, and a large surface module. For this investigation the re-entry capsule occupied by the crew during transit was set to 12,100 lb, and the small ascent/descent-only capsule was set to 5,500 lb. (The re-entry/transit capsule is carried on the LOI/TEI stage.) For the eight ETO flight case (column 5), the surface module deliverable weight is 18,100 lb. For the nine ETO flight case this increases to 24,500 lb. (Five propellant transfer tanker flights are required for the column 5 vehicle set and six for the column 6 set.)

Notice that column 3 and 5 deliverable surface module weights are nearly equivalent (within 300 lb), as are the module weights for columns 4 and 6 (within 900 lb). This suggests that about the same amount of surface cargo can be delivered via the split-delivery approach as the all-up option at the penalty of one extra ETO flight for both the 18,000-lb and the 24,000-lb module case. That is, 9 flights (columns 1 and 3) compare with the 8 flights for the all-up case (column 5), and 10 flights for the split-delivery set (columns 1 and 4) compare with the 9 flights for the all-up case where the 24,000-lb class module is carried (column 6). Table 1 summarizes the payload capabilities listed in Fig. 3. Mission delta velocity budgets are presented in Table 2.

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Calculation of Pitch Damping for a Flared Projectile

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Nomenclature

C_m, C_n = pitching and side moment coefficients, (moment)/$\frac{1}{8}\pi\rho V^2 D^3$
$C_{m_q}, C_{m_{\dot\alpha}}$ = rate of change of pitching moment with respect to q and $\dot\alpha$
D = reference length, the projectile's diameter
M = freestream Mach number
q = transverse angular rate nondimensionalized by V/D
Re = Reynolds number based on D
V = freestream speed
x_{CG} = distance of projectile's center of gravity from nose nondimensionalized by D
α = angle of attack, deg
$\dot\alpha$ = rate of change of α with respect to time nondimensionalized by V/D
ρ = freestream density
Ω = angular rate of coning/helical motion nondimensionalized by V/D

Introduction

SCHIFF[1] has proposed to predict dynamic pitch-damping coefficients (PDCs) of bodies from steady flow computations, avoiding costly time-accurate solutions. Previously, much of this aerodynamic data was obtained from either simplified analytical approaches, empirical methods, wind-tunnel testing, or full-scale range firings. Lunar coning motion is imposed upon the projectile, and the flow-governing equations are solved in the rotating framework for which the flow is steady. Coning motion is the motion

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