SAE TECHNICAL
PAPER SERIES

2009-01-2366

Comparative Configurations for Lunar Lander Habitation Volumes: 2005-2008

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The Engineering Society For Advancing Mobility Land Sea Air and Space®
INTERNATIONAL

39th International Conference on Environmental Systems
Savannah, Georgia USA
July 12 - July 16, 2009

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ABSTRACT

This paper presents an overview of the progression of the contemplated candidate volumes for the Lunar Lander since the beginning of the Vision for Space Exploration in 2004. These sets of data encompass the 2005 Exploration Systems Architecture Study (ESAS), the 2006 Request for Information on the Constellation Lunar Lander, the 2007 Lander Design Analysis Cycle -1 (LDAC-1) and the 2008 Lunar Lander Development Study (LLDS). This data derives from Northrop Grumman Corporation analyses and design research. A key focus of this investigation is how well the lunar lander supports crew productivity.

INTRODUCTION

Under the Constellation Program for exploration systems, NASA has engaged with the industry and academic communities on the analysis, design, and development of concepts for the crewed Lunar Lander. This interaction has followed two-year cycles of NASA publishing a concept, followed by the industry responding with a review of the design and innovative ideas. Northrop Grumman's approach defines crew productivity as how well the system supports the crew to perform their mission. The first order metrics for crew productivity are how efficiently the crew can use their time and how safely they can do their jobs.

In the first cycle, in 2005, NASA published the Exploration Systems Architecture Study (ESAS), which focused upon the Orion CEV but included a substantial chapter on the Lunar Surface Access Module (LSAM). In 2006, NASA issued a Request for Information for the Lunar Lander Concepts Requirements Description, based largely upon ESAS, to which industry responded (which soon became known as the Constellation Lunar Lander or CLL). In the second cycle in 2007, NASA published the Lander Design Analysis Cycle – 1 (LDAC-1). In 2008, industry responded to a NASA Broad Area Announcement for the Lunar Lander Development Study (LLDS) based on LDAC-1.

This paper identifies the habitable volume allocation in each of these four studies of the Lunar Lander and examines the design assumptions for each lander option. As these study cycles progressed, there has been considerable variation in functional allocation and total volume. In the 2005 ESAS, NASA allocated 16 m^3 for the habitation function in addition to the Ascent Module (AM). In our 2006 CLL RFI response, Northrop Grumman recommended a 23.2 m^3 habitation volume. In the 2007 LDAC-1, NASA proposed a bare-bones minimum functionality of 10 m^3 for the entire Ascent Module, including all habitation functions. In the 2008 LLDS, Northrop Grumman recommended a 19 m^3 Ascent Module, incorporating the habitation functions. TABLE 1 presents these volumetrics. The Summary present a comparative break-down and analysis of these volumes.

This paper traces the progress of the Lunar Lander habitation concepts through this formative period of analysis and design. It makes some observations and

ISSN 0148-7191

remarks about the amount of free circulation volume necessary for the crew of four to live and work in the Ascent Module in space and on the lunar surface for the mission durations specified by NASA.

THE LUNAR MISSION TIMELINES

The lunar lander story begins with NASA's publication of several sets of lunar mission timelines. TABLE 2 shows these timelines specifying the durations for the mission segments, which can vary substantially over the contemplated time spans. The most detailed set of data came from NASA Exploration Systems Mission Directorate (ESMD) at the December 2006 2nd Space Exploration Conference in Houston (Lavoie, 2006). It is the only set of mission profiles to date that addresses the Outpost Construction missions from 14 to 30 days. The 2008 Exploration Life Support Metric (Yeh, 2009) is the most recently published, and is consistent with the Exploration Conference for both Sortie and Outpost Occupancy missions.

Although the relationship between mission duration and volume is well-established in an empirical sense (Cohen, 2008), it has yet to be reflected in design concepts for the "extended duration" lunar landers shown in TABLE 1 or in the Lunar Surface Outpost. However, the designs of the lunar lander until now focus upon the transportation aspect of the mission requirements, while neither yet addressing the requirements for the crew to carry out the mission, nor the integration of the vehicle with the habitation systems for longer outpost missions.

TABLE 1. Pressurized volume in meters^3 for various recent Lunar Lander baseline concepts.

	2005 NASA ESAS LSAM	2006 NGC Constellation Lunar Lander RFI Response	2007 NASA Lander Development Analysis Concept (LDAC-1)	2008 NGC Altair Lander Development System Study (LLDS)
Ascent Module (AM)	10	8	10	8
Habitat Module (HM)	16	23.2	none	11***
Airlock (AL)	8*	10*	7.5 to 8**	8**
TOTAL Pressurized Volume	34	41.2	18	27

* Requirement for four crew members to transit the airlock at one time.

** Requirement for two crew members to transit the airlock at one time.

*** Habitat function combined with Ascent Module in one module.

TABLE 2. Candidate Lunar Exploration Mission Durations

Mission Type	2005 ALS Metric pp. 7- 42.	2005 ESAS pp. 200-209.	2nd Exploration Conference pp. 19, 34-41.	2006 ELS Metric, p. 40.	CxP-70007 Lunar DRM pp. 13-16.	2008A ELS Metric pp. 29-31.
CEV-Cislunar Transit	14 days	14 days	N/A	18 days	N/A	N/A
Lunar Sortie	6 days	7 days	N/A	5 days	7 days	N/A
Outpost Build-up, Years 1-2	N/A	N/A	7 days	N/A	N/A	N/A
Outpost Build-up, Year 3	N/A	N/A	14 days	N/A	N/A	N/A
Outpost Build-up, Years 4-5	N/A	N/A	30 days	N/A	N/A	N/A
Outpost Occupancy	98 days, "Destination Surface System"	6 months	6 months	181 days "Lunar Outpost"	N/A	3600 days
Maximum Surface Mission Duration	118 days	~194 days	> 6 months	204 days	210 days	180 days (no contingency)

LUNAR LANDER CONFIGURATION VOLUMETRICS

TABLE 1 shows the pressurized volume results from four baseline studies for the lunar lander. It explicates the designations of the modules and the allocation of functions and volumes to them for these four efforts:

- 2005 NASA ESAS LSAM
- 2006 Northrop Grumman RFI Response
- 2007 NASA LDAC-1 Lander
- 2008 Northrop Grumman LLDS concept.

2004-2005 CONCEPT EXPLORATION AND REFINEMENT STUDY

Soon after President Bush announced the Vision for Space Exploration (VSE) in February 2004, NASA solicited proposals and awarded 11 contracts for the Concept Exploration and Refinement Study (CE&R). While most of this study addressed the Crew Exploration Vehicle (CEV, later named Orion), part of it addressed the lunar lander that would become part of the Constellation Systems to carry out the VSE. The lander requirements in the CE&R were rather flexible, and did not afford a rigorous treatment of pressurized volumes for the crew.

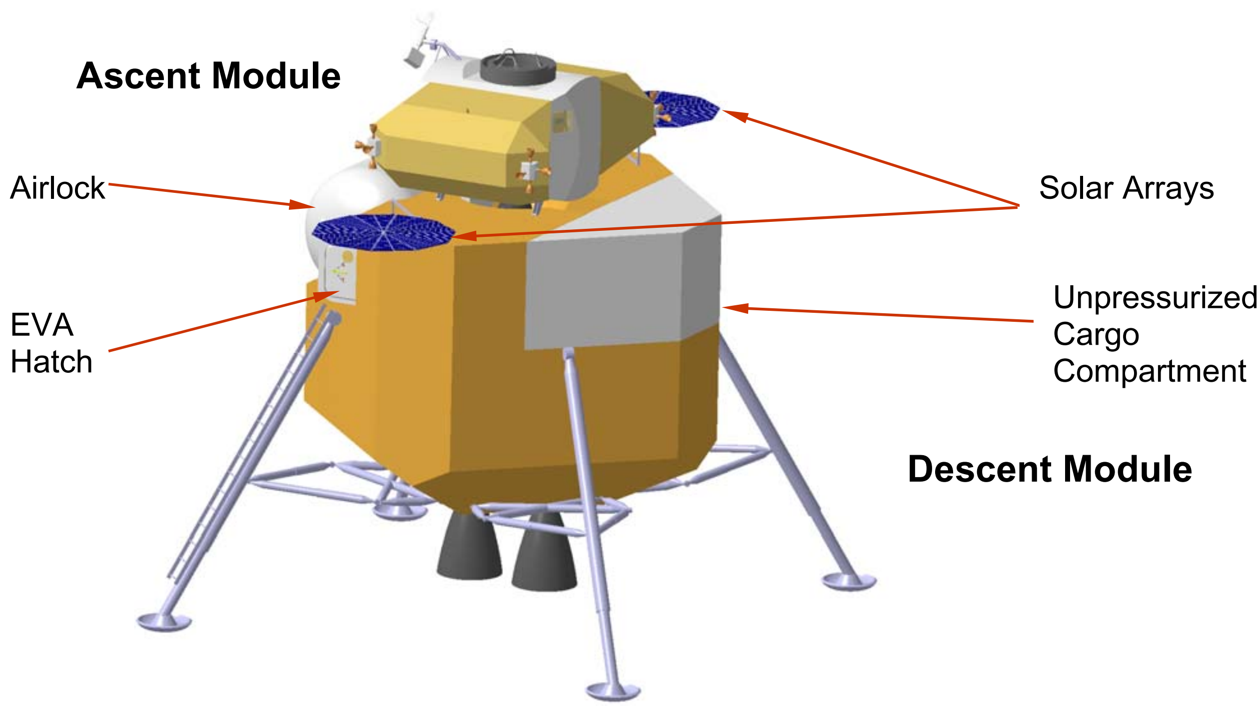


FIGURE 1. Northrop Grumman sketch of a lunar lander concept for the 2004-2005 CE&R study. Drawing credit: Bruce Rouleau.

In performing the CE&R study, Northrop Grumman began to address some of the broader configuration issues such as minimizing the distance the crew would need to climb for access to the lunar surface and accommodating cargo on the descent stage so that it too would be closer to the surface for easier unloading. FIGURE 1 shows one Northrop Grumman concept from the CE&R, with a split in the pressurized volumes between an Ascent stage and a separate EVA airlock that is part of the Descent module. A flexible tunnel would connect the Ascent Stage to the EVA Airlock.

2005 ESAS LUNAR SURFACE ACCESS MODULE CONCEPTS

NASA published its first family of concepts for the Lunar Surface Access Module (LSAM) in the Exploration System Architecture Study (ESAS) report. This chapter designated a fixed volume of 10 m^3 for the piloting and ascent function, 16 m^3 for the habitation function and 8 m^3 for the airlock. ESAS decomposed the problem of assigning these volumes to three configurations of pressurized volumes. These three configurations appear in FIGURES 2a, 2b, and 2c.

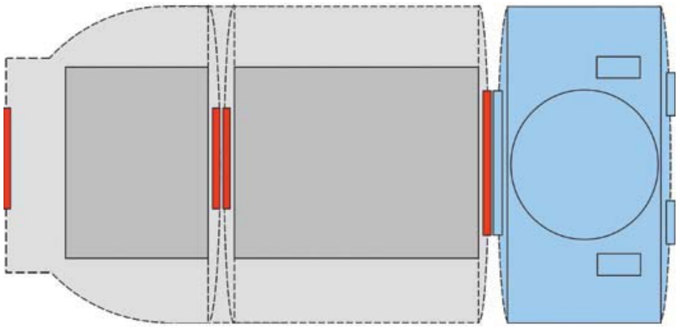


FIGURE 2a. NASA ESAS Concept A for the LSAM combined Airlock/Habitat Module on the left in grey and the separate Ascent Module on the right in blue, connected by the red tunnel.

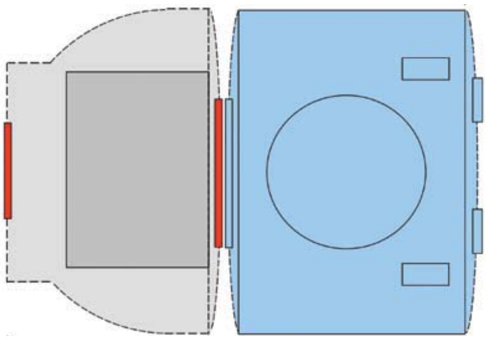


FIGURE 2b. NASA ESAS Concept B for the LSAM combined Ascent Module and Habitat Module on the right and the separate Airlock module on the left, connected by the red tunnel.

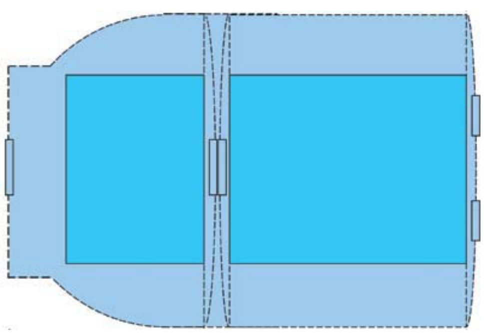


FIGURE 2c. NASA ESAS Concept C for the LSAM as an "all-in-one-module" combining Airlock, Ascent and Habitat Module; all three functions share a single outer envelope, although the Airlock and Ascent Module comprise separate pressure vessels.

The ESAS approach assumed that the functionality and volume to accommodate the crew and their mission would be exchangeable from one configuration to the next. Northrop Grumman's analysis indicates that both functionality and volumetric allocation must adapt and change in response to the ways in which the designers assign and configure the modules. As an etiological note, where the CE&R Study employed the Apollo Lunar Module nomenclature of Ascent Stage and Descent Stage, the ESAS used Ascent Module, Habitation Module, Descent Module and Airlock (module), making it linguistically possible to distinguish the piloting station from the living environment. FIGURE 3 shows an interpretation of the module configuration that represents ESAS Concept A (FIGURE 2a) as developed by NASA's in-house Lunar Architecture Team (LAT) atop a full lander configuration.

FIGURE 3. NASA Lunar Architecture Team LAT-1 concept for LSAM Concept A with combined Airlock and Habitat; it has a separate Ascent Module. Credit: NASA.

FIGURES 4 and 5 show the interior of the 2006 Ascent Module Mockup by Kriss Kennedy at NASA-JSC. This design exercise began during the ESAS deliberations using the same volumetric value of 10 m^3, but it is not constrained by the ESAS assumptions about geometry shown in FIGURE 2. Rather, the mockup in FIGURE 4 shows an effort to understand the architectural design problem of the lunar lander ascent stage on its own merits. FIGURE 4 shows two side-by-side pilot stations with different candidate window geometries and potential locations for controls and displays. While flying this lander, the two pilots would stand in front of the flight deck and the other two crewmembers would stand behind them. One notable feature is the shallow ledge below the window that could accommodate switches, other controls, or small displays. The two hand controllers (joysticks) appear both in the right hand position in front of each window.

FIGURE 5 shows a detail of the interior, including the protrusion of the engine head cover rising through the floor deck. Behind the engine cover is the EVA hatch, about the same size and in roughly the same position relative to the floor as the Apollo LM EVA hatch. The main difference is that the LM EVA hatch was on the front side of the LM, below the two windows whereas Kennedy's is opposite the windows and control consoles.

FIGURE 4. Interior of 2005 Ascent Module Mockup by Kriss Kennedy at NASA-JSC. Photo credit: author, December 2006.

FIGURE 5. Detail of the Interior of the Ascent Module, 2006, showing the EVA hatch in approximately the same position as on the Apollo LM, behind the top of the ascent engine head shell. Photo credit: author, December 2006.

2006 CONSTELLATION LUNAR LANDER RFI

In May 2006, NASA released the Lunar Lander Concept Requirements Description Request for Information, better known as the Constellation Lunar Lander (CLL) RFI. The RFI defined several "concept study products," of which the two most relevant to crew habitation and operations were:

- Innovative lander design concepts
- Concepts for integration of the lander and surface systems, e.g., deployment of surface outpost habitation

The goal of integrating the lander with an outpost led the Northrop Grumman team to identify functional allocations that would serve not only the primary flight and landing function of the CLL, but also its continued life as part of the lunar surface infrastructure. In formulating these concept study products, the RFI stated these "fixed requirements:"

- Dual Rendezvous mission mode, Earth Orbit Rendezvous plus Lunar Orbit Rendezvous (EOR+LOR).
- Cargo Launch Vehicle (CaLV) Trans-Lunar Injection (TLI) capability from 296 km (160 nmi) circular (assuming 20 mT CEV at TLI) for the payloads and shroud diameters shown in TABLE 3.
- Cargo mission (single launch) TLI mass: 53.6 mT.
- Low-Impact Docking System (LIDS).

- LSAM performs attitude control and Trajectory Correction Maneuvers) TCMs during trans-lunar coast.
- LSAM performs lunar orbit insertion, deorbit, powered descent, hazard avoidance, terminal landing, ascent, and rendezvous.
- CEV remains in 100 km (54 nmi) circular Low Lunar Orbit (LLO).
- 4 crew members for lunar missions
- 500 kg minimum science/technology down payload to lunar surface
- 100 kg minimum up payload return from lunar surface to Earth
- Surface airlock [The RFI requirements called for four crewmembers to transit the airlock at the same time].

The 2006 RFI also stated these “desirements:”

- Common systems with CEV
- 2200 kg of additional landed cargo payload on crew flights
- Leaving hardware behind that can be used for incremental Outpost buildup
- Capable of reuse or evolving to reusability
- Unpressurized cargo stowage volume
- Ease of surface access for crew and cargo
- Extensibility to a dedicated cargo lander

The *desirement* for commonality with a dedicated cargo lander gave the lunar lander an aspect of being a robot that can also carry people. From this robot cargo lander, the “derived desirement” for autonomous landing and hazard avoidance suggests that the lander can perform its mission without intervention by the crew. Unfortunately, this construct can lead to overlooking the importance of excellent human system integration for the crew to pilot the lander and to explore from it on the surface. On the contrary, the plan for an autonomous cargo robot vehicle does not reduce the imperative to design a crewed flight vehicle that accommodates the pilot’s requirements to see ahead where he or she is flying, to provide the best flight handling qualities, and to make a safe piloted landing. This crew productivity question is pivotal for the pilot’s performance and the overall safety of the crew and the success of the mission.

The 2006 RFI also provided the values in TABLE 3 to show the relationship between launch vehicle shroud diameter and mass. During the 2006 RFI period of performance, the Northrop Grumman team found that the 8.4 m exterior diameter shroud was sufficient to accommodate the lunar lander concepts. As the shroud diameter increases, so does the mass. The trade implicit in this table is that by making the lander descent module wider, it may be possible to lower the center of gravity and the top deck height.

The down mass payload of 500 kg and the up mass payload of 100 kg are key attributes of the Altair’s capabilities. These payload figures have stayed in the Altair requirement since first promulgated in May, 2006, so they appear to be stable and well-established within the Altair mission architecture. The *desirement* for 2200 kg in additional down payload remains a greater challenge. TABLE 4 compares these Altair values to their counterparts on the Apollo LM. These Altair payload masses are subject to two questions.

TABLE 3. Lunar Lander Shroud Diameter and Net Lander Payload to Trans Lunar Injection (TLI) from NASA’s 2006 Lunar Lander RFI.

Shroud Exterior Diameter (m)	Shroud Interior “Working Diameter” (m)	Net Lander Payload to TLI (mT)
8.4	7.5	45.0
10.0	8.8	40.7
12.0	10.3	38.0

<u>500 kg Down Payload Mass</u> -- The first question concerns whether this down payload is pressurized or unpressurized. NASA’s statements of vehicle level requirements so far have been silent on this matter. If the design of the Altair flight regime must include an abort during descent that carries 500 kg in pressurized payload, then all the other numbers should reflect it. For example, where in the vehicle would it be possible to stow so much pressurized mass? Given the rules of thumb that pressurized equipment in a spacecraft weighs on the order of 100 to 200 kg per cubic meter, then this 500 kg pressurized cargo would take in the range of 2.5 to 5 m^3 of precious cabin volume.

<u>100 Kg Up Payload Mass</u> -- The second question is what are the implications of the 100kg up payload? TABLE 4 shows that it is less than the return mass in the Apollo LM missions, especially if one includes the sample boxes and the EVA suits with Portable Life Support System back packs. The Constellation Program plans two editions of a new space suit. *Configuration 1* is a lightweight space and flight suit attached to life support by an umbilical to the Orion or Altair life support system. This suit is known also as the Flight Operations (FO) or Launch, Entry, and Ascent (LEA) suit. *Configuration 2* is a space suit arranged to carry its own life support system as a PLSS, but that can also plug into Altair life support via an umbilical. This suit is known also as the Lunar Surface Operations (LSO) suit. *Configuration 2* suits will serve for the surface EVAs.

On the Sortie Altair (but not the Outpost Altair), it will be possible to leave behind the *Configuration 2* suit PLSS backpacks, but not the suits themselves – unless the crew wears an entirely separate and distinct light weight flight suit. The overall EVA suit plan is expected to emerge from Oceaneering International, Inc's contract to develop and produce the Configuration 1 and 2 space suits for NASA (Reuters, Feb 27, 2009).

Insofar as the up payload limitation for returning lunar samples to earth affects the science crew's ability to perform productive and meaningful science, it means they will need to become much more selective about the lunar samples they bring back. In this way, the availability or limitations of up payload mass can affect the crews' surface scientific exploration mission and their productivity. To implement this selectivity, the crew will require scientific instruments and facilities to conduct real time analysis on the surface and in the lander itself. These instruments might fly as part of the pressurized portion of the 500 kg down payload.

2006 CONSTELLATION LUNAR LANDER RFI CONCEPTS

TABLE 1 shows the volumetric values that Northrop Grumman recommended in the RFI response. A careful analysis of the Ascent Module showed that as a "minimal Ascent Stage" without any habitation functions beyond life support for the crew while flying to land and to ascend, it would be feasible to reduce the AM volume from 10 to 8 m^3. Conversely, Northrop Grumman's analysis of the EVA airlock showed that to meet the requirement that four crewmembers transit the EVA Airlock simultaneously, it would be necessary to increase the Airlock volume from 8 to 10 m^3. These changes somewhat neutralize each other, but before long, NASA reduced the requirement for four crew doing a simultaneous egress and ingress to two crewmembers.

The Habitation volume was a different story. Taking the NASA objectives to support crew productivity and effectiveness on the lunar surface as suggested in the Constellation Human System Integration Requirements, Northrop Grumman found it necessary to increase the pressurized volume in both the 2006 RFI and the 2008 LLDS submissions. Northrop Grumman sees good habitability and human factors design as a critical facilitator of crew productivity. The Northrop Grumman analysis, (using our Crew Accommodations Tool) yielded a pressurized habitation volume of 23.2 m^3; making a 50 percent increase over the ESAS baseline of 16 m^3. The reason for this increase in volume was to accommodate fully the recommended crew living and working environment in the lander.

FIGURE 6 shows a range of concepts from the Northrop Grumman 2006 RFI submission. The Northrop Grumman approach was to expand the inquiry by design to the limits of the "design envelope." For each concept, the RFI response studied the lander and its pressurized modules, its propulsive staging, and how to stage it within the shroud of the Ares V rocket. In all cases, the Ascent Module reflected the ESAS Concept A.

The 2006 RFI submission made a distinction between two constructs for the descent propulsion system. These two constructs were conventional staging at the lunar surface between the descent and ascent stages as in Apollo and the drop-stage approach in which a separate Lunar Orbit Insertion stage performs the LOI burn and initial descent burn.

<u>Mission Durations And Scenarios</u> – TABLE 4 presents a comparison of Apollo LM and Altair mission durations and associated properties. The crewed mission durations for Altair and the volumetric design for crew accommodations align only for the one week mission. For missions longer than one week, the crew will probably require a supplemental cargo of supplies and consumables possibly including an additional pressurized module. The values in TABLE 4 suggest that for the Outpost Construction missions of 14 and 28 days (NASA, Dec. 2006), a cargo lander must first deliver an additional payload where the crew can live. Current planning includes a pair of the Small Pressurized Rovers initially, and later the "cargo habitat" that becomes a building block of the Outpost.

TABLE 4. Comparison of Apollo LM to Altair Crew Operations Parameters.

Criteria	Apollo 17 Lunar Module (NASM, 2009)	Altair Lunar Lander (NGC LLDS, 2009)
Number of crew on the lunar surface	2	4
Mission duration on the lunar surface	3 days	7 days
Down payload mass	309 kg scientific & comm equipment	500 kg unspecified
Up payload mass	110 kg samples + 110 kg PLSSs = 220 kg	100 kg of Samples
Highest number of buddy pair EVAs	3	6
Typical EVA time	7 hours	8 hours
Total buddy pair EVA time (x2 crew)	22 hours	48 hours

Similarly, for an "extended Global Access" ("go-anywhere, return anytime") mission with a planned surface stay beyond the designed mission duration of the Altair, the mission might require a second lander or delivery of two small pressurized rovers. This provision is a current NASA mission architecture option to meet the global access requirement. However, it is not yet clear which exploration partner will provide this equipment or its delivery -- commercial, international, or NASA.

In FIGURE 6, *Concepts 1 through 3* represent the conventionally "surface-staged" approach in which the Descent Module performs the Lunar Orbit Insertion burn, the descent initiation burn, and all the other propulsive maneuvers on the trajectory to the surface. There, the vehicle is "surface staged" when the crew launch in the Ascent Module, leaving behind the Descent Module with its habitat and Airlock.

Concepts 4 though 6 employ the Lunar Orbit Insertion and Descent Stage (LOIDS) that appears in the packaging drawings as the large orange stage (with the arrow pointing to it) within the Ares V shroud, below the lander. This stage performs the LOI burn, initiates the descent, and then separates from the lander, which performs the terminal descent and landing maneuvers with its own fuel tanks and engines.

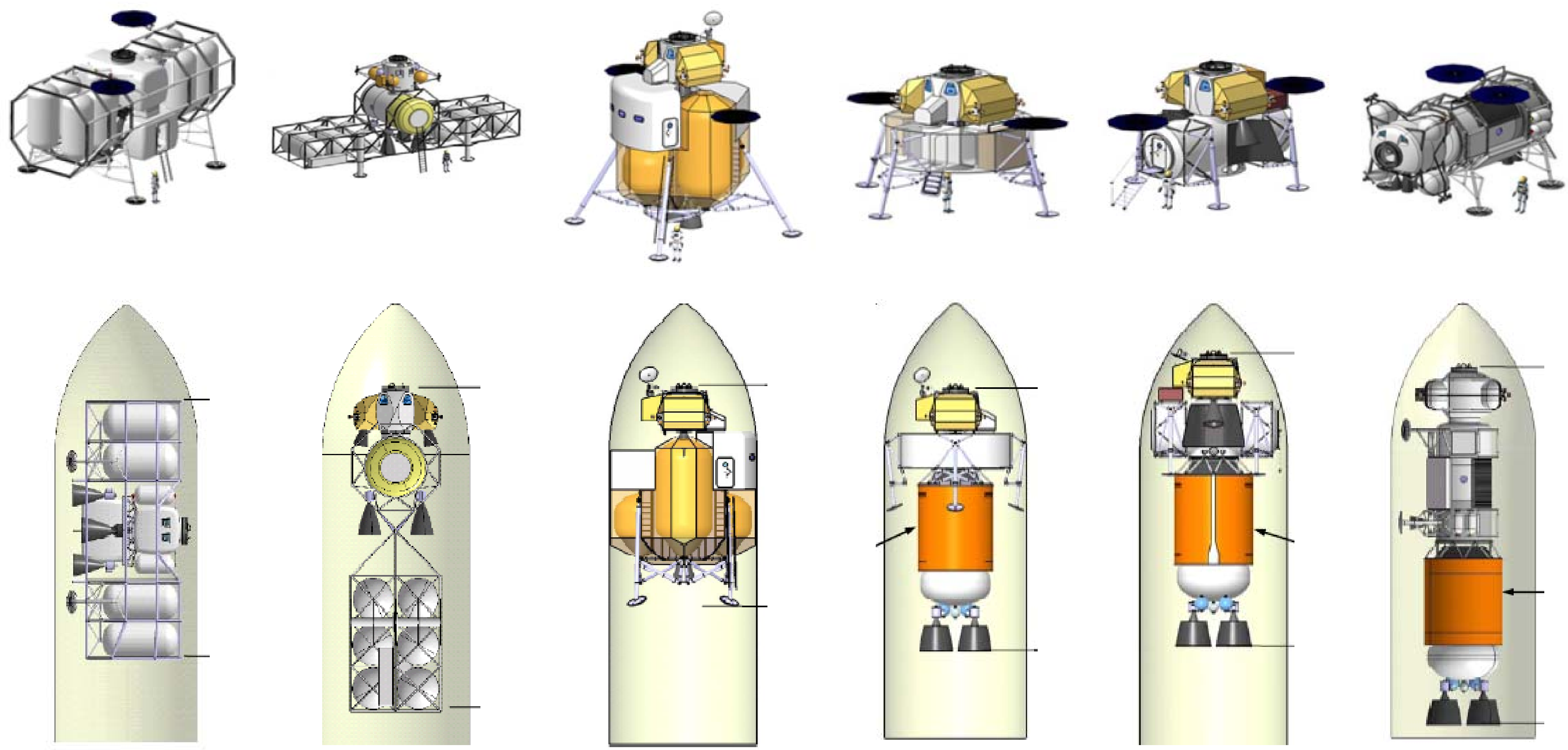
<u>Concept 1. Surface-Staged Drop Tanks</u> features a semi-cubic ascent module atop a semi-cubic descent habitat and airlock. A vertical hatch or tunnel connects the two pressurized modules. The unique feature of this concept is the *drop tanks*, which provide fuel for the LOI and initial descent burns, then separate from the Altair to reduce the final landing burden. This design aids crew productivity by shortening the access from the Airlock to the surface to virtually the minimum possible. It also affords an almost completely unobstructed pilot view angle from the AM over the long side of the DM below.

<u>Concept 2. Surface-Staged Deployed (Tanks and Descent Engines)</u> features a vertical cylindrical Ascent Module atop the center of a long horizontal Habitat and Airlock on the Descent Module. The Ascent Module would connect to the Habitat through a vertical tunnel. The unique feature of this concept is the way the "wings" fold up inside the Ares V shroud to form a compact payload that could fly within a shroud diameter as small as 7m, thereby potentially affording a substantial saving in mass to Low Earth Orbit (LEO) and throughout the mission architecture. This design also puts the Airlock close to the surface, although perhaps not as close as Concept 1. It combines the Airlock and habitation cabin into the same module as in the ESAS Concept A, which may enhance crew productivity insofar as it is not necessary for the crew to pass through a tunnel from one to the other.

<u>Concept 3. Surface-Staged "ESAS-Type"</u> features an "ESAS-Type" arrangement of its propulsion system in terms of the descent and ascent engines and propellant tankage. The Ascent Module sits on center of the vertical thrust axis, with the Habitat Module and Airlock below, off-center. Opposite this off-center pressurized section was the unpressurized cargo section, resembling the CE&R concept in FIGURE 1. The Ascent Module connected to the Habitat through the white protruding "nose tunnel" that secured to a hatch in the top of the Habitat. Sadly, the position and shape of the Habitat Module partially obstructs the pilot's sight line to the surface. However, if the designers turn the AM 180 degrees in plan so that it looks out over the lower unpressurized payload compartment, that might improve the view angle.

<u>Concept 4. LOIDS + Single Stage Toroidal</u> uses the LOIDS drop stage, so it stages during descent. It employs essentially the same Ascent Module as Concept 3, but the Descent Module is different. It contains a unique toroidal-shaped habitation zone. The Habitat, Airlock, and unpressurized cargo are all sandwiched between the upper and lower decks as part of this toroidal envelope. The AM engine fires through the center opening of the toroid, serving as a single stage both for descent to the surface and ascent from the surface. In this design, the AM sits closest to the surface except perhaps for Concept 6. It also enjoys a relatively unobstructed pilot site line.

<u>Concept 5. LOIDS + Single Stage Bottom Cargo</u> employs the LOIDS for descent staging. Its AM is a variant of the Concepts 3 and 4 design, except that the vertical connection is right below it so it does not need the "nose tunnel." As in Concept 4, the AM provides both the terminal descent and landing propulsion and launch propulsion, except that it has two engines offset to the sides of the Descent Module Habitat. The unique feature of this configuration is the provision of an unpressurized cargo compartment at the bottom of the lander structure. Otherwise, this Habitat and Airlock configuration of a long horizontal cylinder is similar to its counterpart in Concept 2. This design aligns the pilot station/flight deck to the long axis of the Hab Module/Airlock below. Regrettably, this alignment creates the maximum interference with the pilot sightline. However, if the designers rotate the AM 90 degrees so that it looks "over the side" of the cylinder, it will greatly improve the pilot's view angle, assuming that the vehicle can fly and land on that vector.



Concept 1. Surface-Staged Drop Tanks

Concept 2. Surface-Staged Deployed (Tanks and Descent Engines)

Concept 3. Surface-Staged “ESAS-Type”

Concept 4. LOIDS + Single Stage Toroidal

Concept 5. LOIDS + Single Stage Bottom Cargo

Concept 6. LOIDS + 2 Stage (3 Stage Vehicle)

FIGURE 6. The six Northrop Grumman 2006 Constellation Lunar Lander RFI concept(s).

Drawing Credits: Concepts 1 and 2 drawn by Rush Wofford; Concepts 3-6 drawn by Bruce Rouleau.

Concept 6. LOIDS + 2 Stage (3 Stage Vehicle) uses the LOIDS and the DM for descent staging and the AM for surface-staging. It takes the long horizontal cylinder concept one step farther; it puts the Ascent Module – a shallow cylinder on edge -- in line with the Habitat and Airlock cylinder, in a manner similar to the LAT-1 configuration shown in FIGURE 3. The difference is that the modules in this concept lie much closer to the surface upon landing. This concept is notated as the LOIDS + 2 or because in addition to the LOIDS, it has both the separate Descent and Ascent Modules as stages.

The Concept 6 design places the AM closest to the surface of any of the six concepts. The pilot's view angle is completely clear and unobstructed except by the limitations of the front windows themselves. This design raises a different question, which is that the launch on descent and launch from surface vector is far-removed from the conventional plus-nadir thrust axis through the center of the Descent Module. In fact, the launch from surface vector is turned 90 degrees from the thrust vector in the Ares V fairing, so the guidance and navigation systems and the flight deck will need to be able to handle the spacecraft in two completely different orientations.

2007 LUNAR DEVELOPMENT ANALYSIS CYCLE ONE

The Lunar Development Analysis Cycle One (LDAC-1) was an in-house exercise in which NASA implemented a radical new paradigm of design for spacecraft known as "minimum functionality." In the minimum functionality approach, the writers of requirements and the designers and engineers attempt to determine what would be the "single string" minimum configuration necessary to perform the mission successfully without having to make provisions for failures or other "contingencies." The reason for this minimum functionality methodology was so that NASA could design the spacecraft "from the bottom up," so as to understand why every component, subsystem, and system is there, why there are a specific number of these parts, and how they work together.

The background to this minimum functionality initiative was the perception within NASA that the traditional design and system engineering approach made human spacecraft too costly. Subsequently, in the Feb. 11, 2008 Lunar Lander Development Study BAA, NASA articulated the Lunar Lander Project Office's (LLPO) minimum functionality philosophy and strategy they began pursuing a year earlier for LDAC-1:

> The LLPO's first design analysis cycle (LDAC-1) for the Lander was based on a minimum set of requirements, three design reference missions, and the concepts of *minimum functionality* and *minimum implementation*. This initial design is not intended to be a flyable vehicle. This design is intended to provide as close to a minimum configuration as reasonable to evaluate in order to conclusively buy down risk through a deliberate "add back" process. Minimum functionality means that the LDAC-1 Lander design does not incorporate any additional capabilities beyond those required to perform the reference missions. Additionally, the LDAC-1 Lander design does not protect for contingency situations (except delays as specified in the mission timeline). Minimum implementation means a 'minimum mass' design that does not incorporate redundant strings to protect for system failures. . . .
>
> These safety and reliability improvements / upgrades / design changes shall be based on an integrated safety and design analysis of the minimum functional vehicle. Safety and reliability changes should be implemented with the intent of minimizing mass additions to the system. The Lander office recognizes that optimal solutions may deviate from the currently recognized safety posture of the agency. ***These solutions are encouraged to foster a paradigm shift from the typical blanketing of redundancy / increased fault.*** [emphasis added] (NASA, Feb. 11, 2008, pp. 4-6)

This "blanketing" consisted of entitlements to the various technical disciplines concerned with safety and mission assurance. These entitlements included multiple backups, redundancies, and other unexamined assumptions about what a human spacecraft design needs. The perception was that once the designers satisfied the blanketing of all these *a priori* assumptions of requirements, there might be precious little budget or mass remaining to build the spacecraft or perform the mission.

Minimum Functionality seeks a fresh start to the design of the lunar lander. The advocates of any redundancy or backup must argue for it and justify why it should be included and document the calculated increase in safety, reliability, and probability of mission success. The concern that the minimum functionality approach raised for the Northrop Grumman team was how it would affect crew productivity – whether in fact the crew could perform their mission in this extremely tight package.

In concert with the release of the LDAC-1 exercise in December 2007, NASA named the lander ***Altair,*** the first name for a NASA program that was not of Greco-Roman origin. Altair is Arabic for the brightest star in the constellation Aquilla (also known as Alpha Aquillae), and serves as one of the vertices of the Southern Triangle.

FIGURE 7 shows the LDAC-1 minimum functionality concept for Altair. TABLE 1 shows the truly *minimal* as in *austere* volumetric values for LDAC-1. The Ascent Module in which the crew will live and work for seven days is 10 m^3 and the Airlock remains at 8 m^3. This rendering, with the blue struts supporting the airlock, suggests the question: where do the crew place their feet when stepping out of the Airlock hatch? The presence or absence of an EVA "front porch" is fundamental for surface EVA productivity and safety. The design space includes whether to provide a complete walkable deck on the top of the Descent Module or a "front porch" as a transition between the Airlock hatch and the ladder down to the lunar surface.

Another challenge that this design has yet to address is the pilot's line of sight to the lunar surface for final descent and landing. Providing an effective line of sight for the pilot should be one of the highest design priorities for Altair; indeed it is a design imperative that affects the design of both the Ascent Module itself and the configuration of modules upon the Descent Module deck. One unfortunate side-effect of the minimal functionality strategy was to make the pressurized modules so small that the LDAC-1 scheme of placing it on the vertical axis of the Descent Module impairs the pilot's view to the surface. The edge of the LDAC-1 Descent Module top deck will at least partially obstruct the view angle to where the pilot wants to set down the lander.

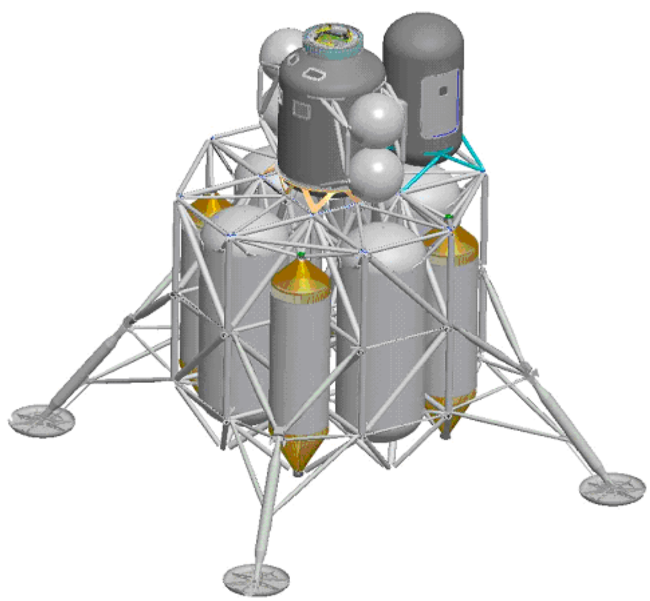


FIGURE 7. December 2007 NASA LDAC-1 Minimum Functionality concept for the Altair with a 10 m^3 Ascent Module and 8 m^3 Airlock; the EVA surface access ladder and top deck on the Descent Module do not appear in this view.

The rationale for this alignment is to achieve cleaner load paths and a better mass properties balance. However, Northrop Grumman's analysis showed that it is more important to arrange the modules and masses as symmetrically as possible about the common thrust axis than to place it right on that axis. Northrop Grumman pursued this solution for the pilot station/flight deck in the LLDS contract and implemented a leading-edge pilot station with a superior view angle.

FIGURE 8 shows a scale model of the LDAC-2 configuration. The scale model shows more features such as the cold nitrogen thrusters extending from the Ascent Module and the Descent Module. The engine model on the table top to the left represents the Ascent engine that would attach to the underside of the Ascent module, with the head protruding into the crew cabin, creating a dome in the floor as shown in FIGURE 5.

FIGURE 9 shows the full scale mockup of the LDAC-2 Altair in "Hangar X," Building 220 at Johnson Space Center. This mockup presents the two pressurized volumes of the Ascent Module and the Airlock, connected by a tunnel with a cross-section that is a rectangle with rounded corners. The design of this mockup system is intended to allow rapid and easy reconfiguration of the light weight mockups that are actually suspended from the framework above. This reconfiguration centers upon varying the diameter and the outfitting of equipment mocked up in foam core. The square EVA hatch in the Airlock appears to be about the size of the standard 1.25m square International Space Station (ISS) hatch, with 25 cm radius corners. The frusto-conical form at the top of the Ascent Module represents the mounting for the Low Impact Docking System (LIDS) mechanism and hatch.

FIGURE 10 shows a detail of the flight deck in the Ascent Module. In this design, there appear two windows, each of which could accommodate a pilot station, but instead there is a single flat panel display between the two potential crew stations. The hand controller under the right window (left side) indicates where a pilot's controls might be mounted. The keyboard would serve the crew to access the computer, but likely not to fly the Altair.

As part of the 2007 Lunar Development and Analysis Cycles, Litaker, Thompson, and Howard (Feb 8, 2008) performed a detailed analysis of an Altair mockup that incorporated the Ascent Module and the Airlock in the "DAC-1 Delta" configuration. The foam core construction and size of the AM was similar to FIGURES 4 and 5. The AM was approximately 9.36 m^3 and the Airlock was approximately 6.12 m^3 (Litaker, Thompson, Howard, p. 7) in essentially the LDAC-2 configuration, of which the DAC-1 Delta appears to represent the smaller possible diameters. These DAC-1 Delta pressurized volumes were 93.6 percent the size of the original LDAC-1 AM and 76.5 percent the size of the original LDAC-1 Airlock. This evaluation involved four crew team arrangements: four crewmembers space-suited, four crewmembers unsuited, two crewmembers space-suited, and two crewmembers unsuited. Litaker, Thompson, and Howard's key findings regarding habitable and usable volume in the DAC-1 Delta configuration were (pp. 25-26) were:

> <u>When Using a Crew of Four or Two Suited Participants</u> --
>
> > Emergency task, suit removal of an incapacitated crewmember, and emergency translation through the airlock was not acceptable due to the fact there was not enough habitable volume to conduct these activities. Removal of EVA equipment and limited floor space were major factors thus indicating a need to increase the habitable volume of the lunar sortie habitat.
>
> Donning/Doffing PLSSs in the confined volume resulted in high controllability and discomfort ratings especially in the shoulder and waist areas. Participants could barely turn around while assisting others with donning their PLSS. Range of motion for any functional EVA operations is unacceptable. Ratings and comments indicate habitable volume for any EVA activity needs to be increased.
>
> Suited participants indicated the current volumetric configuration of the lunar sortie habitat was unacceptable.
>
> <u>When Using a Crew of Four or Two Unsuited Participants</u> --
>
> Volume was enough to hold four people but not to adequately perform tasks especially ones involving bunk setup, suit maintenance on the floor, conducting maintenance on suit when using wall support to hold back of suit, and simultaneous mission activities.
>
> Functionality of the habitable volume, which was deemed unacceptable was volume for donning/doffing EVA suits, crew privacy, access to hygiene area and WCS, crew workstation areas, access to and from the CEV, internal translation areas, translation areas for emergency ingress/egress or assisted of an incapacitated crew member, operational contingencies, cross-contamination prevention and separation, and number of windows to support normal operations.
>
> Controllability performance decreased when participants exercised, conducted suit maintenance and attempted CPR on a crewmember. For exercise, participants noted lower body activities were questionable due to space limitations. . . . CPR was very difficult to perform due to limited floor space, moving equipment, and awkward positioning made performing this task near impossible.

It was very much with the results of this evaluation in mind -- the findings of inadequate volume and their multiple negative impacts upon crew productivity -- that the Northrop Grumman Human System Integration Team prepared for the 2008 Lunar Lander Development Study.

2008 LUNAR LANDER DEVELOPMENT STUDY

In March 2008, NASA awarded five contracts for the Lunar Lander Development Study (LLDS). The purpose of this study was for the offerors in the aerospace industry to provide analysis and feedback to NASA on the LDAC-1 *Minimum Functionality* exercise. The focus of the LLDS was upon the Sortie lander that would be capable of flying to the "go anywhere" global access sites of scientific interest. The programmatic assumption was that the crewed Sortie Altair would supply the transportation and basic living environment for the crew for up to seven days on the lunar surface. For an "extended" global access mission that exceeds that mission period, there are two possibilities. First, the 500 kg of down payload mass might supplement the supplies and consumables that the Altair carries to support the crew. Second, a Cargo version of the Altair might precede the crew to the landing site to deliver two Small Pressurized Rovers in which they could live and explore the vicinity.

In performing the LLDS, Northrop Grumman's work consisted of three parts:

<u>1. Minimum Functionality</u> -- Is the LDAC-1 truly "minimal" as a "single string" design; is there any way to reduce or simplify it further? Conversely, was the LDAC-1 complete and sufficient as a single string approach? Was anything missing?

<u>2. Evolvable Baseline</u> – What does NASA need to change or add to LDAC-1 to make it possible to prepare to handle real mission contingencies, errors, failures, etc? Developing the evolvable baseline involved changes that did not affect mass or size significantly, such as repositioning equipment or reallocating some functions among the Ascent Module, Airlock, and Descent Module.

<u>3. Safety-Enhanced</u> – What simple changes to the LDAC-1 design and equipment will improve the Probability of Loss of Crew (PLOC) and the Probability of Loss of Mission (PLOM). The typical solutions involved providing redundancy to the original "single string" baseline, principally doubling up on high failure rate or high duty-cycle items.

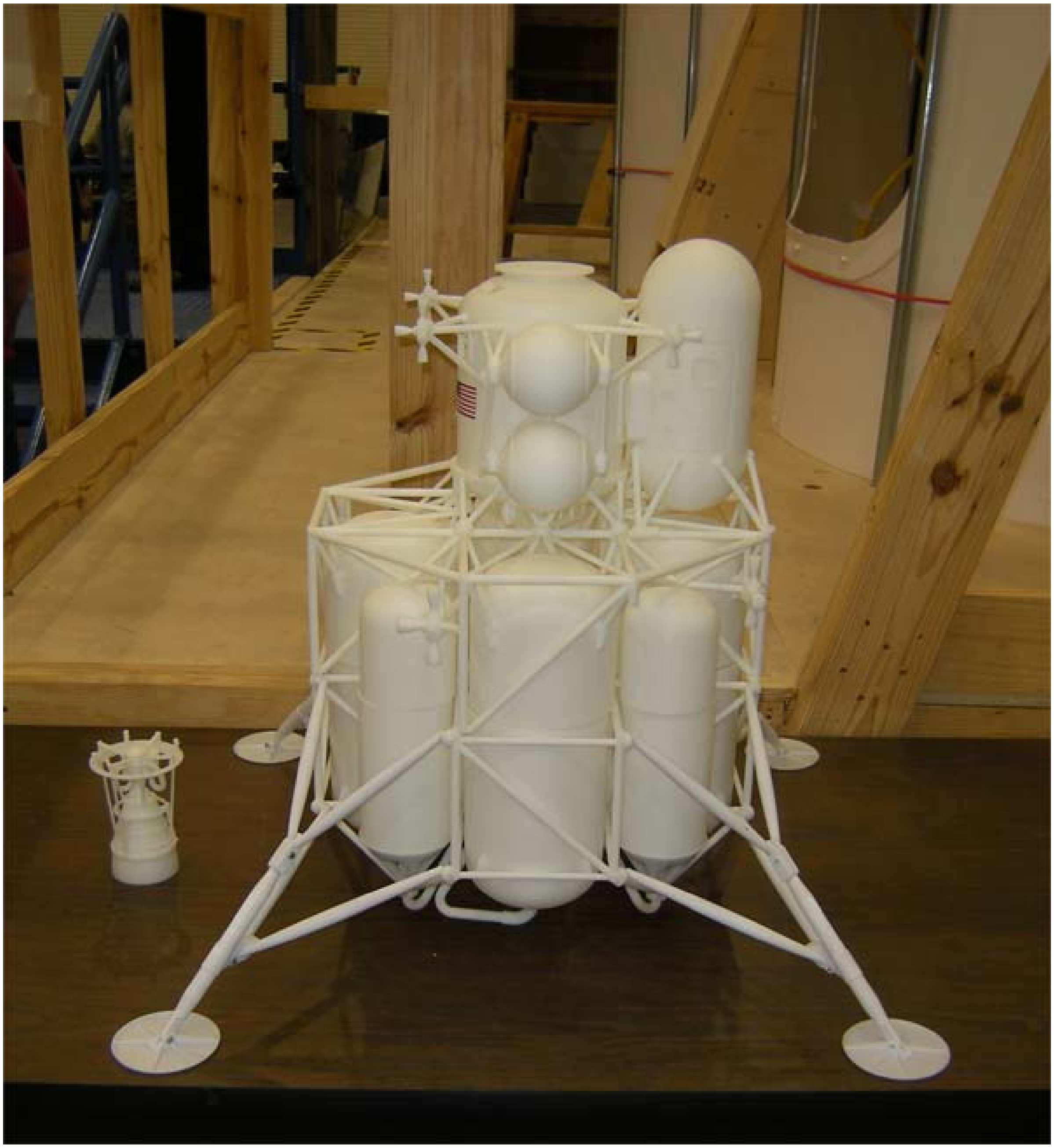


FIGURE 8. Scale Model of the LDAC-1 Altair at Johnson Space Center in front of the full scale LDAC-1 mockup; the Ascent Module is on the vertical centerline and the Airlock is to the right, connected by a tunnel of rectangular cross-section. Ascent Module Engine appears to the left. Photo credit: author.

FIGURE 9. Altair LDAC-1 Mockup at JSC; design project by Robert Howard, Habitability Group Lead; the Ascent Module appears on the left and the EVA airlock on the right. Photo credit: author, 18 NOV 2008;

FIGURE 10. LDAC-1 Altair Mockup Ascent Module Flight Deck at JSC. Photo credit: author.

While some of the engineering systems such as propulsion, power, and life support required complex and sophisticated analyses – especially for part *3 Safety-Enhanced,* the pressurized volume for crew accommodations was more straight-forward. In response to *Minimum Functionality*, the Northrop Grumman analysis indicated that 10 m^3 for the Ascent Module and Habitation functions was too small to support four crewmembers for the duration of the mission. On a go-anywhere/global access mission, the crew would spend up to seven days "loitering" in LLO – with or without Orion -- before initiating descent. They would spend seven days on the surface. Then, they could spend up to six or seven days back in LLO waiting for the correct TEI opportunity.

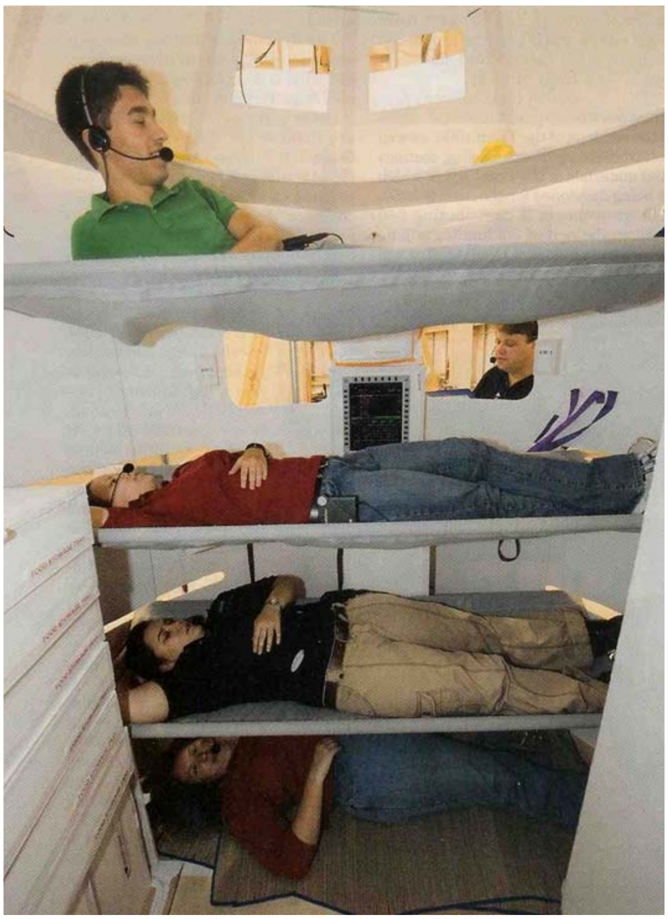


FIGURE 11. Concept for sleep accommodations for four crew members in the LDAC-1 Ascent Module. Photo Credit: NASA.

FIGURE 12 shows the Northrop Grumman final design concept for the Lunar Lander Development Study. This version incorporates the results of all three phases of the LLDS Study as it embodies the *Safety-Enhanced* outcome. This design for Altair addresses several of the key design challenges. It reduces the overall height and mass of the lander by employing toroidal tanks for liquid hydrogen and liquid oxygen. Our mass-balance analysis indicated that so long as the LIDS hatch can align on the thrust vector, it is more important for the module and payload configuration to cluster symmetrically in balance around the thrust vector than to pack tightly on the vertical axis of the Descent Module.

FIGURE 13 shows an interior view of Northrop Grumman's Ascent/Habitat Module for LLDS. In this view, the pressure vessel wall is rendered transparent to reveal the crew sleeping arrangements when the bunks are deployed. The Altair accommodates four crew members to sleep at the same time. The forward end of the module is looking away from the reader. The pilot station and windows appear on the far end dome in this view. There is a dense packaging of equipment in this near end dome for life support, thermal, power, and other systems.

SUMMARY: FUNCTIONAL ALLOCATIONS OF VOLUME

FIGURE 14, the histogram of pressurized volume for the lander configurations, shows how the allocation of volume changes from one lunar lander concept to the next. This analysis served as a point of departure for the Northrop Grumman concept for LLDS. The major portions of this column chart include:

<u>Architectural Volume</u> -- The architectural volume consists of the circulation space, human range of motion, ergonomic reach envelopes and anthropometric clearances. For equipment, the architectural volume provides deployment room for many stowed items and swing-out or tear-down space for maintenance. This volume addresses some of the negative findings that Litaker, Thompson, and Howard reported, particularly for "shirtsleeve" (unsuited) activities; it constitutes a specifically targeted increase from the 2005 ESAS to the 2006 Northrop Grumman RFI and from the 2007 LDAC-1 to the 2008 Northrop Grumman's LLDS.

<u>Internal (Secondary) Structure</u> – The internal structure in the modules includes floor decks and their framework, plenums, stand-offs and brackets to mount equipment, including the life support system ducts and piping.

<u>Crew Health Care</u> – The health care volume includes at a minimum the medical kit and supplies. As Litaker, Thompson, and Howard found, there needs to be sufficient space for the crew to take care of an incapacitated crew member, which may mean deploying supplies such as medical oxygen or traction from the crew health care stowage volume to an area where the patient can lie down.

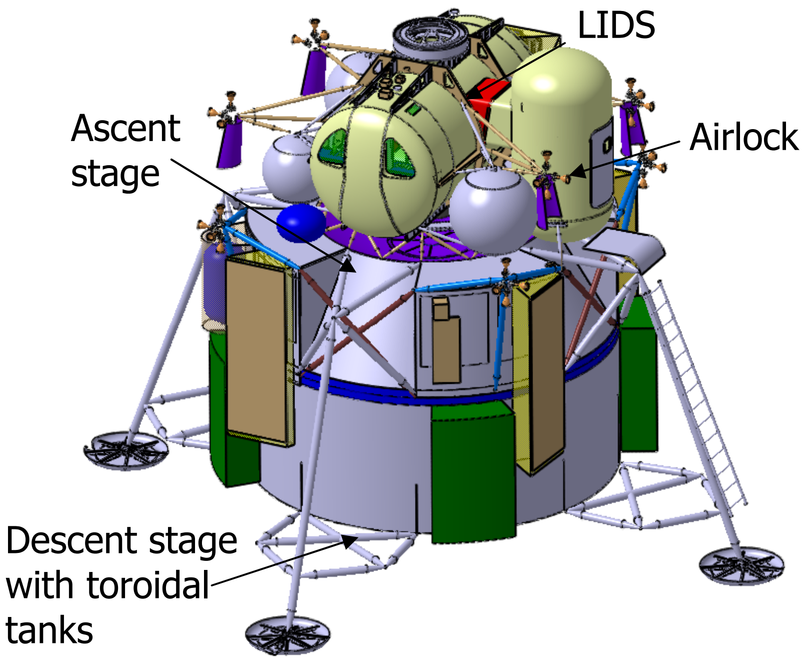


FIGURE12. Northrop Grumman concept for the Lunar Lander Development Study, October, 2008, with a combined Ascent Module/Habitat and separate airlock. The pilot station windows have a clear view angle to the surface on the plus velocity vector. Drawing credit: Syed Abid Ali-Khan

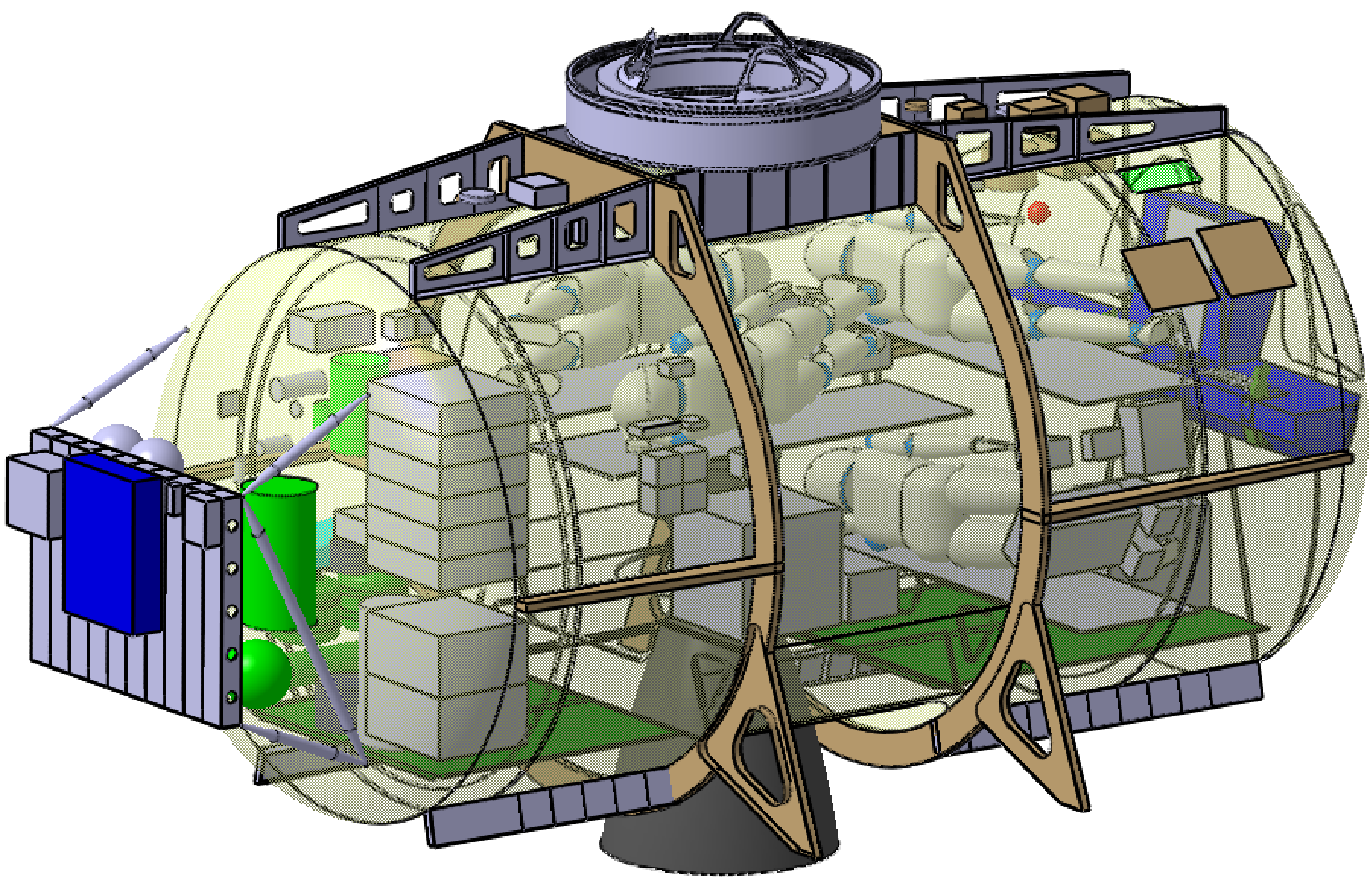


FIGURE 13. Interior view of the Northrop Grumman LLDS combined Ascent /Habitat module. Drawing credit: Syed Abid Ali-Khan

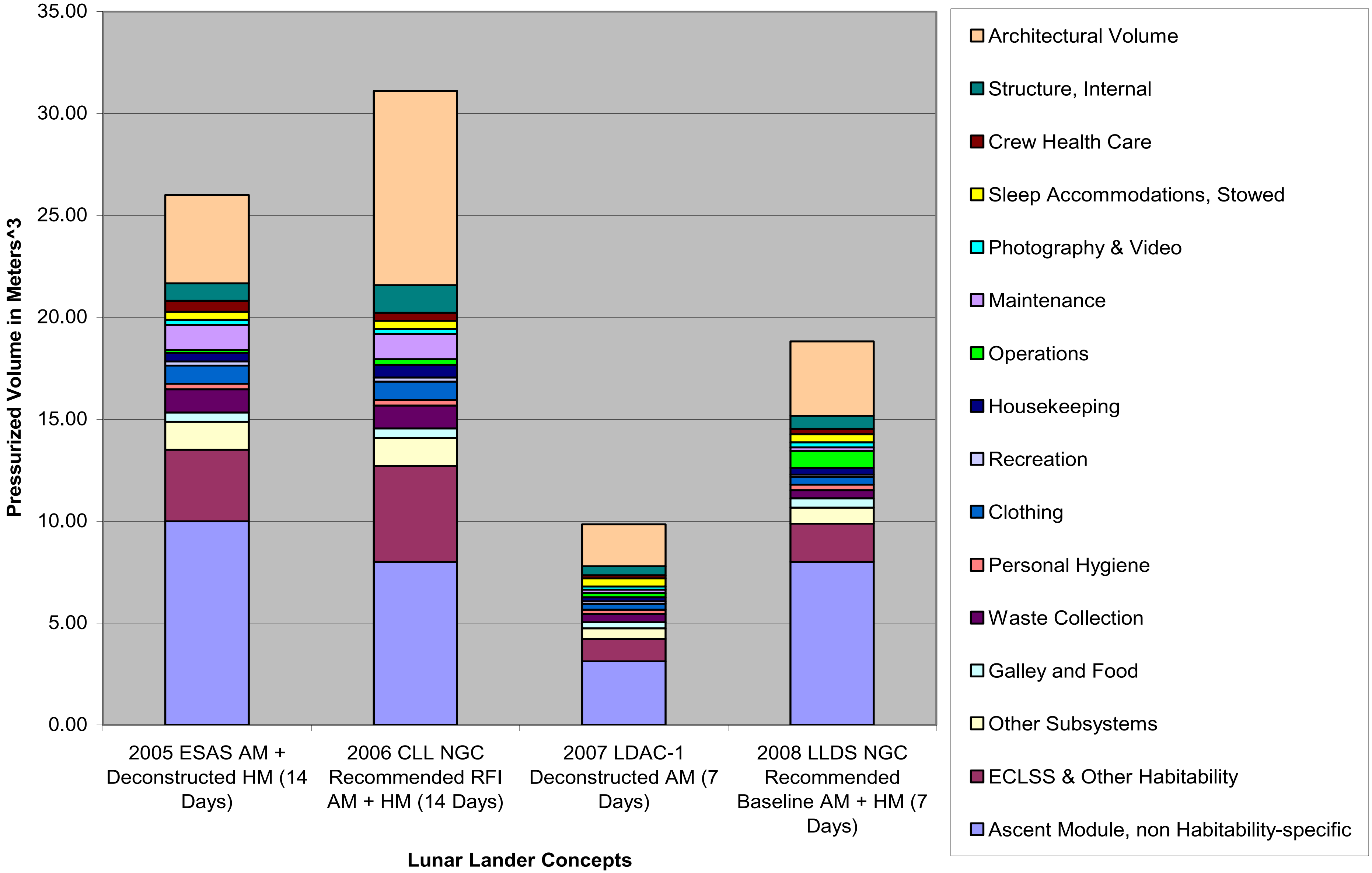


FIGURE 14. Comparative column chart of four Lunar Lander Concepts for the allocation of pressurized volume.

Sleep Accommodations, Stowed – The sleep accommodation may consist of a rigid bunk that folds out to lock into position, a semi-rigid cot that opens up, or a hammock that hangs from hard points on the internal structure. Whatever the sleep accommodation design, the crew will deploy it within the architectural volume for "nighttime" sleep and stow it for "daytime" activities.

Photography and Video – NASA exploration missions typically involve extensive documentation of what the crew is doing and where they go to do it. This visual documentation requires a variety of still and video cameras. Although the miniaturization from digital technology allows some reduction in this volume, it remains a significant functional allocation.

Maintenance – Maintenance refers to equipment servicing and repair, characteristically over a longer period than the one week LDAC-1 or LLDS mission. For the 2006 CLL concept and its reference ESAS LSAM, the need for maintenance would be greater because of the goal stated in the 2006 RFI seeking "concepts for integration of the lander and surface systems, e.g., deployment of surface outpost habitation" (2006 CLL RFI). For an Outpost mission of 180 days or more, maintenance will be vital to mission success.

Operations – Crew operations are probably the least well defined and substantiated aspect of the four lunar lander concepts, but they are the essence of crew productivity. The Litaker, Thompson, and Howard evaluation showed that the design of the pressurized modules and the sufficiency of the volume can make a profound impact on the ability of the crew to perform their mission. In the first three lander concepts, the dedicated operations volume was nominal, but for the LLDS, Northrop Grumman implemented 0.84 m^3 for operations, This operations volume provides space to hang or stow an EVA suit and PLSS inside the AM or Habitat Module, to move the lunar sample boxes through the circulation zone and secure them, or to organize tools and instruments for tasks such as taking them through the airlock for an exploration EVA on the surface. This operations volume does not include space to conduct science work or experiments in the Altair; that requirement remains to be determined.

Housekeeping – Housekeeping refers to the daily upkeep of the living and working environment within the lander. It includes cleaning up spills, collecting trash or vacuuming dust and other particles.

Recreation – Recreation is largely a placeholder for a crew that will be extremely busy working throughout the mission. Recreation includes a minimum provision of exercise equipment as a floor mat for stretching or yoga and elastic "therabands" for strength exercises.

Clothing – The crew will bring all the clothing with them for "one time wear;" they will not wash their laundry, but will need fresh changes of clothing at least several times. The Northrop Grumman assumption was that the crew would bring at least three complete changes of clothing plus IVA athletic shoes or slippers. The clothing scenario would relate to the schedule for EVAs. After an EVA, the crewmembers would shower or take a sponge bath, and then change into fresh clothing that they would wear for about 36 to 40 hours until their next EVA.

Personal Hygiene – Personal hygiene covers washing, bathing, brushing teeth, and personal grooming. The cleaning can occur with wet wipes or soap and water in a sponge bath or possibly a shower. Skylab had a deployable shower compartment, so the precedent for a shower in space is established; it would deploy into the architectural volume.

Waste Collection – Waste collection refers to the toilet functions of urination and defecation. These fixtures will be hard-plumbed in the Altair, presumably in the habitation volume whether it is part of the AM or a separate Hab module. The crew achieves privacy by the simple means of a curtain. Waste collection includes one or more storage tanks for the human waste products and wash water that could be saved as a resource for the outpost for recycling.

Galley and Food – The food system on the Altair assumes the seven day Space Shuttle menu. This diet involves rehydration with cold or hot water and the ability to heat some foods in a forced-air convection oven. Food service on the surface of the moon will probably involve some kind of plates or bowls plus utensils. The galley and food system includes stowage of the food, but not the water to rehydrate it, which comes from the life support system.

Other Subsystems – Other subsystems serves as an umbrella category to cover items that do not fall neatly into the other definitions. For example, avionics and communications equipment would normally fall under the Ascent Module, non habitability area. However, communications or video monitoring equipment within the Hab module or the Airlock might qualify as "other subsystems."

ECLSS and Other Habitability – The Environmental Control and Life Support System (ECLSS) provides all the life support functions such as air revitalization, removal of CO_2, maintaining pressure, temperature, and atmospheric gas mix, mass constituent analysis, and contaminant control. The ECLSS provides the suit loop that backs up the vehicle life support in addition to providing umbilical support to the FO and LSO suits. The ECLSS provides the water for the crew to drink, to prepare food, and for the sublimators in the AM. The waste collection and stowage is technically part of the ECLSS, but it occupies a distinctive, separate volume.

Ascent Module, Non Habitability Specific – This category encompasses all the flight system-related contents and functions of the Ascent Module: the flight deck and pilot stations, the stations for the other crew members during flight, all the avionics, controls, and displays. The AM volume provides life support during flight and pressure suit accommodations for the FO suits in the Sortie Lander and for the LSO suits in the Outpost Lander. It includes the four short and two long suit umbilicals. The AM provides the volume for the returning lunar sample boxes during ascent from the surface and rendezvous with the Orion. The AM carries the LIDS hatch and its associated power, command other subsystems, and must maintain a clear access passage to the LIDS for crew access and egress.

The Northrop Grumman results confirmed the findings of the Litaker, Thompson, and Howard evaluation; we found for our Evolvable Baseline that the addition of 9 m^3 of living volume to the LDAC-1 AM was necessary for a total of 19 m^3 in the combined Ascent and Habitation Module. With regard to the Airlock, the Northrop Grumman configuration did not reduce the volume from the 8 m^3 baseline. Neither did it increase; the LLDS contract did not cover the intensive modeling and mockup simulation that would be necessary to justify such an increase. In any case, the Airlock does not appear in the FIGURE 14 histogram.

FINDINGS

This chronological survey of lunar lander concepts yields useful findings. These findings concern the effect of mission timeline; pressurized volume and how it is distributed among the several modules; module configuration, location and orientation. FIGURE 14 presents a summation of the pressurized volume allocation among the four principal concepts reviewed in this survey. The 2004-2005 CE&R result is omitted because it was so much less defined and precise than the others. The EVA Airlock is omitted because the only variation from the consistent 8 m^3 volume would occur with a contingency requirement for four crewmembers to transit the airlock simultaneously that NASA has since dropped.

Measures of Crew Productivity – This survey of the four lunar lander concepts shows how almost every design decision can influence crew productivity. The key attributes of the design that have this effect include:

- the pilot view angle to fly, navigate, and land the Altair,
- the architectural circulation volume that makes possible sufficient range of motion envelopes, including ergonomic reach envelopes and anthropometric clearances for all functions and operations,
- safe access to the surface, and
- the provision of adequate living space for all habitation activities.

Pilot Station View Angle is a Design Imperative – Despite the plan for the Altair program to extend to a cargo vehicle that can fly and land autonomously, it is still primarily a piloted human spacecraft. The design of the modules – particularly the Ascent Module, the configuration of the modules on the Descent Module deck, and the design of the DM must all contribute to efficient and safe handling qualities for the pilot to fly the Altair. The ability to place modules off-center, to reduce the height of the Descent Module top deck and to reduce the diameter of the top deck can all improve the pilot view angle to the lunar surface for final descent and landing.

Required Volume For Living Environment For The Seven Day Sortie Mission – After extensive study, it appears definitive that the realistic minimum for crew cabin pressurized volume accommodating the ascent and living functions separate from the Airlock is about 19 m^3. This result comprises the 10 m^3 Ascent Module functions and the 9 m^3 additional habitation volume, as illustrated in FIGURE 13. However, this value applies to the piloting tasks and basic living and EVA support; it does not consider working environment support for lunar surface science except insofar as it allows the crew to move equipment through the Airlock to the surface.

Most Mass Effective Configuration Is The Minimal Ascent Module And Separate Habitat -- Despite the success of the LLDS design in solving many of the design problems intrinsic to the LDAC-1 minimum functionality exercise, the fact remains that the biggest “mass gear ratio” in the entire Altair system is the propellant mass to launch the Ascent Module from the lunar surface. Therefore, an absolutely minimum Ascent Module such as the ESAS Concept A in FIGURE 2a or the LDAC-1 promises superior overall system performance. Even more so, the Northrop Grumman 2006 CLL RFI result of an Ascent Module reduced to 8 m^3 *or even less,* promises better performance. This finding implies that the Habitat module must be separate from the Ascent Module, whether or not the habitat is combined with the Airlock in some fashion.

Required Volume For Working Environment In Support Of Lunar Science Is To Be Determined -- NASA may not have these working environment requirements available until it has in hand the lunar surface exploration requirements and transmits them to the Altair Project Office. Once NASA ratifies those requirements, the lunar scientists will want to do much more than just collect rocks to return to earth. They will want to do their jobs as world-class scientists, processing and analyzing their samples in real time. The Altair may need to accommodate a lunar science work station, such as a sample airlock passing from the exterior into a "glovebox." Inside this *glovebox*, (although it will probably use robotics instead of gloved hands) the scientists will have the tools to break, drill, slice, and dice lunar samples and the instruments to examine and process them while the science exploration crew is on site. In this way, the scientists can decide if they have enough of one type of sample, or if they need return to that site on their next EVA.

Required Volume For EVA Airlock Depends Upon The Concept Of Operations – The discourse about the sizing and technology of the EVA Airlock remains open. The reason for the requirement that all four crew members should be able to transit the airlock together appears to have been that in the event of an emergency (such as fire or toxic contamination) the evacuation should happen quickly, without leaving anyone behind for lack of EVA access (Culbert and Leonard, Feb. 25, 2009). Northrop Grumman's analysis during the 2006 RFI showed that the Airlock would require 10 m^3 for all four crew to be able to suit up inside the airlock and then egress it. The current baseline for the Airlock ranges from 7 to 8 m^3, which allows only two crew members at one time to suit up inside it and then egress.

Pressurized Down Payload Needs To Be Recognized And Accounted – The requirements stated for payload, both down payload and up payload need to receive more complete consideration. The requirements allow the 500 kg of down payload to be all pressurized on a given Altair flight. This 500 kg could credibly occupy 2.5 to 5 m^3 -- or even more -- cabin volume. In a 19 m^3 pressurized volume, the worst case could impact 25 percent of the minimal living volume.

Pressurized Up Payload Has Far-Reaching Implications For Lunar Surface Science – Given that the baseline up mass payload for Altair will be less than it was for the Apollo LM, the implications for surface science come into play. How will the science crew process and select the samples for return to earth? The relative decrease of up payload mass plus the more than doubling of crew EVA time translates into an increased need for surface science instruments, tools, equipment, and facilities. All these considerations will add down payload mass and volume to the Altair -- at least in the non-Ascent Module portions – to provide the equipment and laboratory facilities the science crew will need.

Symmetry About the Thrust Axis -- It is more important for the lunar lander modules to be arranged symmetrically in balance about the thrust vector than that the major mass should align directly upon the thrust axis through the Descent Module.

CONCLUSION

This survey presented the major developments in Lunar Lander design over the past four years with regard to pressurized volumes and the modules that accommodate them. Two things stand out in this longitudinal perspective. First, the constancy has been remarkable for the requirements for the Ascent Module and the Airlock throughout this period. In contrast, the requirements for habitation volume to accommodate the crew living and working environment have varied considerably, whether incorporated into the AM or as a separate Habitat module. Second, the aerospace community consisting of academia, industry, and NASA has been making gradual but steady progress toward understanding how to fulfill the Altair requirement.

The area where the community needs to make more progress is in understanding what meeting those requirements will mean in terms of lunar crew productivity, lunar science, and lunar surface systems. Human system integration in support of habitability and human factors should play a much more prominent, indeed leading role in the design of the Altair and the development of its operations. Once the community achieves the understanding that lunar crew productivity is a *vehicle* top level objective, it will be time to revisit some of the requirements discussed in this essay and reshape them to better support this objective.

ACKNOWLEDGMENTS

I wish to thank my colleagues at Northrop Grumman whose hard work made the RFI and LLDS studies: Abid Ali-Khan, Jim Berry, Shyama Chakrobroty, Blaine Clark, Henry Hoeh, Warren James, Val Kraut, Carl Meade, Oliver Philippi, Steve Robles, Bruce Rouleau, Ken Rourke, and Rush Wofford. I especially want to thank my reviewers Carl Meade, Ken Cameron, Noel Fletcher, Aziz Soltani, and Jordan Spatz, whose diligent attention to detail helped me complete this effort. Northrop Grumman Public Release Clearance Authorization #09-1007. Revised 31 AUG 2009.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AL: Airlock

Altair: NASA's name for the crewed Lunar Lander, 13 December 2007.

AM: Ascent Module

BAA: Broad Agency Announcement

CaLV: Cargo Launch Vehicle, the Ares V rocket

CE&R: Concept Exploration and Refinement study

CEV: Crew Exploration Vehicle, Orion

CLL: Constellation Lunar Lander, 2006, also called the Lunar Lander Concept Requirements Description RFI.

Configuration 1 Suit:

A space and flight suit attached to life support by an umbilical to the Orion or Altair life support system; Also known as the Flight Operations (FO) suit.

Configuration 2 Suit:

A space suit arranged to carry its own life support system as a PLSS, but that can also plug into Altair life support via an umbilical; also known as the Lunar Surface Operations (LSO) suit.

CPR: Cardio-pulmonary Resuscitation

Crew Productivity: How well the system supports the crew to perform the mission efficiently and safely.

DAC: Development and Analysis Cycle

DM: Descent Module

ECLSS: Environmental Control and Life Support System

EDS: Earth Departure Stage

EOR: Earth Orbit Rendezvous

ESAS: Exploration Systems Architecture Study, 2005.

EVA: Extravehicular Activity

FO: Flight Operations, refers to Configuration 1 suit.

HM: Habitation or Habitability Module

Hab: Habitat or Habitation Module

Habitability: How well the living and working environment supports crew productivity (Yvonne Clearwater).

ISS: International Space Station

JSC: NASA's Lyndon B. Johnson Space Center

LAT: Lunar Architecture Team

LDAC: Lunar Development Analysis Cycle

LEA: Launch, Entry, and Ascent suit, the *Configuration 1* suit, also known as the Flight Operations suit.

LEO: Low Earth Orbit

LIDS: Low Impact Docking System, which incorporates the hatch between the Orion and the Altair.

LLDS: Lunar Lander Development Study contract, 2008.

LLPO: Lunar Lander Project Office at Johnson Space Center, Houston Texas

LLO: Low Lunar Orbit

LM: Apollo Lunar Module

LOIDS: Lunar orbit insertion and descent stage

LOR: Lunar Orbit Rendezvous

LRV: Apollo Lunar Roving Vehicle

LSAM: Lunar Surface Ascent Module, from the ESAS report, 2005.

LSO; Lunar Surface Operations, refers to Configuration 2 suit.

m^3: meters^3

NGC: Northrop Grumman Corporation

nmi: nautical miles

Orion: Crew Exploration Vehicle that carries the crew to LEO rendezvous with the Altair then travels with it to lunar orbit to serve as the earth return vehicle.

PLOC: Probability of Loss of Crew.

PLOM: Probability of Loss of Mission

PLSS: Portable Life Support System backpack for an EVA suit.

RFI: Request for Information

TCM: Trajectory Correction Maneuver

TEI: Trans-Earth Injection

TLI: Trans-Lunar Injection

VSE: Vision for Space Exploration