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Lunar Lander Concepts for Human Exploration

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A new generation of lunar lander is to be the reference payload for the NASA Ares-V heavy-lift launch vehicle, still in conceptual development. The surface-payload capability of the lander is primarily a function of propulsion choice, staging method, and configuration choice. A variety of staging methodologies are investigated, and the benefits and disadvantages of staging in low lunar orbit and staging later in the final descent burn are presented, as are the benefits of dropping tankage before touchdown to reduce the lander size and mass. Storable and methane propellants for the ascent burn are evaluated. A variety of configuration options are presented, and the discussion includes the context for downloading heavy payloads for outpost buildup. The transportation architecture variations assume the basic NASA Exploration Systems Architecture Study architecture, and the surface operations are traded to match compatible lander configurations.

Introduction

THE lunar lander occupies a unique position within NASA's Constellation programs: it is the interface between the two primary system architectures: the transportation and surface systems. And in some scenarios, the lander performs functions for both architectures. Subsequently, the design of the lander must satisfy the requirements established by the two architectures. Optimization of the design not only satisfies the requirements, but also maximizes a set of criteria (i.e., figures of merit). Alternative designs are established by examining and evaluating different potential designs within a trade space. Although the trade space is broad, resulting in numerous potential designs, this paper explores three critical portions of the trade space: the staging approach, ascent-propulsion technology, and general arrangement. Although there are numerous potential figures of merit, the discussion here is limited to evaluation of one of the primary performance parameters as part of the transportation architecture: payload mass delivered to the lunar surface.

Translunar Injection and Lunar Orbit Insertion

A new generation of lunar lander is to be the reference payload for the NASA Ares-V heavy-lift launch vehicle, still in conceptual development. After solid rocket booster drop-off and core stage separation, the Ares-V's second stage finalizes the burn to place the lunar lander into a 160 by 160 nm, 28.5-deg, low Earth orbit (LEO). Subsequently, the crew exploration vehicle (CEV), placed in orbit with the Ares-I, docks with the lander. The Ares-V's second stage, still attached to the lander, serves as the Earth-departure stage (EDS). From LEO, with 40% of its propellant load remaining, the EDS will inject both the lander and CEV into a three-day transfer. Later, the crew will depart back to Earth using the CEV's service-module (SM) propulsion system. An illustration of the Ares-V is given in Fig. 1. In Apollo, the command-module/SM was launched together with the lunar excursion module (LEM) on a single Saturn-V. The Saturn's suborbital-start third stage also served as the EDS. Like Apollo, the Constellation CEV SM uses storable propellant for trans-Earth injection (TEI), but unlike Apollo, it will not provide propulsion for the lunar orbit insertion (LOI) burn; this is instead done by the lander, with LOI propellant contained in the descent tanks. Offloading the LOI propellant from the SM keeps the CEV from exceeding the lift capability of Ares-I. The CEV is projected to weigh 20 t in LEO. The Ares-V second stage/EDS, weighing about 247 t fully loaded, expends about 60% of its propellant boosting the lander to LEO. Once in orbit (and after the docking of the CEV), the second stage fires again to boost the 65-t lander/CEV stack to translunar injection (TLI).

Descent and Ascent

After lunar orbit capture, the lander separates from the CEV and initiates descent from a 100-km circular low lunar orbit (LLO) into a 100 by 15 km elliptical phasing orbit; at 15 km, initiation for final descent begins. By the time the lander nears touchdown, all of its LOI and its descent propellant has been burned off and the vehicle is significantly less massive than when it started its LOI burn. Because of this, significant engine throttling is required. (NASA Marshall Space Flight Center is presently investigating deep-throttling technology, including RL-10-derived and Pintle injector engine options.) Following surface operations, the crew boards the ascent stage, which ascends to LLO and docks with the CEV. In Fig. 2, the NASA Exploration Systems Architecture Study (ESAS) lander is pictured. Mission delta-velocity (delta-V) values used in this paper are given in Table 1. Note that this paper is focused on lander designs that support the outpost build, and the LOI delta-V for the polar mission is used.

Several other top-level requirements are imposed on the design beyond the preceding delta-V and mission operations: specifically, a shroud diameter of 10.0 m maximum, a low-impact docking system, four crew members for lunar missions, a 100-kg minimum payload return from the lunar surface to Earth, and a surface air lock.

In addition to its role in delivering crew and cargo to the lunar surface, it is desirable to have a variant of the basic lander serve in a cargo-only mission role. For these missions, only the Ares-V launch is required, which places up to 53.6 t to TLI. The remainder of the mission is as previously described, but without the crew or ascent vehicle.

Surface Architecture and Requirements

Although the transportation architecture and requirements, as previously described, are fairly well-established, the surface architecture, and hence the requirements for the lunar lander as the interface to the surface architecture (and possibly an element of the surface architecture), is less mature. Surface architectures range from the following:

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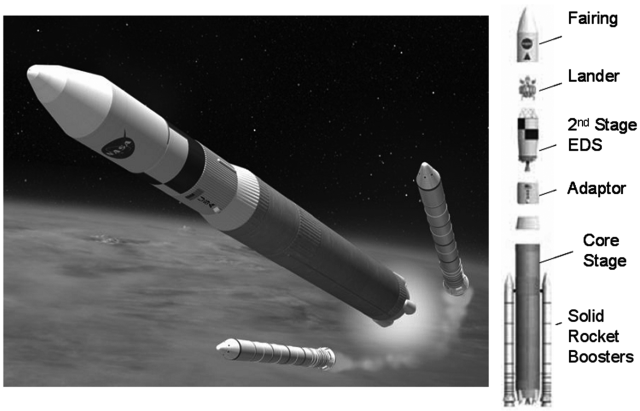

Fig. 1 Ares-V launch vehicle.

Surface architectures range from those in which the lander plays a relatively passive role to architectures in which the lander is highly active. The former is a surface system infrastructure in which cranes and trucks offload, transport, and assemble the lunar outpost from cargo delivered to the surface. This category might also include landers that provide a relatively minor assist to the surface architecture, such as provide partial offloading of cargo, but that still rely on a surface infrastructure and play no other role. At the other end of the spectrum, the high active role, the lander may include mobility and docking features to provide surface transportation and assembly capability, as well as functionality with the constructed lunar outpost (i.e., reuse of the lander in some capacity such as descent tanks providing oxygen storage). There are roles that are between passive and highly active, such as the lander serving as part of a loosely connected lunar colony without surface transportation capability.

The lander can be further influenced by the surface architecture plans for outpost build regarding the use of dedicated cargo missions versus mixed crew/cargo missions (for example, if the build architecture preemplaces a habitat module close to the surface, surface access from the lander on subsequent crewed missions would be less of a concern). The lander designs described make no assumption regarding surface architecture or impose architecture-derived requirements, but some designs will be noted as capable of supporting particular surface architectures.

Lander Surface-Payload-Delivery Capability

As already noted, the figure of merit considered for this paper is the payload mass delivered to the surface. The lander's payload-delivery capability is a function of launch vehicle capability, propulsion efficiency, staging method, and lander mass exclusive of the payload (i.e., structure, mission requirements, and mission design). For purposes of this trade study, the mission requirements and design are assumed to be fixed from the ESAS report. Finally, the performance for this paper is assumed to be independent of lander general-configuration trades. Although the particular lander configuration will, of course, impact mass, the evaluation regarding propulsion technology and staging is simplified with this assumption.

Lander Engine Technology (Propellant-Type) Trades

In Fig. 3, information is listed for the Ares-V upper-stage engine (J2-X), The lunar lander descent-stage engine (RL10-A4) and a potential-ascent engine (Bell 8258 LEM ascent engine). Two propellant types are considered in the trade for ascent: storable nitrogen tetroxide (N_2O_4) with monomethyl hydrazine (MMH) and oxygen (LO_2) with methane (CH_4). No trade is performed regarding the LOI and descent propulsion; LO_2 with hydrogen (LH_2) is baselined. The engine I_{sp}, nozzle area ratio Æ, and engine thrust-to-weight ratio T/W are shown in Table 2.

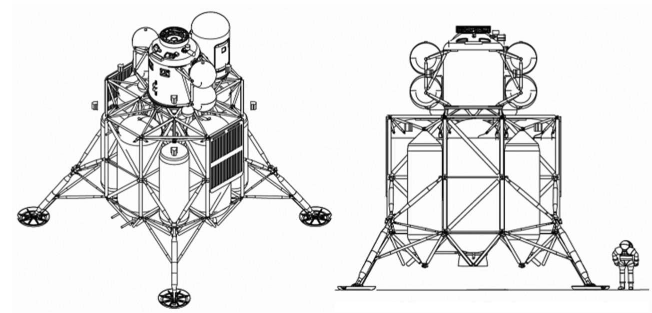

Fig. 2 NASA lunar lander concept.

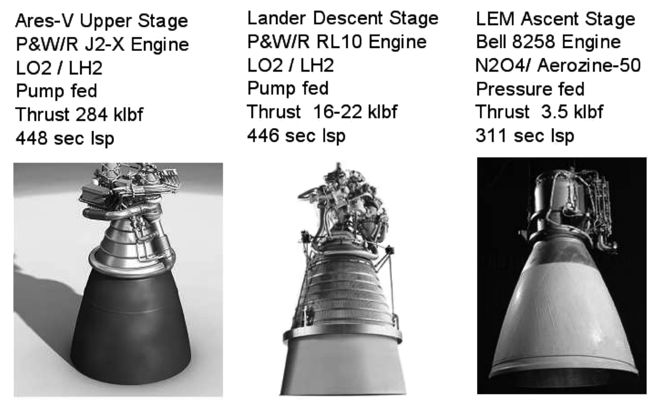

Fig. 3 Reference Ares-V upper-stage, lander descent-stage, and ascent-stage engines.

The RL10-A4 is a production O_2/H_2 engine; its demonstrated I_{sp} is 451 s, but for this analysis, the I_{sp} is reduced by 5 to 446 s, for conservatism. For the ascent's all-cryogenic O_2/CH_4 option, advanced passive insulation, including vapor-cooled shields and multilayer insulation (MLI) is used to limit boil-off on the surface. Additional cryocooler units may be required, specially should a breach in the integrity of the passive insulation occur; these were added in the calculations to provide additional conservatism (later missions may feature south pole stays of up to six months). Recent NASA Johnson Space Center analysis indicates the capability of O_2/CH_4 systems to use the shared main and reaction control system (RCS) propellant tanks.

Lander Staging-Methodology Trades

The second major element of the trade space to consider is the staging strategy. In principle, this could range from a single stage to perform all propulsive events to a separate stage for each propulsive event (and variants thereof, such as drop-tank stages in which only the tanks are jettisoned, sometimes referred to as a half-stage, or propulsion systems that are used for certain events but are not staged away). Table 3 illustrates a trade space for staging. Each of the major propulsion events is considered with the potential staging combinations. Note that the table divides the braking burn into two phases: the initial 1693-m/s-descent braking burn that removes most of the velocity and a 300-m/s final-descent-to-touchdown burn.

Table 1 Lander delta velocity

Burn	Name	Delta-V, m/s	Stage	Burn	Name	Delta-V, m/s	Stage
1	Earth departure	3327	EDS	4	Descent	1963	Descent
2	Outbound midcourse	20	Descent	5	Ascent	1905	Ascent
3	Lunar orbit insertion	892	Descent	6	Trim and rendezvous	60	Ascent

Table 2 Lunar lander engine parameters

	Name	Type	I_{sp}	AR	T/W	Feed system	Notes	Use
1	N_2O_4/MMH	Storable	329	200	35.0	Pressure	Hypergolic	Ascent
2	LO_2/LCH_4	Light cryogen	360	200	35.0	Pressure	New design	Ascent
3	LO_2/LH_2	Deep cryogen	446	84	60.3	Pump	RL10-A4	LOI/descent

Table 3 Lander staging trade space

Burn	LOI	Descent braking burn	Descent final	Ascent	Comments
Delta-V, m/s	892	1663	300	1905	
1 stage	1	1	1	1	Single stage does all
	1.5	1	1	1	Drop tanks after LOI
	1.5	1.5	1	1	Drop tanks after braking burn (at 4 km)
1.5 stage	1.5	1.5	1.5	1	Drop tanks after landing (on surface)
	2	1	1	1	
	2	2	1	1	CLDS design
2 stage	2	2	2	1	ESAS/Apollo
	2.5	2	2	1	Drop tanks after LOI
2.5 stage	2.5	2.5	2	1	Drop tanks after most of the descent burn
	3	2	2	1	Approximately same size LOI/descent stages
3 stage	3	3	2	1	Only 300 m/s for stage 2
3.5 stage	3.5	3	2	1	Drop tanks after LOI, 300 m/s for stage 2
4 stage	4	3	2	1	Only 300 m/s for stage 2

Table 3 indicates, for each major propulsive event, which stage performs the event. LOI values of 1.5, 2.5, and 3.5 indicate that the event is performed by a drop-tank stage with the tanks present, and the whole number for the following event indicates that the tanks were dropped. For example, 2.5 for LOI followed by 2 for descent indicates that tanks were dropped following the LOI burn; the full complement of tanks was present for LOI, but only a partial set of tanks are used for the descent: that is, the tanks were dropped following LOI. By inspection, a number of possibilities can be discarded, at least for an initial evaluation; single-stage versions have, in the past, provided insufficient performance (without surface refueling) and have no independent abort capability (i.e., ascent punchout). Providing a separate stage for the final descent (last 300 m/s) is probably not a good mass trade, although doing so preserves the ascent stage for ascent-only use if that becomes required. This leaves the 2- and 2.5-stage configurations (5 of the 13 from the trade table) as a reasonable starting point for staging trades and is discussed in the remainder of the paper.

Two-Stage Surface Staging

The two-stage surface-staging concept is the classic Apollo approach, which is also the current nominal ESAS report design and reference design for this paper. The system is referred to as surface staging, because that is where the staging event occurs (upon initiation of the ascent burn). We will not discuss this approach in detail, because it is well-documented, but note a few advantages:

1) The independent ascent stage provides an abort capability independent of the descent propulsion system.

2) Ascent propulsion only requires a single start (i.e., no prior use of the ascent system before ascent).

3) There is only one staging event, which occurs in a benign environment.

4) There is no dropped debris to control impact.

The primary disadvantage relates to landing the large tank volume required to support both the LOI and descent burn. This presents configurational challenges relating to surface access and cargo offloading. These may be nonissues, depending upon the surface build architecture, particularly if it is based on a construction infrastructure (i.e., cranes available to offload the payload). In addition, a substantial throttle range is required for the descent engines, due to the large change in lander mass as LOI and descent propellants are expelled.

Drop-Tank-Staging Concepts

Drop-tank-staging variants attempt to ameliorate some of the issues associated with the surface-staged designs: specifically, the configurational advantage of staging a substantial portion of the tank volume before landing. The tanks may be dropped either following the LOI burn (in LLO) or during descent (with the lander final-descent tanks serving as feeder tanks from the drop tanks to avoid a descent-engine restart). In either scenario, the dropped-debris scenario remains a disadvantage. The concepts also seek to gain some payload mass advantage that comes from staging away empty tankage.

Descent-Staging Concepts

The descent-staging option consists of a separate, complete, dedicated stage that is used for the LOI burn and most of the descent burn. This common LOI-descent stage (CLDS) would be roughly the size of a Delta-IV upper stage. Once the CLDS is released 4 km above the surface, the terminal descent–ascent stage (lander) descends the final 300 m/s to touchdown. Terminal propellant is contained in the ascent tanks, and the engine(s) used for the final descent may be reused for the ascent. This approach reduces the physical size of the landing craft, when compared with the reference ESAS lander, and significantly increases its surface-payload capability.

There are other advantages, including a much-reduced throttling requirement for final descent. The Surveyor robotic lunar lander used descent staging in the 1960s. In Fig. 4, a plot of terminal descent altitude vs range to go is given. The lander is approximately 2 km above the empty CLDS at the time of its impact; the lander touches down about 4 km downrange of the impact point. Both distances are subject to trade; increasing the separation requires either earlier separation or a shallower flight path, either of which requires additional descent propellant, which adversely affects the delivered payload. In Fig. 5, the CLDS lander separation maneuver is shown.

The advantages of descent staging are many. First and foremost, descent staging removes most of the LOI and descent burn tankage before touchdown. This provides for a much smaller lander, significantly increases lander payload capability, and simplifies surface access. It also allows for similar vehicle T/W requirements for final descent and initial ascent, allowing a common terminal descent–ascent engine. The terminal descent stage requires some throttling, though not as significant as the deep-throttling requirement of the reference ESAS mission lander. Descent staging

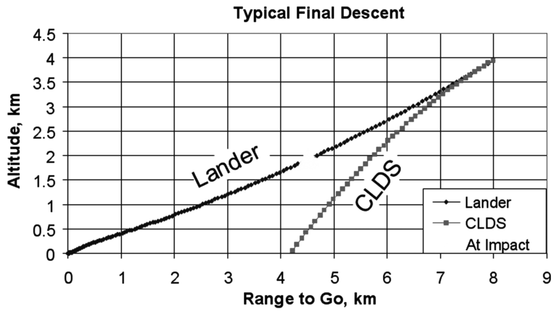

Fig. 4 Descent-staging: altitude vs range to go.

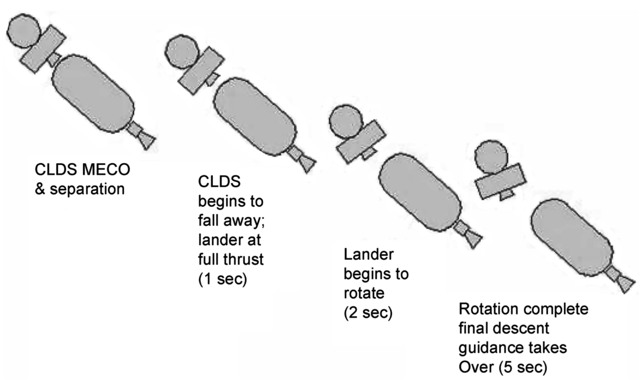

Fig. 5 Descent-staging: separation maneuver (MECO is the main engine cutoff).

allows the separate CLDS to use a long-nozzle, high-I_{sp} (458 s) RL10-B2 engine, and the engine for this stage does not require any throttling. This separate CLDS would be similar in size to an existing upper stage, allowing it to come off a common assembly line.

There are disadvantages to descent staging. First, it requires a time-critical engine start of the terminal stage 4 km above the surface, and the engine must be restarted for ascent. Also, descent staging leaves a spent stage on the surface 4 km away from the landing site.

Performance Assessment

Performance (payload mass to the surface) was assessed as a function of the staging concept and ascent propellant. A common ascent payload is used in all cases, as described next. The two-stage surface-staged lander is used as a reference. The mass of the ascent cab for a crew of four is determined from a series of interdependent algorithms that capture the intricacies of habitat subsystems as functions of the number of crew, duration, volume, radiation shielding, internal pressure, redundancy, spares, and other considerations. Additional masses of 400, 440, and 125 kg are allocated for docking port, crew/effects, and extravehicular activity (EVA) suit masses, respectively; total ascent-crew-module payload is 2655 kg. Reasonable propellant margins, residuals, tank gage uncertainty, boil-off, dry-weight growth, gravity losses, throttling losses, and other margins are applied. For this analysis, only 2- or 2.5-stage landers were considered; subsequent briefings may address single-stage and stage-and-a-half concepts.

A *reference crew-mission lander* uses a single O_2/H_2 RL10-A4 engine for LOI and descent and a single pressure-fed N2O4/MMH engine for ascent. Its total mass is 45 t (the maximum that the Ares-V EDS can boost to TLI), and it delivers, in addition to the ascent stage, a surface payload of 4.8 t. The lander performance model optimizes the surface-payload mass within the boundaries defined by the assumptions and the various propulsion and staging options. The surface payload is the variable to be maximized given fixed CEV and Ares-V to TLI mass values (see Table 4). From this reference case, ascent-propellant and staging-mode trades were run. Ascent stages use a single pressure-feed engine (either storable or O2/CH4) and ascend to a 100-km LLO.

For a cargo-only case, in which no CEV or ascent stage is carried, the reference ESAS descent stage, if unchanged, could carry 16.4 t of surface cargo (Table 4). This descent stage is the same as the crew-mission descent stage (the LOI/descent propellant load is less and the propellant split is different). However, at this capability, it does not take full advantage of the Ares-V capability to TLI, which, if the CEV is not taken, is 53.6 t.

A redesigned descent stage, sized to maximize the surface payload and take full advantage of the Ares-V capability, could deliver 19.8 t to the surface. This is a descent stage with increased thrust, larger descent tanks, increased propellant, and a heavier frame than the reference crew-mission descent stage.

Figures 6 and 7 show how crew-mission lander mass varies with ascent-propellant choice and staging mode; the first two bars refer to ESAS staging cases, the middle two bars refer to drop-tank-mode cases, and the last two bars refer to descent-staging-mode cases. For each pair, the first bar refers to the storable-propellant-ascent-stage case and the second bar refers to the methane-ascent-stage case. Surface payloads range from 4.8–5.0 t (ESAS), 5.2–5.4 t (drop tank), and 5.6–6.1 t (descent staging). Methane-ascent propulsion provides a slight (0.2–0.4-t) increase in surface payload over N_2O_4/MMH (Fig. 7). The drop-tank mode provides a payload gain of 0.4 t compared with the ESAS reference, whereas a larger gain (0.9–1.1 t) is achieved with descent staging. The drop-tank- and descent-staging-mode landers are physically smaller than the reference.

Figure 8 illustrates lander propellant tank volumes for each of the three staging modes. Only the "landed" tank volume is shown. For each of the staging modes, two values are given: the landed descent-stage tank volume is given first and next to it is the ascent-stage tank volume. For the ESAS case on the left, 70 m^3 (cubic meters) of LO_2/LH_2 LOI/descent tank volume is landed, along with 4 m^3 of N_2O_4/MMH ascent tank volume. For the drop-tank mode in the center (with all LOI propellant in the jettisoned tank), 32 m^3 of LO_2/LH_2 tankage is landed (4 m^3 for N_2O_4/MMH ascent tankage): less than half the volume of the reference ESAS lander volume. Finally, for the descent-staging mode (right), the all-LO_2/LH_2 CLDS is not landed; only the N_2O_4/MMH terminal descent–ascent

Table 4 ESAS mode reference lander mass statement, 65-t ARES-V to TLI value

	Element	Crew mission (ref.)	Cargo common descent stage	Cargo optimized lander	Comments
To TLI	Total	65,000	45,000	53,600	Ares-V Earth-departure-stage payload
CEV	In LEO	20,000	0	0	In LEO, service module with TEI propel
Lander	Total	45,000	45,000	53,600	In LEO (Ares-V upper-stage payload)
	Dry mass	6756	6756	7710	Single-engine, 446 I_{sp} RL10A4 (84 ER)
	Descent prop	11,855	13,196	15,735	LO_2/LH_2
	LOI prop	12,004	8302	9899	LO_2/LH_2
	RCS prop	385	348	416	280-s I_{sp}, storable
Descent	**Payload**	**4781**	**16,350**	**19,840**	Left on surface
	Dry mass	2320	n/a	n/a	Single-engine, pressure-fed, 329 I_{sp}
	Ascent prop	4133			NTO/MMH, storable
	RCS prop	111			280-s I_{sp}, storable
Ascent	Crew cabin	2655			Cab, port, crew, EVA suits, etc.

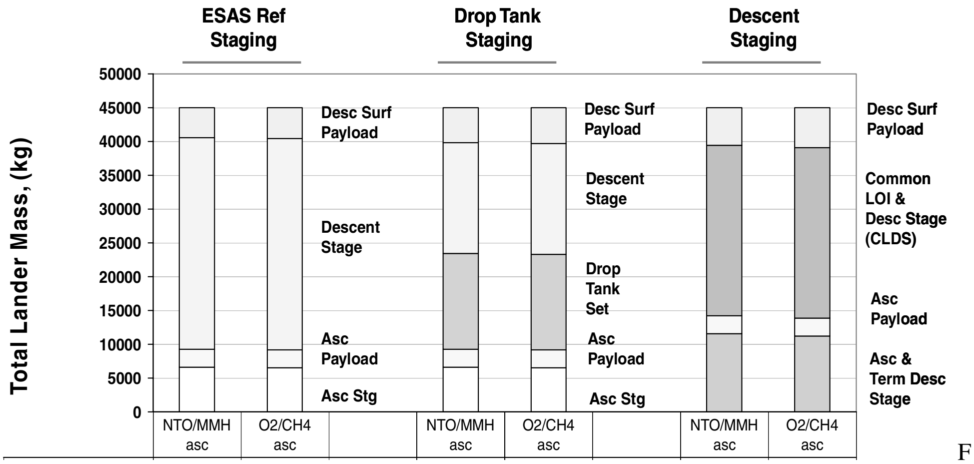

Fig. 6 Lander masses vs staging and ascent-propellant choices; 45-t lander.

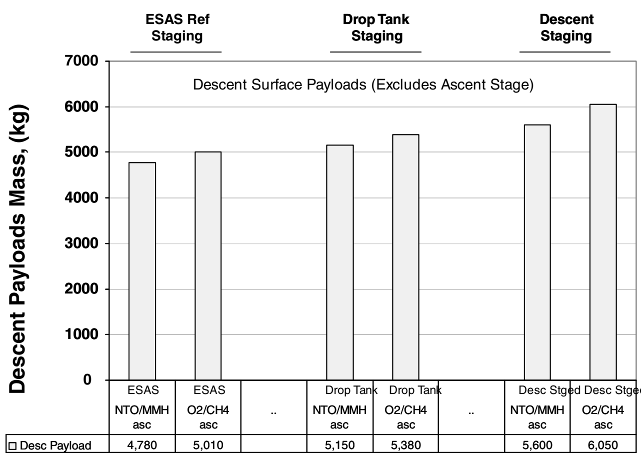

Fig. 7 Surface payload vs staging and ascent propellant; 45-t lander.

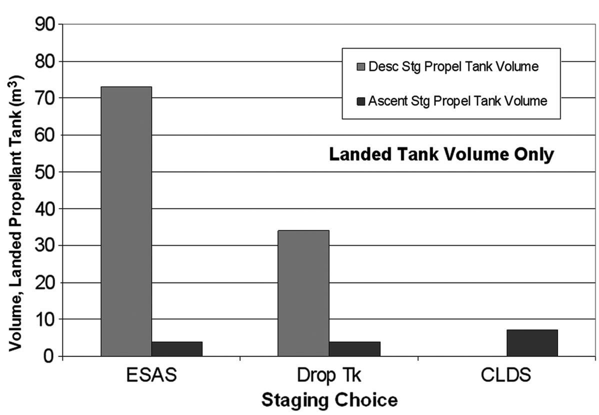

Fig. 8 Landed propellant tank volume comparison; 45-t lander.

stage is landed and its total tank volume is 9 m^3: an order-of-magnitude reduction in landed propellant tank volume compared with the reference. The benefit is a much smaller, shorter, and lighter lander that does not require the deep throttling that is characteristic of the larger ESAS lander.

Sensitivity to Ares-V EDS Capability

For Ares-V EDS mass to TLI values of 60, 62.5, and 65 t, lander total mass values are 40, 42.5, and 45 t. In Table 5, lander payload mass is given. Ascent mass values are 9.2 and 9.0 t for storable and LO_2/methane propellants, respectively. Delivered descent-stage surface payloads (in addition to the ascent stage) are 2.8–3.0 t for the 40-t lander, 3.9–4.0 t for the 42.5-t lander, and 4.8–5.0 t for the reference 45-t lander. Values for the other two staging modes are also listed.

Lander Configuration Options

The lander configuration trades examine the arrangement of equipment that achieves the lander requirements. These general arrangements are dominated by the larger equipment: notably, the ascent module, tanks, engines, and payload. Requirements are first dictated by the transportation and surface architectures, then further derived in terms of particulars such as tank size, staging, etc., as described in the previous section. Because these trades are still open and the surface architecture is being refined, the configuration option set is quite large and a survey of potential designs is presented. Typically, the trades involve evaluating one figure of merit against another (e.g., delivered mass vs accessibility).

As discussed earlier, the role of the lander in the surface architecture can influence its design:

1) The passive lander has the salient design characteristic of readily offloadable payload (i.e., good clearances for access and removal of payloads). In some cases, this may be aided by mechanisms on the lander.

2) The active lander has the salient design characteristics of payload (such as habitat modules) close to the surface, provisions for self-powered surface transportation, preferably smaller to aid in access and transportation issues, and adequate engine clearance for surface transportation.

3) The colony lander has the salient design characteristic of payload (such as habitat modules) close to the surface.

For each staging strategy, configurations can be developed and evaluated in regard to how well they will tend to support a particular surface strategy (ascent-propellant trades for those propellants discussed have a relatively minor impact on the configuration trades).

An approach to evaluating and shaping the lander design is shown in Fig. 9. The figure illustrates a trade tree that describes various options in regard to creating a lunar outpost and, ultimately, the role of the lander in the creation of the outpost (beyond the role of transporting the crew and cargo from LLO to the surface). As shown in the figure, the highest level of trade is the basic architecture for the lunar outpost. Two basic alternatives are suggested, although there are, no doubt, others. The term "tightly coupled" refers to a lunar outpost built from modular components, which are subsequently connected together on the lunar surface through a hard connection, and likely includes a pressurized interconnect between at least some of the modules. The loosely coupled surface architecture either has no connection among the surface elements or relatively little connection (such as power). In other words, each lander provides a relatively self-sufficient habitat, and so the collection is a "colony," which approximately suggests that the landers are relatively close to each other, some small number of meters implying that they were

Table 5 Descent surface-payload variation with total lander mass (all mass is in metric tons)

	ESAS mode				Drop-tank mode				Descent-staging mode			
	Storable-ascent stage		Methane-ascent stage		Storable-ascent stage		Methane-ascent stage		Storable-ascent stage		Methane-ascent stage	
Lunar lander mass	Desc surf payl	Asc-stage total	Desc surf payl	Asc-stage total	Desc surf payl	Asc-stage total	Desc surf payl	Asc-stage total	Desc surf payl	Term desc–asc	Desc surf payl	Term desc–asc
45.0	4.78	9.22	5.01	8.99	5.15	9.22	5.38	8.99	5.60	14.4	6.05	14.0
42.5	3.79	9.22	4.02	8.99	4.14	9.22	4.37	8.99	4.75	14.0	5.18	13.6
40.0	2.81	9.22	3.03	8.99	3.12	9.22	3.35	8.99	3.91	13.6	4.32	13.2

transported from the landing site. Scattered colonies have no surface transportation; the outpost simply consists of a number of landers that remain in their original landing site, the distance between them determined by the minimum safe landing separation. The tightly coupled architecture is usually what is associated with lunar outposts, although a loosely coupled architecture is not precluded.

The next level of the trade tree evaluates the construction method: either via emplacement of basic construction infrastructure (cranes or other offloading equipment and surface transportation) or no infrastructure is required, in other words, the lander provides surface mobility, leveling, connectivity to another node of the outpost, etc. Self-transportation eliminates the need for designing and emplacing an infrastructure and allows outposts built with the fewest number of flights, but also requires that each lander (or payload) provide its own mobility features. The mass for mobility features is estimated at about 1.2 t (wheels, motors, and leveling features found on the surface transporter). The next layer further defines the lander role in the construction and outpost architecture (either the whole lander is used or some cargo is offloaded). In some architectures, a surface transporter can drive under lander surface payloads and transport these payloads to the base and then return to service the next lander's payload. The final two layers of the trade relate to trades regarding the lander itself once its role in the overall surface architecture has been established. The staging trade discussed earlier is critical, because it dictates the tankage at the surface (drop tanks are included in the descent-staging category). Finally, there is an entire tree that relates to the physical trades for the lander.

At this point, no assumptions are made regarding the trades at the higher level of the trade space, and the discussion merely serves to illustrate the linkage between the surface architecture and lander design.

The trade space for the lander configuration includes 1) general order and arrangement (i.e., stacking), primarily of the surface-payload module, ascent module, tankage, and main engines; 2) orientation of the primary axis at landing (horizontal or vertical); 3) tankage trades (multiple tanks provide flexibility, single tanks provide greater efficiency, particularly for cryogenic thermal control, and toroidal tanks provide volumetric efficiency in some configurations); 4) fixed configurations vs post launch deployed or reassembled in orbit; and 5) habitat or other major cargo shape.

Clearly, the trade space is quite large. As an illustration of a subset, Fig. 10 lists elemental drawings of a diverse set of lander configurations. All sketches are representative. Five types are illustrated and the title of each corresponds to the position of the main payload module. The module may be placed on the top (types 1 and 3), sides (type 2), bottom (type 5), or axially integrated into the center (type 4). Main engines may be located at the bottom center (types 1, 2, 3, 4, 5B, and 5C), sides (type 5A), ends, or corners. There may be twin modules [types 2A, 2B, 3 (right), and 5C]. Propellant tanks may be mounted on the sides (5A), top (5B and 5C), or bottom (types 1, 2A, 3, and 4).

Undercarriage concepts (type 5), locating their payload on the bottom, allow ease of cargo offloading; representatives in Fig. 10 are 5A–5C. The cargo is lowered to the surface by hoists. Engine exhaust shields are not shown. A module preintegrated with a surface transporter may be ready for use immediately after touchdown (5A). Outpost buildup might be simplified compared with other concepts, because modules could be offloaded, transported, and mated together to form a surface base without the use of cranes or ramps.

Undercarriage configurations also provide short ingress/egress paths for personnel and a low vehicle c.g. lessens the tip-over hazard when landing on sloped terrain. Engine-out options include opposed engine shutdown and/or RCS assist. Missions carrying a single large payload benefit the most from this approach. Proponents cite its cargo positioning; opponents cite its spread-engine arrangement, because it is not directly under the c.g. (though the sum of the thrust component is through the c.g.). As in all designs, engines gimbal to track the changing c.g. as propellant is consumed. Type 5B differs from 5A in that the engines are centered, and at the bottom of the vehicle, the ascent and descent tanks are positioned above the crew cab (rather than to the sides, as in 5A). Type 5C locates twin modules just outboard of bottom-center-positioned engines (the tankage is

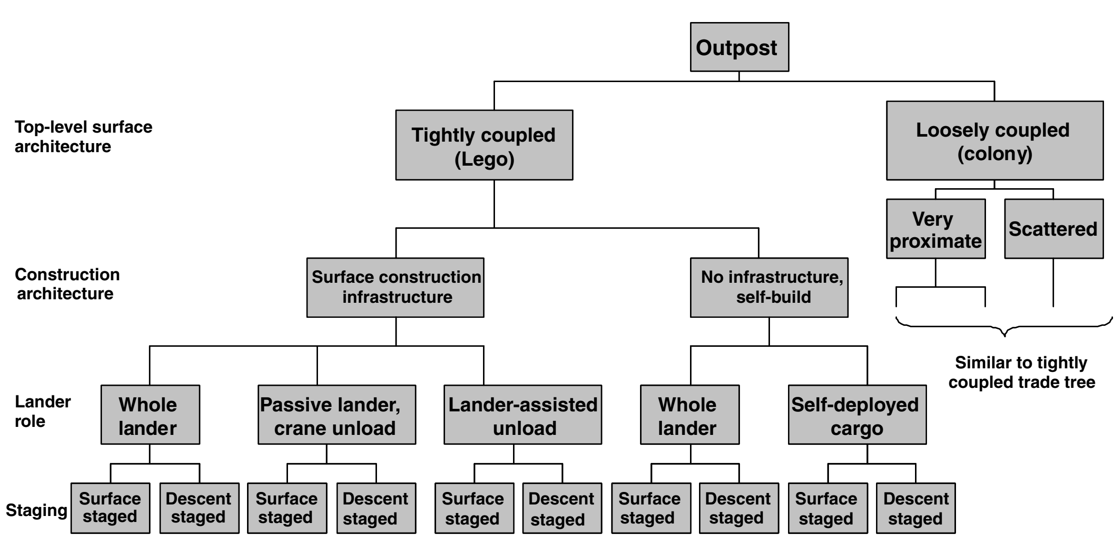

Fig. 9 Surface architecture trade tree.

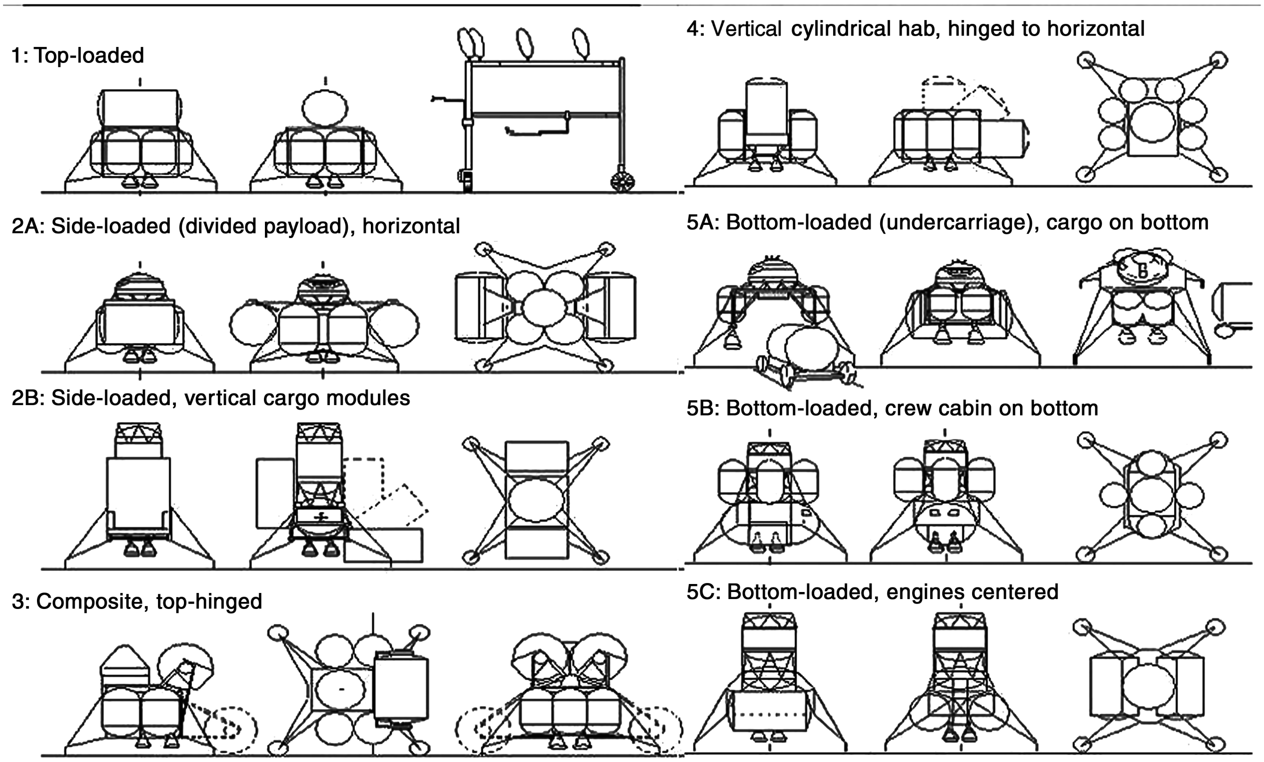

Fig. 10 Cargo lander configuration-options montage.

directly above), and type 5D (not shown) locates the engines and tankage on the vehicle ends.

Top-loaded concepts (type 1) require large offloading cranes to lift cargo modules off the top. If the module is heavier than the crane, there is a danger that the module will pull over the crane, unless the crane is so large that it can straddle the lander. The cost to launch, emplace, transport, and service a straddler crane of this size (physically larger than the lander) may become problematic. The cost and complexity of a three-story-high straddler crane/offloader may be a sizable disadvantage of this "lift off from the top" option. If modules are not to be downloaded and only single-module outposts are envisioned (or colony-type outposts), then type 1 might be preferred. To lessen the difficulty of offloading payload and allowing top placement without requiring a crane, the top-hinged concept (type 3) may be considered.

Top-hinged concepts do not require an offloading crane, though they require a mechanism and hinged-cradle system to rotate the module off the top, around the sides, and onto the surface. In Fig. 10, type 3, both single-module (left) and dual-module versions (right) are shown.

Side-loaded concepts do not require cranes, though the cargo must be split into two equally weighted pieces to retain symmetry and proper c.g. for flight control during the descent.

Center-loaded concepts also do not require an offloading crane, and the main cargo can be one piece. The type-4 central-habitat configuration locates the module vertically and in the center of the descent stage. The illustration shows the module surrounded by tankage (except on one side), with main engines directly underneath, in the center. Once landed, the module is rotated down from a hinge point at the bottom until it is horizontal.

Fixed-habitat concepts are not designed for habitat removal. A centrally located habitat is either surrounded by descent propellant tanks or propellant tanks are located above. To allow for close surface proximity, descent engines are located at the vehicle corners, leaving the center position for the habitat.

Specific Configurations

With the requirements, trade space, and typical high-level configurations identified, a few landers were defined to the next level of detail. The following describes a few specific configurations over a broad range of the trade space.

A *top-mounted* configuration (Fig. 11) is similar to the ESAS lander pictured in Fig. 2. This configuration would likely support a tightly coupled outpost with the aid of some surface infrastructure. An ascent stage is located on the top, with its single ascent-engine nozzle sitting in a central void that runs through the descent stage, which has circumferential descent tanks. The ascent stage features a cylindrical crew cabin, with tanks positioned on the sides. The descent stage may be common for both crew and cargo (Fig. 12) variants.

Undercarriage concepts have the virtue of providing payload proximate to the surface, either for simplified offloading (which may include self-transportation) or accessible modularity for an outpost built using the entire lander. Figures 13 and 14 illustrate two undercarriage concepts.

In Fig. 13, an undercarriage-cargo configuration featuring a doughnut-shaped surface habitat is shown. A single descent engine occupies the central void in the habitat. The configuration features a single descent hydrogen tank with several oxygen tanks located on the side (the large single hydrogen tank is more easily insulated than several smaller hydrogen tanks). An ascent stage sits atop the hydrogen tank and features two side-mounted engines. This configuration requires ascent-module EVA upon arrival and departure; for all remaining surface activities, the crew has a short egress path to the surface. The addition of surface mobility and docking features (not shown) would permit this lander to support self-built, tightly coupled, outpost architectures.

A second undercarriage configuration is illustrated in Fig. 14, featuring side engines and descent tanks. The illustration does not show the LOI drop tanks (only descent tankage is shown). This concept is suited to delivery of cylindrical payloads that may initially be preintegrated with wheeled transports. The transport drives up under the payload, which is lowered onto the transporter and is driven off to be jointed to other payloads. This would facilitate the buildup of a base made from joined modules, without cranes, simplifying site buildup. A variation of concept 2 is given in Fig. 15; pictured is a cargo-only vehicle that features full LOI and descent tankage, no CLDS is used.

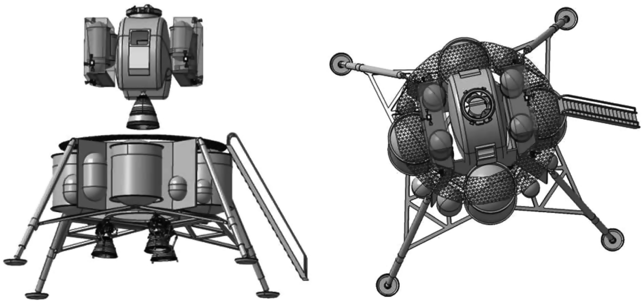

Fig. 11 Top-loaded lander, storable-propellant ascent.

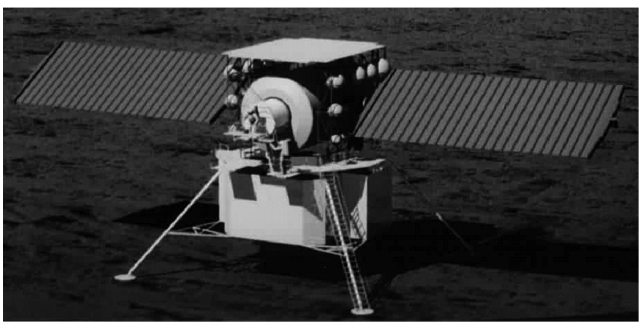

Fig. 12 Top-loaded cargo-mission lander with surface habitat.

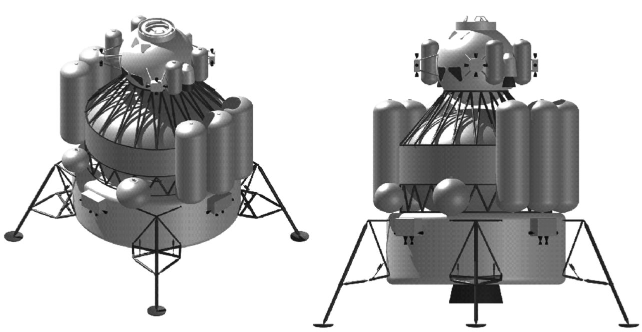

Fig. 13 Undercarriage concept 1, center engine.

A LOI *drop-tank* configuration is shown in Fig. 16. It features a vertical, central, cylindrical surface habitat. Around it, LOI and descent tanks are positioned. The cylindrical habitat is divided into two sections. The bottom is doughnut-shaped, with a central void occupied by the descent engine. The lower pressurized section contains the surface air lock and storage areas; the section above the central void is a pure cylinder and contains the crew area. The ascent

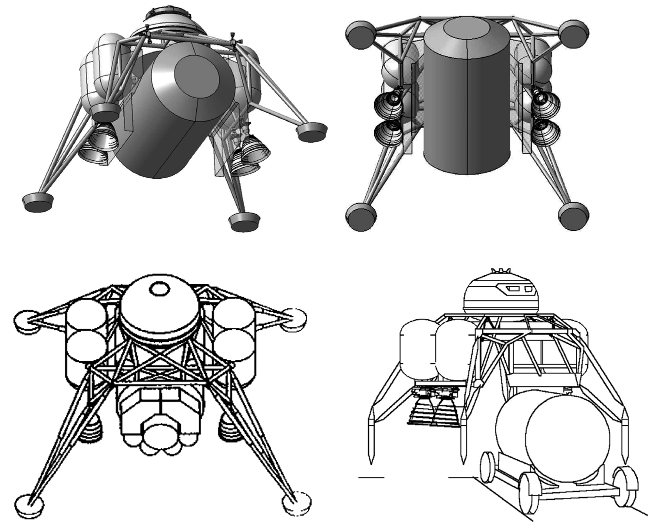

Fig. 14 Undercarriage concept 2 with side engines.

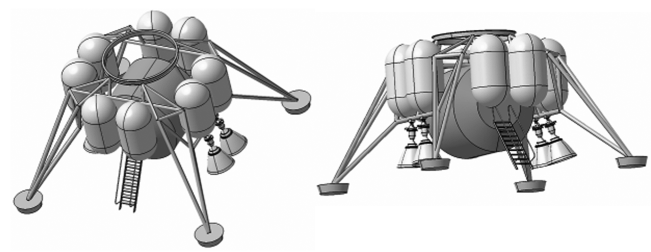

Fig. 15 Undercarriage concept 2 with LOI tankage

cabin has an access port at its bottom that connects directly to the top of the surface habitat. This approach allows the cylindrical habitat to take all launch and landing loads in the axial direction. For cargo-only missions, the ascent stage is omitted and a much heavier habitat can be delivered.

Another *drop-tank* configuration is shown in Fig. 17. LOI tanks are dropped in LLO. After orbital capture, the CEV backs away from the lander, the empty LOI tanks are jettisoned, and the CEV redocks. The crew transfers to the lander and the CEV undocks and remains in LLO. Another variant of this concept jettisons tanks that also hold a portion of the descent propellant partway through the descent (in a lower phasing orbit). In this case, there is a tunnel between the CEV and the lander for crew transfer in LLO, or EVA is used.

A *side-loaded* configuration is shown in Fig. 18. Surface payloads are divided into two equal mass modules and are carried on either side of a descent stage with central-bottom-placed main engines. After landing, these modules can be downloaded without the use of

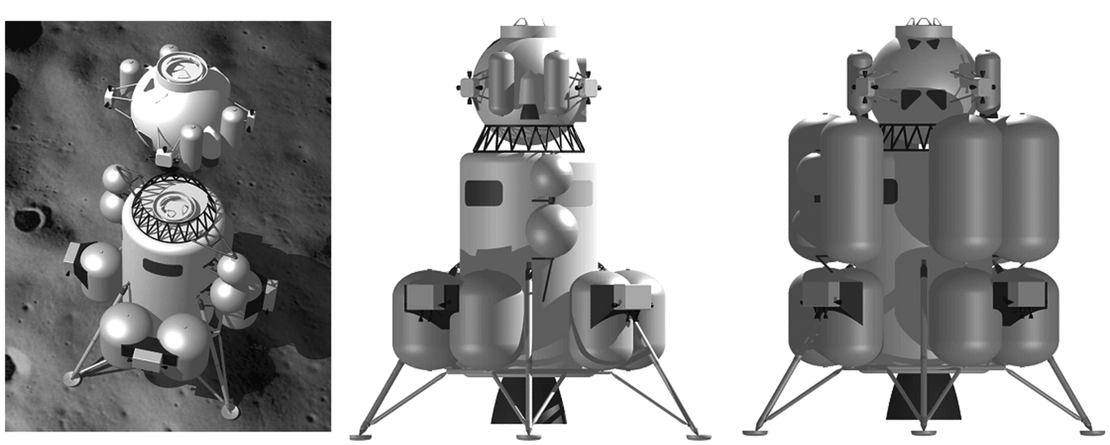

Fig. 16 Drop-tank configuration 1: LOI tanks dropped in orbit: crew and cargo mission.

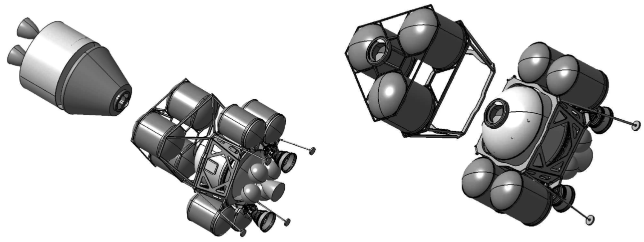

Fig. 17 Drop-tank configuration 2: LOI tanks jettisoned after lunar capture: crew mission.

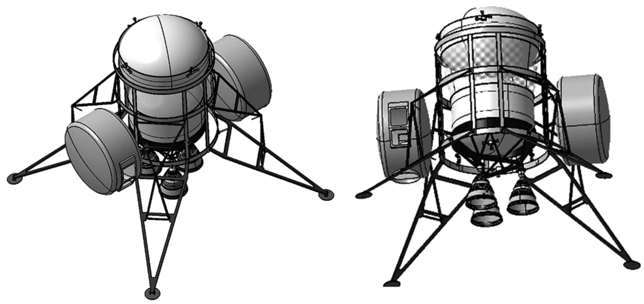

Fig. 18 Side-loaded cargo-mission configuration.

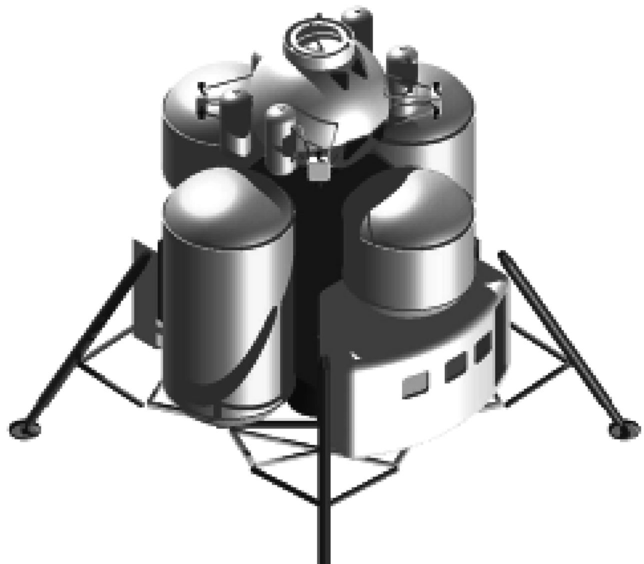

Fig. 19 Fixed-habitat configuration with LOI-descent tanks at the sides, center engine version: crew cargo mission.

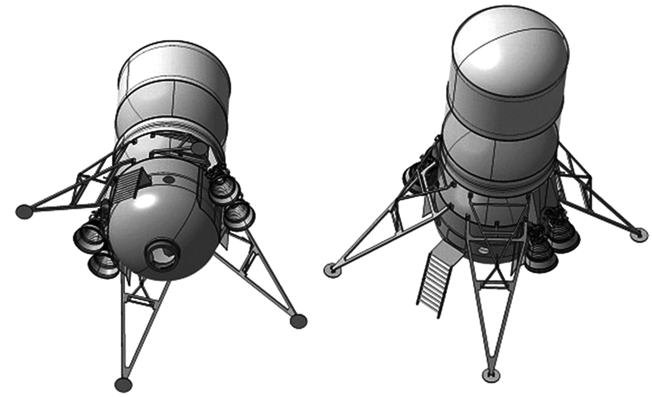

Fig. 20 Fixed-habitat concept 2 with LOI/descent tanks at the top, engines at the side: cargo mission.

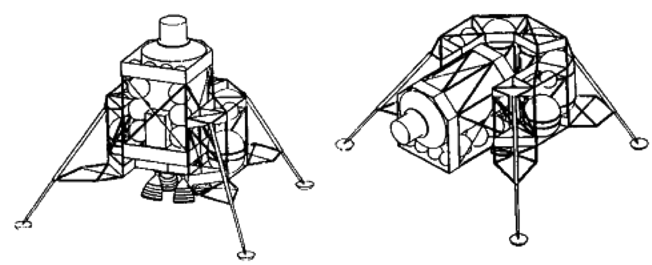

Fig. 21 Hinged vertical payload lander: cargo mission.

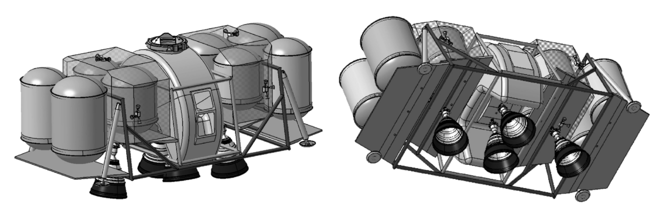

Fig. 22 Horizontally integrated lander: crew mission.

dedicated cranes. In some variants, the side modules may be tall and have a hinge at the bottom; once landed, the modules are rotated about the hinge point into a horizontal position for placement onto a wheeled transporter. Modules are then taken to the base for use.

Fixed-habitat configurations are not intended to have the surface habitat removed. Figures 19 and 20 show vehicles that have descent tankage that holds all LOI and descent propellant together. In Fig. 19, a habitat is shown at the bottom on one side; on the opposite side is a corresponding module, or a container holding consumables, spares, and science equipment. Landers such as this may be intended for multiple reuse; after an initial mission, returning crews landing nearby return to this habitat or rely on it as a backup in case their primary habitat fails. After several landings in close proximity, multiple habitats would be available (though not physically linked), and through the use of these "logistically coupled" modules, long-duration surface missions might be undertaken.

Colony base buildup proceeds from this initial outpost formulation, in which inflatable structures might be added, eventually leading to a base made up of both fixed, inflatable, and moveable assets. In Fig. 20, a spherical habitat is shown at the bottom of the vehicle. Single H2 and O2 tanks are at the top. The descent engines are at the bottom sides of the habitat. Engine exhausts shields are shown. The spherical habitat pressure vessel may be nearly identical to one of the propellant tanks and come off the same assembly line.

A *hinged-vertical-payload* configuration, shown in Fig. 21, has descent tankage that surrounds the centrally located payload on all but one side. In the center, above the descent engine, is a void (central core) in which a cylindrical payload is positioned. Once landed, the payload is rotated down to a horizontal position. A surface transporter drives under it and transports it away to be joined to other modules, if necessary. There is a hinge mechanism, or hinge cradle, that attaches at the payload bottom that is designed for a one-sixth-gravity operation. This configuration allows the payload cylinder to take all launch, transfer, and landing acceleration loads in a vertical direction along its axis. An ascent stage is located in the central core for crew missions, and thus both cargo and crew versions would use identical descent stages.

A *horizontally integrated* configuration, shown in Fig. 22, has mirror-image descent tankage on the ends, with an ascent stage in the center. The vehicle has a cylindrical ascent cab in the center (with ascent engines underneath). In this case, the descent tankage, engines, and surface air lock are left on the surface. One variation provides for the jettison of the descent tanks on the ends before

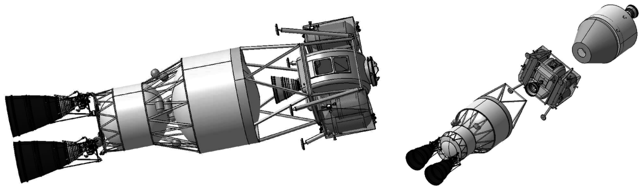

Fig. 23 Descent-staging lander: crew mission.

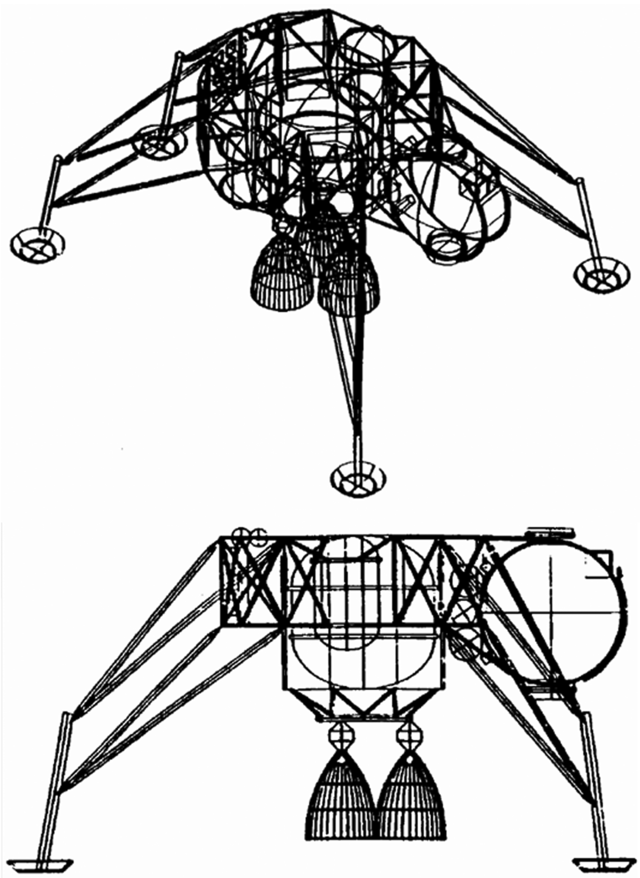

Fig. 24 Side-cabin terminal descent–ascent stage

touchdown to reduce the landed mass. In that case, the terminal descent and touchdown propellant is drawn from the ascent tanks.

A *descent-staged* configuration is shown in Fig. 23. Its combined LOI and descent stage (CLDS) is very similar to a Delta-IV or Centaur upper stage, with the addition of an extra engine to provide an engine-out capability. The CLDS allows the terminal descent–ascent stage to be much-reduced in size compared with the reference lander. Deep throttling is no longer required by either stage, and the modest propellant required for terminal descent is held in the ascent tanks. The terminal descent–ascent stage uses a pressure-fed storable-propellant engine of 6-klbf thrust. The crew has a short path to the surface.

A terminal descent–ascent stage is shown in Fig. 24. It is characterized by a side-positioned ascent crew cabin, central tankage, and bottom-center engine placement. This vehicle separates from the CLDS and descends to touchdown. After the surface mission, it ascends to LLO.

A side-loaded concept is shown in Fig. 25. The side-cargo elements are hinged and are set to the top position to fit within the launch vehicle payload shroud. While in LLO, the modules are rotated down to a fixed and locked side position before the vehicle descends. A crew cabin is shown on top. This illustration is taken from [13].

An all-cryogenic O_2/H_2 ascent stage and lander are shown in Fig. 26. This illustration shows a descent stage that is common for the

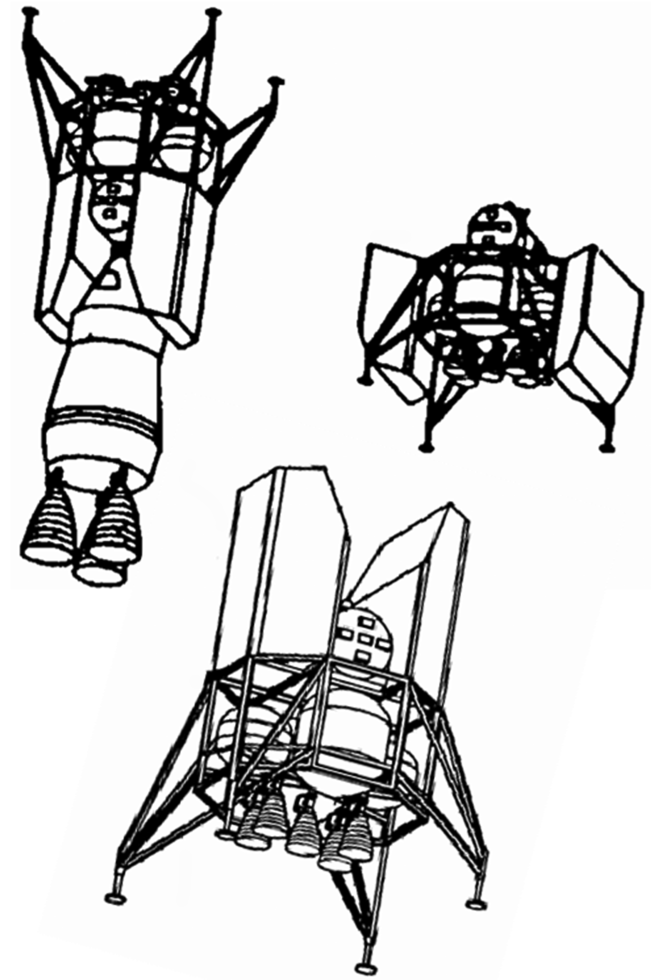

Fig. 25 Side-cargo type-2 concept.

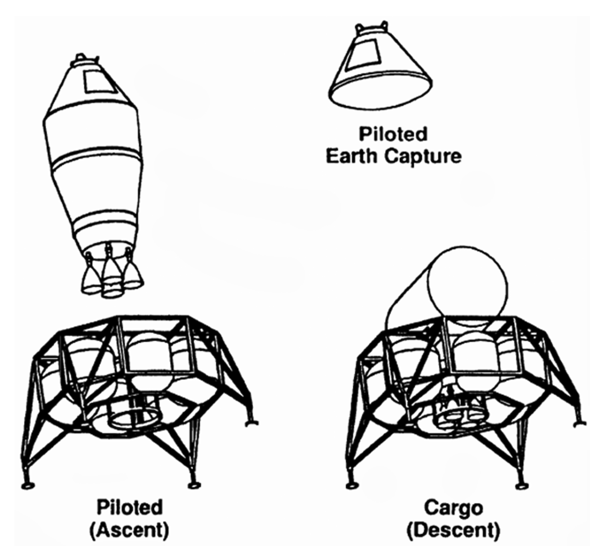

Fig. 26 Cryogenic O_2/H_2 ascent lander.

piloted and cargo-only variants. Shown on the left of Fig. 26 is the piloted version with a cryogenic O_2/H_2 ascent stage. This stage sits within a central void in the descent stage. The engines, located at the bottom of the ascent stage, are used for the descent, ascent, and TEI burns. During descent, propellant is routed to the engines from the descent-stage tanks. On the right of Fig. 26, the cargo-only version is shown. This illustration is taken from [13].

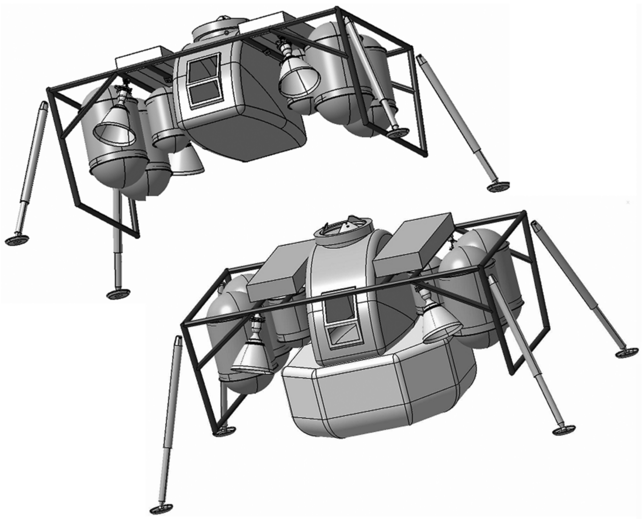

Fig. 27 In situ propellant single-stage lander.

A single-stage reusable concept that is refueled on the surface with propellant provided by an in situ propellant plant is shown in Fig. 27. Operating between LLO and the surface, this vehicle receives a payload in LLO and descends to the surface. After payload offloading, the vehicle is refueled for its next mission. This design features a centrally located ascent crew cabin, flanked on both sides by propellant tankage. Engines are positioned for ease of access and change out on the surface. The tanks are located in positions that allow for easy inspection; refueling interconnects are easily accessed. In Fig. 27, several structural elements are excluded from the illustration for clarity.

Conclusions

Seen from a logistical viewpoint, those lander types that allow cargo offloading without the use of cranes may be preferred for base-buildup scenarios. For scenarios in which the joining of habitats is not desired, the close grouping of fixed-habitat landers may be preferred. Most of the configurations discussed in this section do not preclude descent-staging or drop-tank-staging modes. Boeing is continuing its work in this area, focusing its lander concept refinement in concert with lunar surface architecture studies. For additional Boeing published material, see the five-year Space Transfer Concepts and Analysis for Exploration Missions (STCAEM) 1989–1994 reports, such as [1–4]; for Boeing material specifically on lander design, see [5–12]. This preliminary design study is part of a larger effort to define the attributes of future lander vehicles and is only partially complete. The following summary statements are preliminary and will be revised as the work progresses and as NASA refines both its architecture and surface-asset plans.

1) The ESAS-Ares-V architecture will place, via the reference ESAS lander, in addition to a 2.7-t ascent cabin, a surface payload of about 4.7 t, given a 45-t lander, and a 20-t CEV is injected into lunar trajectory by the Ares-V EDS. If the lander is 40 t, the surface payload is about 2.8 t.

2) If maximizing landed payload is paramount, then the *descent-staging* approach provides a significant advantage over the ESAS report approach. Its other benefits (reducing the size of the lander and reducing the final-approach deep-throttling requirement) are also significant, though descent staging requires an engine start in the final portion of the descent and creates a "graveyard" of used stages. Other factors must be accounted for: for example, a complete risk analysis, which was not done in this study, would be necessary. *Drop-tank staging* also provides a modest payload advantage without the disadvantage of a time-critical engine start.

3) The ascent-propulsion analysis indicates that the oxygen/methane choice provides a slight surface-payload-delivery advantage over the storable choice. Though O_2/CH_4 I_{sp} is 31 s higher than storable propellant, its fuel is less dense and more thermal conditioning would be required. More work needs to be done in this area, and recent O_2/CH_4 engines tests, sponsored by the NASA Johnson Space Center and the NASA John H. Glenn Research Center at Lewis Field, are encouraging.

4) Lander configuration choice is linked to the lander requirements, including its intended participation in the surface architecture. If a base is to be constructed by the joining of habitats, the undercarriage or side-loaded concepts may be preferable, because they offer an easier pathway to site buildup. Habitats preintegrated to wheeled transports could be moved to the base immediately after landing without the additional steps of placing a dedicated crane on the surface and conducting a host-off maneuver. *Side-loaded* configurations require the main cargo to be divided but to retain bottom-center engine placement. If offloading and joining of habitats is not an objective or if the offloading and joining is to be performed with the aid of preemplaced surface equipment, then the *top-loaded concept* may be preferred.

Acknowledgments

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