Lunar Lander Structural Design Studies at NASA Langley

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Abstract

The National Aeronautics and Space Administration is currently developing mission architectures, vehicle concepts and flight hardware to support the planned human return to the Moon. During Phase II of the 2006 Lunar Lander Preparatory Study, a team from the Langley Research Center was tasked with developing and refining two proposed Lander concepts. The Descent-Assisted, Split Habitat Lander concept uses a disposable braking stage to perform the lunar orbit insertion maneuver and most of the descent from lunar orbit to the surface. The second concept, the Cargo Star Horizontal Lander, carries ascent loads along its longitudinal axis, and is then rotated in flight so that its main engines (mounted perpendicular to the vehicle longitudinal axis) are correctly oriented for lunar orbit insertion and a horizontal landing. Both Landers have separate crew transport volumes and habitats for surface operations, and allow placement of large cargo elements very close to the lunar surface. As part of this study, lightweight, efficient structural configurations for these spacecraft were proposed and evaluated. Vehicle structural configurations were first developed, and preliminary structural sizing was then performed using finite element-based methods. Results of selected structural design and trade studies performed during this activity are presented and discussed.

Nomenclature

AMA	=	Analytical Mechanics Associates, Inc.
CaLV	=	Ares V Cargo Launch Vehicle
CEV	=	Orion Crew Exploration Vehicle
CLV	=	Ares I Crew Launch Vehicle
CSM	=	Apollo Command/Service Modules
DASH	=	Descent Assisted, Split Habitat
delta-V	=	Propulsive change in motion
EDS	=	Earth departure stage
ESAS	=	Exploration Systems Architecture Study
EVA	=	Extravehicular activity
g	=	Standard gravitational acceleration at Earth surface
KSC	=	Kennedy Space Center
LaRC	=	Langley Research Center
LEO	=	Low Earth orbit
LIDS	=	Low-Impact Docking System
LLO	=	Low lunar orbit
LLPS	=	Lunar Lander Preparatory Study

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LM	=	Apollo Lunar Module
LOI	=	Lunar orbit insertion
LSAM	=	Lunar Surface Access Module
MSFC	=	Marshall Space Flight Center
NASA	=	National Aeronautics and Space Administration
TEI	=	Trans-Earth injection
TLI	=	Trans-lunar injection
VSE	=	Vision for Space Exploration

Introduction

At the beginning of the 21st Century, the National Aeronautics and Space Administration has been tasked with execution of a comprehensive national space strategy for the United States, the Vision for Space Exploration (Ref. 1), which calls for, among other objectives,

1) implementation of a sustained and affordable human and robotic program to explore the solar system and beyond;
2) extension of the human presence across the solar system, starting with a human return to the Moon by the year 2020, in preparation for human exploration of Mars and other destinations; and
3) development of innovative technologies, knowledge, and infrastructures both to explore and to support decisions about the destinations for human exploration.
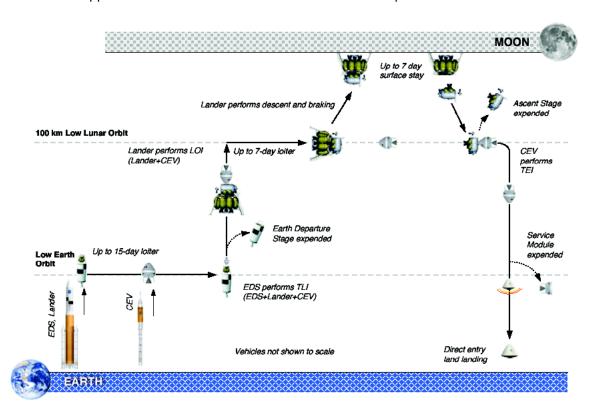

Figure 1. ESAS lunar design reference mission.

Development of the launch vehicles and spacecraft required for implementation of the VSE is vested in NASA's Constellation Program (Ref. 2). As currently envisioned, selected components of the Space Shuttle and other existing launch vehicles are used as building blocks for the Ares I Crew Launch Vehicle

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and Ares V Cargo Launch Vehicle. However, new spacecraft, including the Lunar Surface Access Module and Orion Crew Exploration Vehicle must also be developed. These vehicles correspond, respectively, to the Lunar Module and combined Command/Service Modules developed for the Apollo Program. The main difference between the Constellation lunar mission architecture (shown in Figure 1) and Apollo is that the CEV and LSAM will be launched separately on the Ares I and Ares V launch vehicles and rendezvous in low Earth orbit prior to the trans-lunar injection burn, instead of using a single launch of the Saturn V launch vehicle.

As NASA works to develop these new space vehicles, numerous conflicting objectives, constraints and requirements must also be satisfied. Key among these is the need for highly efficient, lightweight vehicle structures and structural subsystems. Lightweight structures are critical because each kilogram of LSAM mass requires as much as 25 kilograms of dry mass (the so-called "gear ratio") of launch vehicle to put it on the Moon. Therefore, an overweight lander design may easily exceed the performance capability of the CaLV, resulting in an unclosed system.
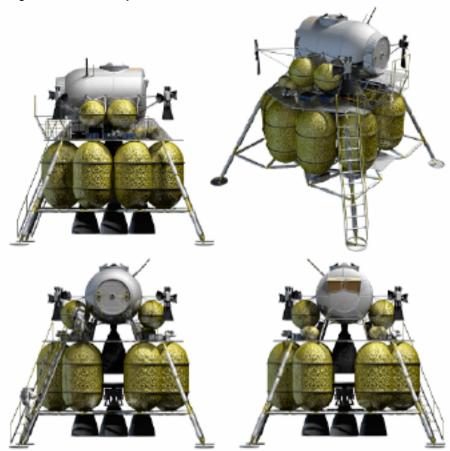

Figure 2. ESAS Lunar Surface Access Module.

A LSAM concept vehicle (see Figure 2) was presented in the Exploration Systems Architecture Study Final Report of Ref. 3. This lander is expected to be much larger and more capable than the Apollo LM, with a crew of four and at least four times the number of crew-days on the lunar surface. However, there are also some potentially unacceptable aspects to this design. The LSAM pressurized crew cabin on this vehicle is about 7 meters above the lunar surface, and the astronauts must repeatedly climb up and down to perform lunar surface operations. In addition, large cargo elements that are on the order of 20 metric tons are envisioned to support a lunar outpost. The cargo deck height above the lunar surface would make unloading these components a challenge.

To develop the best lander design that will satisfy the overall Constellation objectives, constraints and requirements, a wide variety of candidate designs from across the trade space must first be examined. In early 2006, the Constellation Program's Advanced Projects Office initiated a high-level Lunar Lander Preparatory Study (Ref. 4). Phase I of this study generated 37 very different lander configurations that were developed by teams from the various NASA field centers. From this broad spectrum of designs, six spacecraft designs were chosen for further evaluation in a follow-on LLPS Phase II effort in the summer of 2006. The objectives of this later study were to:

   1) provide additional concept development and refinement;
   2) include cost and probabilistic risk analyses; and
   3) include more in-depth systems- and discipline-level analyses.
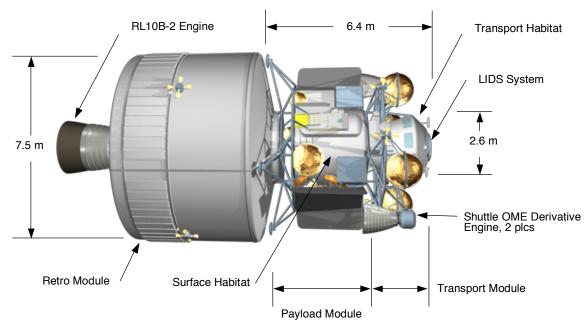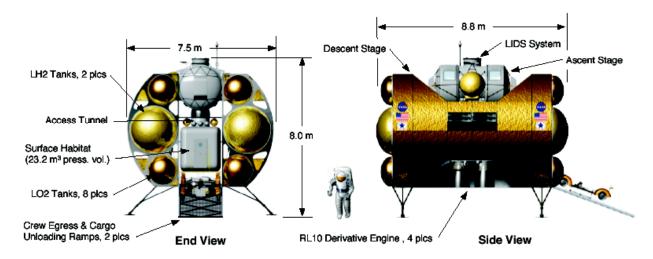

Figure 3. Descent Assisted, Split Habitat Lander.

Figure 4. Cargo Star Horizontal Lander overview.

A multi-organization, interdisciplinary team led by engineers at the NASA Langley Research Center was responsible for developing two different lander concepts during the LLPS Phase II study. These are the Descent Assisted, Split Habitat Lander (Figure 3), and the Cargo Star Horizontal Lander (Figure 4). Both of these vehicles included a minimum-volume pressurized module in which the four-person crew rides during descent to and ascent from the lunar surface, and a separate Surface Habitat for use during lunar surface operations. This split configuration is designed to maximize the cargo mass that can be delivered to the lunar surface.

This paper presents an overview of bottoms-up structural concepts and configuration design, structural analyses and trade studies performed for these two Landers during the LLPS Phase II study. Each Lander design posed different challenges to the structures teams formed for this study. Configuration and trade studies conducted during this activity include definition of requirements, criteria and load cases, configuration, layout and sizing of Lander primary structure and load paths, landing gear, propellant tanks and propulsion systems. Selected results of these studies are presented and discussed in this paper.

Mission Concept of Operations

With only a few exceptions, the mission concept of operations in this study is identical for both of the Landers. The common elements in the mission operations are described here, while the differences are discussed later for each concept. The Lander, mounted atop an EDS, is launched to low Earth orbit aboard a CaLV. The mated Lander and EDS must survive an untended loiter period of up to 95 days in LEO (a significant increase over the 15-day period mandated for the ESAS vehicle) while waiting for the four crew members in the CEV to launch atop the CLV for rendezvous with the Lander. The CEV then maneuvers to rendezvous with the Lander, and they are mated in LEO using an androgynous Low-Impact Docking System (Figure 5) originally developed under the X-38 program.
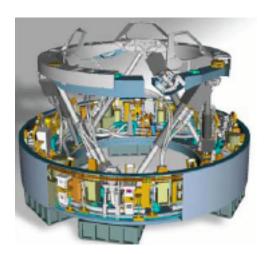

Figure 5. LIDS androgynous docking and berthing mechanism.

The EDS then performs a 1.6g trans-lunar injection burn to put the combined vehicles on an Earth-Moon trajectory. The EDS separates from the Lander and CEV after completion of this maneuver. When the Lander and CEV arrive at the Moon, the Lander then performs a 0.7g lunar orbit insertion burn. This scenario differs from the Apollo mission profile in that the Service Propulsion System engine on the Apollo Service Module was used to perform the LOI maneuver for the mated Apollo LM and CSM. After a loiter period of up to 7 days in low lunar orbit (100 km altitude), the crew boards the Lander and descends to the lunar surface, leaving the uncrewed CEV in orbit. The maximum acceleration during this descent maneuver is 0.7g.

At this point, two different crewed lunar surface mission scenarios, a 7-day sortie mission and a 90-day outpost mission, are envisioned. A third scenario is a one-way, uncrewed cargo delivery mission with autonomous landing capability. Both the sortie and outpost missions require multiple extravehicular activities on the lunar surface by the crew, so ease of crew egress is a major concern. A major objective for all three missions is to enable placement of large infrastructure elements onto the lunar surface. Therefore, ease of unloading for large cargo components is also a key design driver for both of these Landers.

After completion of the surface mission, the crew then boards the Lander ascent stage and launches to LLO for rendezvous with the CEV. After the crew transfers to the CEV and the ascent stage is jettisoned, the CEV's main engine is used to perform the trans-Earth injection burn for the return to Earth. After separating the SM prior to atmospheric entry interface, the Crew Module performs a direct entry to a land landing on Earth to complete the mission.

Study Assumptions and Tools

Several common assumptions are made for both Lander concepts during this study. The CaLV launch loads are modeled using two inertial loads on the Lander; an axial 5g load parallel to the vehicle axis and a lateral 2g load applied in any azimuth normal to the longitudinal axis. For the purposes of this study, these loads were assumed to occur simultaneously. However, this would most likely not be the case in practice, as the maximum lateral load typically occurs early in the flight near maximum dynamic pressure, while the maximum axial load occurs later near orbit insertion and stage separation. As noted above, the maximum load factor is 1.6g during the TLI maneuver, and 0.7g during the LOI burn. The CEV mass during these maneuvers is assumed to be 20.1 metric tons.

An additional desire is to maximize the axial and bending frequencies of the Lander to avoid coupling with launch vehicle resonant frequencies. In lieu of firm requirements for the CaLV, nominal values of 5 Hz (lateral) and 25 Hz (axial) are chosen as goals for this study. The maximum internal pressure in the crewed portions of the Landers is assumed to be 70.3 kPa. Assumed factors of safety (Refs. 5, 6) are 1.1 on limit yield loads, and 1.4 on ultimate loads. Aluminum-Lithium 2195 material properties are used for all structures. Linear structural analyses of the Landers were also performed to determine vehicle load paths and estimate structural weights. Analysis models were first built using the NASTRAN (Ref. 7) finite element code. The resulting internal loads were then used in conjunction with the HyperSizer (Ref. 8) structural sizing code to size the Lander structural components for strength, stiffness and to resist buckling.

DASH Lander – Vehicle Concept

The DASH Lander is comprised of the three modules shown in Figure 3. The first module is the Lander Module, which contains the crew and all critical lander subsystems (propulsion, avionics, hazard avoidance, etc.). A high-reliability, pressure-fed hypergolic propulsion system with two engines derived from the Space Shuttle Orbital Maneuvering Engine is used for terminal descent and ascent. The 3.7m engine height above the surface reduces surface plume debris and permits lower vertical touchdown velocity. The pressurized Transport Habitat, part of the Lander Module, is a biconic-shaped structure that provides efficient working volume and excellent visibility for the crew during descent and ascent. The Transport Habitat can also be reconfigured during surface operations as separate sleeping quarters or for crew privacy.

The second module is the Payload Module, which provides a versatile platform to accommodate both pressurized and unpressurized payloads for transport to the lunar surface, specifically pressurized habitats, outpost infrastructure and cargo, and other surface equipment. The Surface Habitat consists of a hard-shell central core module with an inflatable airlock and alcove located on opposite sides of the central core, or a single larger inflatable volume at the rear. Inflatable habitats allow additional

pressurized volume on the surface, as well as the ability to tailor the pressurized volume for mission needs, while still providing excellent crew visibility during terminal descent. The DASH concept can also support the use of suitports with the surface suits either attached externally during descent or contained within the central core and mated externally once on the lunar surface.

The third module is the Retro Module, which is a high-performance, in-space braking stage that performs the LOI maneuver, as well as 90 percent of the delta-V required for the descent to the lunar surface. The Retro Module is powered by a pump-fed liquid oxygen/liquid hydrogen propulsion system with a single RL10B-2 engine, which is not required to throttle since the Lander Module engines perform the terminal descent and landing. Multiple engines could also be accommodated if additional engines will significantly reduce system risk. Performance estimates suggest that Retro Module staging just prior to landing provides an approximately 1 metric ton lander mass savings over a traditional two-stage lander with a split habitat, and about 3.5 metric tons over an Apollo-like approach with a single habitat.

Structural Configuration

The structural core of the DASH Lander is comprised of two identical, octagonal truss platforms (Figure 6) that are 5m across flats. This dimension was chosen to allow the fixed landing gear to fit within the 7.5m-diameter payload shroud dynamic envelope. These truss platforms offer a high degree of flexibility for tailoring the vehicle configuration to mission requirements, while still minimizing the structural mass fraction. The truss structures are comprised of thin-walled members that are connected to node fittings at both ends. All major vehicle components and subsystems are attached to the truss nodes to minimize induced bending moments.
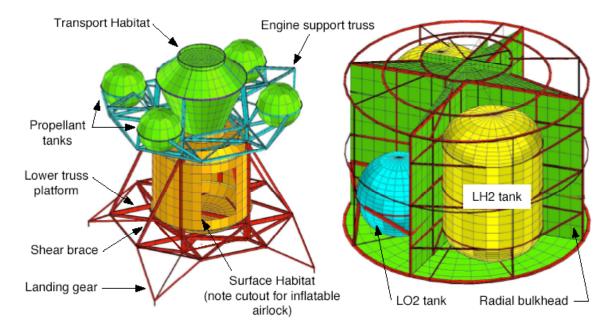

Figure 6. DASH Lander structural components.

The Lander Module's pressurized Transport Habitat is attached to the central nodes of the upper truss platform and stabilized using truss members. These structural members also relieve some of the loads imposed on the Transport Habitat during the TLI and LOI burns. A short tunnel section with hatches on either end is connected to the bottom of the Transport Habitat. This tunnel passes through the upper truss platform to allow access to the Surface Habitat from the Transport Habitat. The Lander Module's main propulsion system, reaction control system thrusters and propellant tankage are also attached to the upper truss platform using lattice trusses.

The large pressurized 2.9m-diameter Surface Habitat on the Payload Module is permanently attached to the lower truss platform central nodes, and is attached with pyrotechnic fittings to the upper truss platform central nodes. Access to the lunar surface is through an inflatable airlock attached to one side of the Surface Habitat, or through the LIDS hatch on the Transport Habitat in an emergency. Additional unpressurized cargo and consumables for lunar surface operations are stowed around the Surface Habitat on the Payload Module. Four identical sets of landing gear trusses are attached at each corner of the lower truss platform. Each landing gear truss member is hinged at both ends, and is designed to either extend or compress to absorb the impact energy. This landing gear arrangement does not rely on mechanical deployment, thus further improving reliability.

The 5g axial and 2g lateral ascent loads size approximately 80 percent of the DASH Lander structures. The 5g axial ascent loads are transferred through the Transport and Payload Modules to the Retro Module, and finally into the EDS. The Surface Habitat also contains two large cutouts to allow integration of the inflatable habitats. The structural analyses Payload Module indicate that the Surface Habitat does not have enough shear stiffness in the plane of the cutouts to carry the 2g lateral ascent loads. External shear braces that connect the lower truss platform to the top of the Surface Habitat were added to help react these loads. When the CEV is docked with the DASH Lander for the later TLI and LOI burns, the Transport and Surface Habitats form the primary structural load path between the Retro Module and the LIDS interface with the CEV. Therefore, additional local reinforcements are required to carry the high compression loads from these maneuvers.

Structural Trade Studies

Two of the structural trade studies performed for the DASH Lander are discussed in more detail in this section. Several different engine configurations were evaluated for this Lander, and each required different support truss designs. Each of the two engines on the DASH Lander is supported by a relatively simple truss structure, as detailed in Figure 7a. Initially, use of four engines arranged in pairs on either side of the Transport Habitat was considered, as the additional engines were thought to increase system reliability. One proposed layout had all four engines mounted along the same transverse line to minimize control issues during an engine-out scenario. The support truss developed for this engine layout, shown in Figure 7b, is relatively complicated, with over two times as many truss members as the single-engine truss. In addition, the outboard engines generate very high bending moments that must be reacted by the support truss, increasing the structural mass. Another proposed four-engine configuration located each engine at one corner of a rectangle. The support truss proposed for this design is shown in Figure 7c. It is slightly more complex than the single-engine truss, but not nearly as complicated as the two-engine in-line arrangement. The selected single-engine support truss in Figure 7a is also compatible with the support truss arrangement shown in Figure 7c if an additional engine is required.

Another study performed for the DASH Lander study involved the use of inflatable habitats to support lunar surface operations. The truss platform dimensions chosen for the DASH Lander permit efficient integration of two hard-shell habitat diameters, 2.9m and 5.4m, with the truss platform node locations. Further examination of the pressurized volume requirements for the sortie mission shows that the smaller habitat with a 2.9m diameter does not provide enough volume, whereas the larger 5.4m-diameter habitat far exceeds the required volume. Therefore, the smaller diameter hard-shell habitat (approximately 14m^3 volume) is selected for use with two 6m^3 inflatable habitats located on opposite sides. One inflatable habitat is used as an airlock, and the other is configured as a storage alcove for equipment or trash, or as sleeping quarters. In addition to possible mass savings, these inflatable habitats also offer increased crew visibility of the lunar surface from the Transport Habitat during landing. Either one of the two smaller inflatable habitats could also be replaced by a single, larger inflatable habitat if additional volume is required for lunar surface operations.
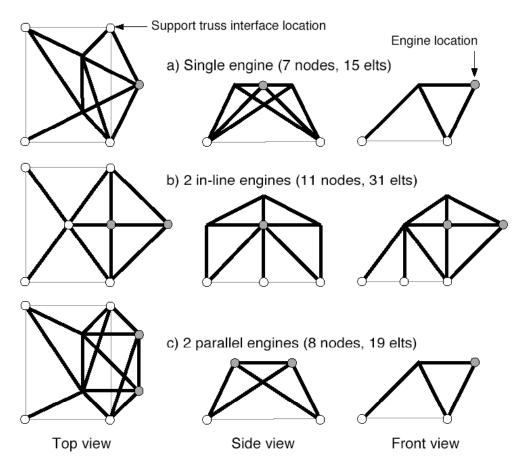
Figure 7. DASH engine support truss concepts.

Cargo Star Horizontal Lander – Vehicle Concept

The primary function of the Cargo Star Horizontal Lander is to simultaneously carry crew and cargo to a lunar surface outpost site or sortie location. Figure 4 shows the general arrangement of the Horizontal Lander, which is sized for four crew and a seven-day surface stay, and global access (1250 m/s LOI delta-V, and 1900 m/s descent delta-V) using four liquid oxygen/liquid hydrogen-fueled RL10-derivative engines. The vehicle is built around a large central cargo bay located on the Descent Stage, which also houses the engines and propellant tankage. A monolithic pressurized Surface Habitat, used for lunar surface operations, is shown stowed in the cargo bay.

The smaller Ascent Stage for the Cargo Star lander is designed for minimum mass and volume for the crew of four. Minimum mass is desired because each kilogram of Ascent Stage dry mass is traded for approximately two kilograms of other cargo to the surface. Minimizing the Ascent Stage mass and volume are possible because the crew will not live exclusively in the Ascent Stage as was done in Apollo. The Ascent Stage is designed for nominal descent and ascent flight times and crew support for one day on the surface. The Ascent Stage configuration is a horizontal cylinder with a central LIDS mechanism for docking to the CEV. There are two pilot stations and two mission specialist stations. The hypergolic propellant ascent propulsion system is pressure-fed and centrally mounted on the vehicle.

The Ascent Stage is connected to the Surface Habitat by a tunnel that is offset from the Ascent Stage engine. This allows crew access from the CEV through the Ascent Stage to the Surface Habitat during the outbound phase. The tunnel also allows full access between the Ascent Stage and Surface Habitat after landing. For missions that do not deliver a Surface Habitat, the Lander can carry pressurized or

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unpressurized cargo elements. After deployment of ramps on either end, small cargo elements can be towed out of the Lander cargo bay using a lightweight rover. For larger cargo, a surface transporter with high mass capability will be used to move the element off of the Lander. The horizontal configuration of this Lander offers a major advantage in facilitating cargo unloading when compared with vertical landers which require the capability to move massive cargo from an elevated cargo bay using cranes, elevators, or scissor lifts.

Structural Configuration

The primary structure configuration (Figure 8) developed for the Cargo Star Horizontal Lander generally resembles that of conventional aircraft structures with a semi-monocoque construction. This configuration results from the requirement that the Horizontal Lander be vertically integrated and launched on an Ares V vehicle, where high thrust loads during launch and TLI are oriented along the vehicle longitudinal axis. Later in the mission, the thrust forces for the LOI burn and the descent to the lunar surface are both perpendicular to the vehicle longitudinal axis. The operational requirement that the Horizontal Lander carry high loads in these two perpendicular axes (for Earth launch and TLI, as well as the LOI and lunar descent maneuvers) increases the vehicle structural weight by about 30 percent over a structure sized for the launch case alone.
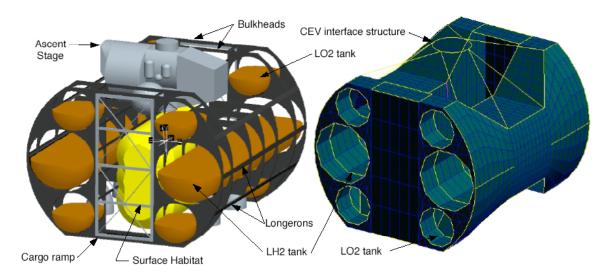

Figure 8. Horizontal Lander structural components.

Large, primary load-bearing structural members are arranged parallel to the longitudinal axis of the Payload Module. These longerons support the Surface Habitat and propellant tankage, and also carry the majority of the axial thrust loads during the launch from Earth. Transverse bulkheads perpendicular to the longitudinal axis react the engine and propellant loads during the LOI and descent to, as well as landing on, the lunar surface. The exterior of the Descent Stage is also covered with isogrid panels to better distribute loads throughout the vehicle.

Several aspects of the Horizontal Lander configuration pose unique structural design challenges that tend to increase the structural weight. Since the Ascent Stage is mounted to the side of the Descent Stage, large shear loads must be carried between these stages during launch and TLI. Prior to the TLI burn, the CEV docks with the Horizontal Lander using an adapter mounted on the Descent Stage forward bulkhead. This adapter is only used during the TLI burn, and is discarded after EDS separation when the CEV undocks from the adapter, and then redocks to the Ascent Stage LIDS prior to the LOI maneuver.

Structural Trade Studies

Two of the structural trade studies performed for the Cargo Star Horizontal Lander are discussed in more detail in this section. A wide variety of landing gear concepts were examined during this study. Key criteria for the landing gear system are the system mass, landing stability, simplicity, reliability and energy absorption capability. An Apollo-style deployable mechanism was finally chosen for application to the Horizontal Lander. However, other landing gear configurations that included inflatable airbags and other energy-absorbing devices were also evaluated to determine their suitability. The airbags were eliminated because the low pressures required to prevent them from exploding would result in high shearing on landing. In addition, plume impingement from the main engines could also affect the structural integrity of the airbags.

As noted above, the Cargo Star Horizontal Lander is required to carry high inertial loads along two perpendicular axes, so the resulting structural weight was considerably higher than a structure sized only by the launch case. Therefore, innovative structural concepts are developed to further reduce the weight of the Lander. One such concept investigated in this study was a structural payload shroud. On most launch vehicles, the payload shroud is nonstructural, and is jettisoned as soon as possible to increase the amount of payload that the launch vehicle can place into orbit. A nonstructural shroud also greatly simplifies the interface between the launcher and the payload, as the shroud design is decoupled from the compression-loaded payload supported by an adapter structure attached to the launch vehicle. This arrangement is shown schematically in Figure 9a.

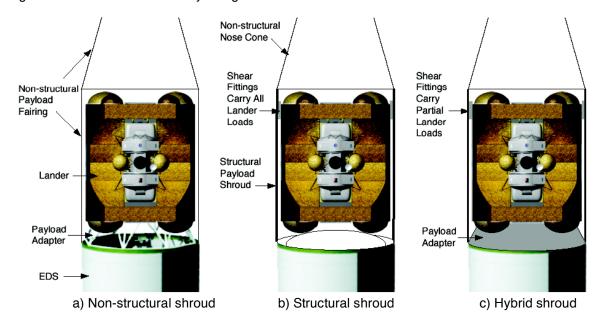a) Non-structural shroud   b) Structural shroud   c) Hybrid shroud

Figure 9. Payload shroud concepts.

However, if the Lander were only attached to the forward edge of the payload shroud (see Figure 9b), then the Lander would mostly be loaded in tension. This arrangement could result in structural mass savings in the Lander as buckling (of the Lander) is no longer a major design driver. However, this payload shroud would be more massive than the nonstructural version, since the buckling-critical shroud would now be heavily loaded in compression. The advantage of this structural shroud concept is that the Lander mass might be reduced, and landed mass is a critical parameter in getting the entire mission architecture to close. A variation of this concept was used on the Saturn V launch vehicle, where the Apollo LM was attached to the Spacecraft/LM Adapter shroud at the landing gear hardpoints near the LM's ascent/descent stage interface plane.

An alternate payload arrangement would combine the structural shroud described above with a conventional adapter structure at the base of the Lander (see Figure 9c). This configuration would react a portion of the Lander inertial loads as compression through the structural shroud and back into the launch vehicle, while reacting some of the Lander loads as compression through the payload adapter. As this design lies somewhere between the conventional payload adapter and the full structural shroud, the Lander mass savings from implementation of this shroud design also are likely between these two extremes. However, the shroud structural design now becomes highly integrated with the structural design of the Lander, as any mismatch in stiffness between the Lander and shroud will result in a majority of the load being carried by the stiffer component.

Although originally proposed for the Horizontal Lander, these structural shroud concepts could also be implemented for the DASH or any other Lander. However, since the structural shroud is both heavier than a standard payload shroud, and must be carried further in the mission profile (at least to LEO, and perhaps through TLI if used to support the CEV), there will be some impact on the EDS performance. This trade-off must be further quantified through additional structural and systems-level studies. Also, the additional attachment points between the Lander and shroud mean that more pyrotechnic mechanisms are required, increasing both the number of single-point failures and mission risk.

Concluding Remarks

This paper presents an overview of two lunar Lander concepts, the Cargo Star Horizontal Lander and the Descent Assisted, Split Habitat Lander, developed at the NASA Langley Research Center as part of the 2006 Phase II Lunar Lander Preparatory Study. In addition, the mission concept of operations and high-level assumptions and requirements are discussed. The Lander primary structure configurations, layouts and concepts developed for these vehicles, as well as results of selected high-level structural analyses and trade studies performed for these two Landers are also presented herein.

Although these two Landers are quite different, several common areas of concern were noted in the course of this study. Combination of the 5g axial and 2g lateral ascent loads into one case is likely to result in some degree of conservatism in the structural sizing. Since these two loads actually occur at different times in the ascent trajectory, future studies should treat them as separate cases. Another key item is the lack of definition regarding the capabilities of the LIDS docking system to support the TLI and LOI loads from the attached CEV. If the compression load rating of the LIDS is insufficient to carry these loads, then additional support structures will be required to react them. The use of composite materials for the Lander primary and habitat structures may also result in some mass savings. However, these must be traded against their relative immaturity when compared to the baseline metallic structures.

Two of the structures technology areas that are identified as requiring additional work are the maturation and demonstration of inflatable structures technology for the DASH Lander airlock and alcove, and the structural payload shroud proposed for the Horizontal Lander. Both areas may be widely applicable to other Lander concepts, but this latter item is especially important for the Horizontal Lander, since it can help to minimize the mass penalty imposed on that Lander by having two different primary axes of loading (axial for ascent and TLI, and transverse for LOI and landing). Additional systems- and discipline-level studies are needed to further refine this concept.

Acknowledgments

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