

Structural Concepts and Materials for Lunar Exploration Habitats

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A new project within the Exploration Systems Mission Directorate's Technology Development Program at NASA involves development of lightweight structures and low temperature mechanisms for Lunar and Mars missions. The Structures and Mechanisms project is to develop advanced structure technology for the primary structure of various pressurized elements needed to implement the Vision for Space Exploration. The goals are to significantly enhance structural systems for man-rated pressurized structures by 1) lowering mass and/or improving efficient volume for reduced launch costs, 2) improving performance to reduce risk and extend life, and 3) improving manufacturing and processing to reduce costs. The targeted application of the technology is to provide for the primary structure of the pressurized elements of the lunar lander for both sortie and outpost missions, and surface habitats for the outpost missions. The paper presents concepts for habitats that support six month (and longer) lunar outpost missions. Both rigid and flexible habitat wall systems are discussed. The challenges of achieving a multi-functional habitat that provides micro-meteoroid, radiation, and thermal protection for explorers are identified.

Acronyms

CLV	= crew launch vehicle (Ares I)	ISRU	= in-situ resource utilization
CaLV	= cargo launch vehicle (Ares V)	LIDS	= low impact docking system
CEV	= crew exploration vehicle (Orion)	LL	= lunar lander
CM	= crew module	LLO	= low lunar orbit
Cx	= constellation	LM	= lunar module
DRM	= design reference mission	MER	= Mars exploration rover
EDS	= Earth departure stage	MMOD	= micrometeoroid and orbital debris
ESAS	= exploration systems architecture study	PMC	= polymer matrix composite
ESMD	= exploration systems mission directorate	SM	= service module
EVA	= extra-vehicular activity	TLI	= trans-lunar injection
FSW	= friction stir weld	TRL	= technology readiness level
ISS	= international space station	VSE	= vision for space exploration

I. Introduction

The Exploration Systems Architecture Study¹ (ESAS) identified baseline elements of the Constellation Program that enables human exploration beyond low-earth orbit. The Constellation Program provides the infrastructure to implement the VSE². The ESAS team also evaluated technologies that could reduce the cost, schedule and risk of implementing the architecture. Two technology areas, designated as ESAS References 1A (lightweight structures)

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and 9D (low temperature mechanisms) were deemed crucial to reduce the mass and risk of various elements of the architecture. These two technology areas, lightweight structures and low temperature mechanisms, are combined into a project under the ESMD Technology Development Program called Structures and Mechanisms. The Structures and Mechanisms project links key researchers and facilities from multiple NASA centers and industry into a single team as described below.

Figure 1 shows key elements of the lunar lander (LL) and habitats that will be targeted by the Structures and Mechanisms project. Lightweight structures have been identified as a critical need since the reduction of structural mass translates directly to additional up and down mass capability that would facilitate additional logistics capacity and increased science return for all mission phases. In addition, improved mass properties may be required if mass growth occurs when designs are matured and when systems needs and functionalities grow. Materials and structures that provide multi-function shielding for radiation, thermal control, and/or MMOD protection are also desired.

In early robotic missions and later in outpost missions, permanently shadowed regions of the lunar surface (*e.g.*, the bottoms of craters in the Polar Regions) are of high interest to science and exploration because of the possibility of water in the form of ice. These areas appear to remain at temperatures of 50 to 80K (-223°C to -193°C). Current Mars surface exploration hardware has demonstrated capability to operate in the range of -115°C to 0°C. However, the technical challenges of developing and demonstrating hardware that can operate over 100°C colder than current capabilities are significant. Technical challenges are present in the area of materials, bearings, lubricants, sensors, actuators and motors, and thermal control.

The paper provides a summary of project plans and goals for implementing a multi-year, multi-participant effort in lightweight structures technology development. Application of the lightweight structures technology to lunar landers and habitats is discussed. A preliminary requirements flow down for the structural system will be used to guide structural design decisions. The paper also presents requirements and concepts for habitats that support six month (and longer) lunar outpost missions. Both rigid and flexible habitat wall systems are discussed such that the benefits and risks of each system are understood. The challenges of achieving a multi-functional habitat that provides micro-meteoroid, radiation, and thermal protection for explorers are shown.

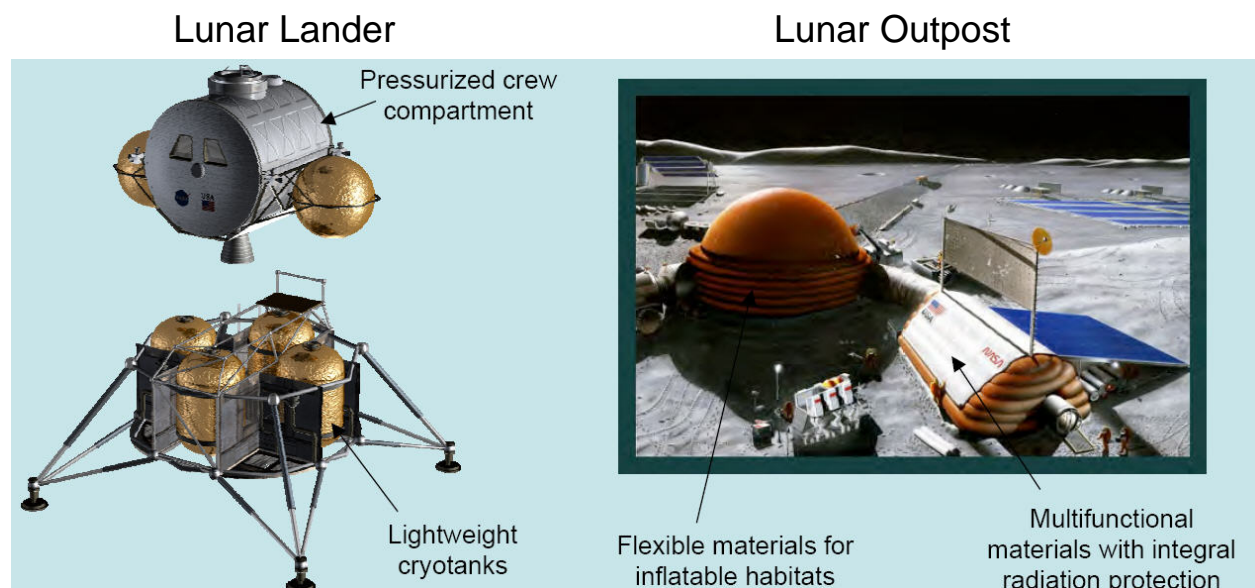


Fig. 1 Structures and Materials Technology for Lunar Lander and Lunar Outpost Missions

II. Structures and Mechanisms Project Overview

A. Lightweight Structures Objectives

The first objective is to develop lightweight structure technology for the primary structure of the pressurized elements of the Constellation program. (In the discussion herein, pressurized vessels include high-pressure vessels for fuel and vessels maintaining atmosphere for crew habitation.) In addition, development for non-pressurized primary structures will be considered where there is synergy with the development of the pressurized structures. The goals of the lightweight structure technology development are to significantly enhance structural systems for man-rated pressurized structures by 1) lowering mass and/or improving efficient volume for reduced launch costs, 2) improving performance to reduce risk and extend life, and 3) improving manufacturing and processing to reduce costs. The targeted application of the technology is to provide for the primary structure of the pressurized elements of lunar landers for sortie and outpost missions, and surface habitats for the outpost missions. As the technology develops, early advancements to Technology Readiness Level³ (TRL) of 6 would be handed off to earlier components of the VSE such as the CEV, CLV and robotic precursor programs for consideration. Success criteria would be to demonstrate the ability to meet mission requirements with improvements in key performance metrics over state-of-the-art of lightweight structural technology.

B. Low Temperature Mechanisms Objectives

The second project objective is to develop low-temperature mechanisms to improve and or allow for reliable and efficient mechanism operation in low temperatures (below -100 deg. C) for long duration surface operation. This effort concentrates on motor and drive systems, lubricants, and actuator systems that are targeted for lunar surface rovers, robotics, and mechanized operations. The goals of the low temperature mechanism technology development are to significantly enhance operation of mechanized parts by 1) lowering the operating temperature for life of the component and 2) improve mechanism performance (torque out put, actuation performance, lubrication state) at the lunar environment conditions of cold and vacuum over the required life of the mechanism. The targeted application of the technology is to provide for operation of motors and drive systems, lubricated mechanisms, and actuators of lunar rovers and mobility systems, ISRU machinery, robotic systems mechanisms, and surface operations machinery (i.e. cranes, deployment systems, airlocks). As the technology develops, early advancements to TRL 6 would be handed off to earlier components of the VSE such as the robotic precursor programs for consideration.

The following tables provide additional information on objectives and goals of the project. Tables 1 and 2 show the challenges outlined by the ESAS studies for lightweight structures and low temperature mechanisms. Table 3 lists some of the driving challenges and risks for the Constellation Program advanced structures technology. The remainder of this paper will focus exclusively on lightweight structures technology with applications to the lunar lander and surface habitats.

Table 1. ESAS challenges for Lightweight Structures

Constellation Elements	Challenges/Risks
CEV (CM, SM, EDS)	Light Weight Structural Systems, Crushable CM Structure For Landing, Reusability, Entry Heating Requirements, MMOD A Risk, Radiation A Concern, Manufacturing For Low Mass And Less Cost, Integrated Structural Systems For Reduced Mass
CLV (Shroud, Cryotanks/Fuel tanks)	Light Weight Structural Systems, Lightweight Cryotanks And/Or Improved Insulation, Manufacturing For Low Mass And Less Cost
Lunar Landers (Crew section, Cryotanks, Lander Platform, Airlock)	Light Weight Structural Systems, MMOD A Risk, Radiation A Concern, Lightweight Cryotanks And/Or Improved Insulation, Manufacturing For Low Mass And Less Cost, Integrated Structural Systems For Reduced Mass, Volume For Crew, Deployable Landing Gear, Multilayer Insulation
Surface Habitats (Primary, Airlock)	Light Weight Structural Systems, MMOD A Risk, Radiation A Concern, Integrated Structural Systems For Reduced Mass, Volume For Crew

Table 2. VSE Challenges for Low Temperature Mechanisms

Constellation Elements	Challenges/Needs
Mobility Systems (Rovers, Transportation Bases... For RLEP, Landers, Rovers, and Surface Operations)	Lifetime Of Gears, Bearings And Lubricants: –223 C; Vacuum; 50,000,000 Revolutions: Reliable Operation Of Drives And Position Sensors at –230 C
Instruments (ISRU, Science Experiments...For RLEP and Surface Operations)	Actuators And Drive Systems For Trenchers, Diggers, Drilling Systems, Winch/Tether Systems: –230C or Temperature Range Of –190C To +130C: Lubricants At –223 C And Vacuum Lifetime Of Operations Or Replaceable Systems; High Power Motors & Drill Bits Long Life Operation at -230 C Gimbal Systems For Cameras, Instruments, And Antennas
Manipulation Equipment (Cranes, Manipulation, Joints, Sample Handling, Robotic Agents...For Surface Operations)	Lifetime Of Gears, Bearings And Lubricants: –223 C; Vacuum; 50,000,000 Revolutions: Reliable Operation Of Drives And Position Sensors at –230 C or Temperature Range Of –190 C To +130 C: Lifetime Of Low Backlash Gear Trains Manipulators, Joints Low Temperature Actuators For Cranes and Site Preparation Equipment
Deployment Mechanisms (Actuators, Joints...For Surface Operations)	Gimbal Systems For Cameras, Instruments, And Antennas Reliable Operation Of Drives And Position Sensors At –230 C

Table 3 Lightweight Structures Challenges/Risks and Technology Solutions

Constellation Application	Challenges/risks to achieve reduce mass	Technology solutions	Technology metrics
CEV CM	MMOD, Structural Reliability, Radiation Protection	Multifunctional Structures, Advance Materials, Radiation Shielding Materials, Composite (Adv. Metals) Reliability	Structural Efficiency, GCR Dose, MMOD Impact Size And Velocity Survival For Areal Mass
Cryotanks (CLV, Landers)	Improved Manufacturing, Structural Reliability	Advanced Manufacturing Methods (FSW), Multifunctional Structures, Advance Materials	Structural Efficiency, Durability
Lunar Landers	MMOD, Structural Reliability, Radiation Protection, Increased Operational Volume	Multifunctional Structures, Advance Materials, Radiation Shielding Materials, Composite (Adv. Metals) Reliability, Inflatable Structures	Structural Efficiency, GCR Dose, MMOD Impact Size And Velocity Survival For Areal Mass, Packaging Density
Lunar Habitats	MMOD, Structural Reliability, Radiation Protection, Increased Operational Volume	Multifunctional Structures, Advance Materials, Radiation Shielding Materials, Composite (Adv. Metals) Reliability, Inflatable Structures	Structural Efficiency, GCR Dose, MMOD Impact Size And Velocity Survival For Areal Mass, Packaging Density

III. Structures and Mechanisms Project Task Descriptions

The objective of the Structures and Mechanisms project is to develop material-structural systems for the Constellation Program elements that are more efficient by mass than current state-of-the-art. The targeted Constellation elements are the crewed lunar lander and lunar habitats. The candidate lightweight primary structural

systems developed must be able to provide for the required structural performance and ensure a safe human environment for the mission durations as described in the ESAS report. Of particular interest are advanced polymer matrix composites and/or advanced metallic material systems, multifunctional structural systems, and inflatable structure systems. An approach will be taken to infuse the lightweight structure candidates into various Constellation elements as alternate technology options become available. Thus, the project would carry the mid-TRL (TRL 4-6) development of the candidate as an option that could be picked up at key decision points by the Constellation element but would not be in the critical path until the technology was sufficiently demonstrated. Material and structural systems that show promise and are able to meet TRL 6 in an accelerated rate will be offered to the CEV, CLV, and robotic precursor programs for consideration.

The development of lightweight structure technology requires acquiring mission and system structural requirements for the targeted Constellation elements, evaluating and advancing advanced material systems for structural application, and maturing those candidate technologies. In addition, all potential loads, internal/external environment, durability, and emergency safety systems requirements need to be defined. Based on the mission requirements and potential loads, material systems criteria will be identified. The most promising of the candidates will be selected for advancement and/or application to structural system technology development. Structural concepts will be investigated for trades between traditional systems and new system concepts such as inflatable structures, scaling of components and systems, and the traditional parasitic systems versus multi-functional concepts. Consideration will be given to the possibility of modular lander structure capable of also functioning as habitat modules. Finally, components and material systems will be validated for performance metrics through testing.

Structures and Mechanisms project tasks for lightweight structures technology development are described below.

A. Mission and Systems Requirements

Mission and system requirements are still being defined for various elements of the Constellation Program. Even the CEV and CLV still have decision points that will affect the design and thereby the design mass. Lunar lander and habitat designs are still conceptual and do not have well defined structures requirements. The mission and system requirements task will help to derive primary structure requirements from the functional requirements. These requirements will guide the direction of the lightweight structure technology targeted for application to the VSE elements. These functional requirements will include but are not limited to; the number of missions per year, the number of crew, mission duration and required design life, the restrictions if any on shape/size/mass for the launch vehicle, the requirements for joints, cut-outs (doors and windows), airlocks, attach points for equipment, and the operating environment.

B. Material criteria definition and evaluations

The materials systems criteria and evaluation task is for the identification and evaluation of advanced material systems for structural application to pressurized primary structures of lunar landers and habitats. Advanced material systems already developed to TRL 4+ for space or aeronautic programs will be identified and evaluated for characteristics that meet the requirements for the VSE primary structure needs. The material systems with the most potential will be evaluated for primary structural requirements of the Constellation elements. Potential sources of information for candidate material systems include databases from previous missions such as Viking, Mars Rovers and Apollo, launch vehicle programs such as the reusable launch vehicle (RLV), orbital space plane (OSP), and Shuttle, advanced aircraft programs as well as other material development programs.

C. Composite Lightweight tank for LOX tank

An industry partner, XCOR, submitted a proposal to the ESMD Broad Agency Announcement (BAA) proposal process in 2005. The selected proposal was for the development of lightweight, oxidation resistant cryotanks. The primary effort in Phase I was the development of a fluoropolymer composite material system. The material system used inorganic fibers and fluoropolymer matrix materials that were inherently oxygen compatible and usable at cryogenic temperatures. The goal of this task is to develop lightweight structure with low CTE, not prone to microcracking under thermal cycling, and LOX compatible (fire resistant).

D. Radiation Shielding Materials Development

Radiation effectiveness will be considered as an integral part of the design of the total material system comprising the structural components. A separate materials development program will not be supported by this activity because

it is realized that radiation effectiveness is one of many figures of merit to aid in the selection and evaluation of multifunctional structural shielding. However as part of this program a survey of existing materials (TRL 3 and above) will be performed to estimate the radiation effectiveness against solar proton events, galactic cosmic radiation, and the appropriate reference design environments. Promising materials currently under development may be selected for continued development within this task based upon need and ability to meet requirements compared with other systems of similar TRL.

E. Inflatable Structures for Crew Habitation

This task is to develop the technology of inflatable structures for crew habitation. Inflatable systems have demonstrated their benefits in the past in space suits, re-entry ballutes, impact attenuation systems such as the Pathfinder and Mars Exploration Rover (MER) missions to Mars, communications satellites such as Echo, and even in the airlock used in the first Russian EVA by Alexei Leonov. They have been proven to offer high packing efficiency and reduced mass for reduced launch costs, and a highly reliable expandable volume for many space systems. This task will evaluate and develop inflatable structure and material technology for use in airlocks, lunar landers, and lunar habitats. Inflatable structures technology has been developed to TRL 3-4 for space habitat applications and is still being investigated by NASA and industry. The objective of this task is to develop inflatable structure for application to VSE elements at TRL of 6.

F. Friction Stir Welding (FSW) of Thin gage Al-Li

Lockheed Martin submitted a proposal to the ESMD BAA proposal process in 2005. The proposal was for development of Friction Stir Welding (FSW) methods tailored to thin sheets of metallic alloys (e.g. aluminum-lithium) in order to reduce the mass of cryogenic tanks. The objective of this effort is to advance the technology to create a cryogenic propellant tank with the highest mass fraction of any large capacity cryogenic tank while simultaneously making it more effective, reliable, flexible and most of all affordable.

G. Multifunctional Structures

This task is to develop multifunctional structures technology for application to primary structure of the lunar lander crew habitat and lunar surface habitats with relevant technology made available to CEV and CLV elements. Multifunctional structure in this project is defined as a structural system that incorporates material systems and structural configurations to combine the functions of required structural performance, radiation protection, MMOD protection, thermal control, and structural health monitoring within one structural system. The goal of this task is to develop a primary structural system with reduced mass compared to the current practices of combined structural and parasitic systems required for the same type of performance and to demonstrate this system in a structural subcomponent demonstration.

H. Polymer Matrix Composite (PMC) Reliability

Organic composite and hybrid material systems have been shown to have potential to reduce the mass of structural systems. However, some aspects of composite structures have limited their ability to reduce mass due to uncertainty in material reliability. For most of the aerospace sector, design practices are often governed by historical standard practice guidelines and constrained by excessive conservatism built into the design to accommodate uncertainty that typically results in additional mass. The objective of this task is to develop the reliability of advance composite systems through analysis and validation, thus reducing the mass of the system for performance requirements. Near term technology application includes the CEV command module and service module primary structure. Farther term applications are lunar lander and habitat systems.

In sections IV and V, requirements and structural aspects are described for the LL and Lunar Outposts, respectively. Application of the Structures and Mechanisms project tasks (A-H) are discussed where relevant.

IV. Application to the Lunar Lander

The first five elements of the Constellation architecture are the Crew Launch Vehicle (CLV, recently named Ares I), the Crew Exploration Vehicle (CEV, recently named Orion), the Cargo Launch Vehicle (CaLV, recently named Ares V), the Earth Departure Stage (EDS) and the Lunar Lander (LL). While lowering the mass of each of these

elements through use of advanced structures and materials technologies is crucial to success of the architecture, this section will focus on the lunar lander.

A. Lunar Lander Concept Requirements Description

The lunar lander derived during NASA's ESAS study was a preliminary concept with the ability to support a wide array of potential surface missions ranging from short science missions distributed across the lunar globe to supporting the build-up of a large lunar outpost at the south-pole. The ESAS LL shown in Fig. 2 was an excellent synthesis of options. It provided a basic understanding of the systems, operations, costs and risks of this vehicle, while acknowledging a significant portfolio of work to be completed in the post-ESAS timeframe. A revised lunar lander, shown in Fig. 2, was sized for an additional 70 days of cryogenic fuel boil-off, and for a smaller CEV diameter (~5m).

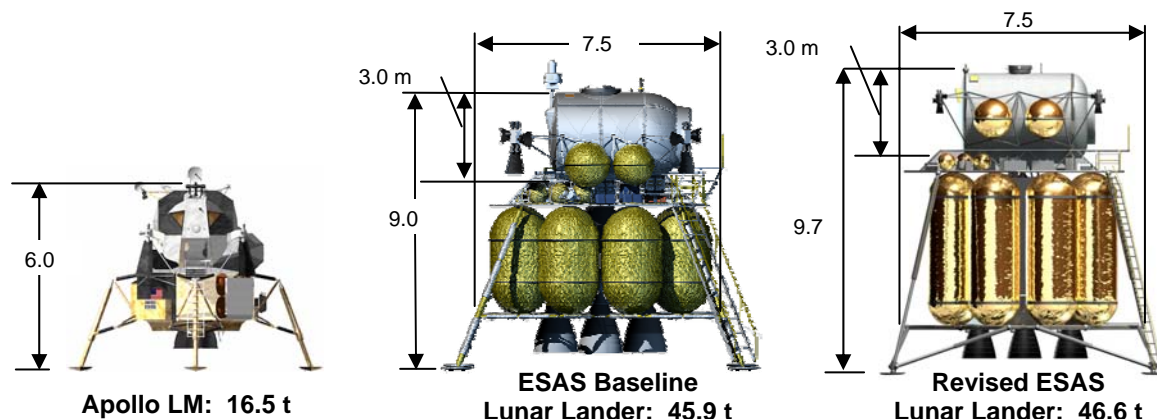


Fig. 2. Lunar Landers – Apollo LM and ESAS LL Concepts

The Apollo lunar module (LM) was designed for a crew of two, a payload of 1,230 lbs. (558 kg), and provided a pressurized volume of 236.5 ft.³ (6.7 m³). The mass of the Apollo LM is about 1/3 of the ESAS LL baseline design (36,300 lbs. [16.5 mt] versus 102,500 lbs. [46.6 mt]). Both the baseline and revised ESAS LL designs provide for a crew size of four, a payload of 5,060 lbs. (2,300 kg) and a pressurized volume of 1,130 ft.³ (31.8 m³).

With a more defined set of exploration requirements in place, it is now prudent to explore diverse sets of lunar lander design configurations that may yield innovative solutions to supporting lunar surface missions. The request for information (Ref. 4) for lander concepts from external sources will add to the conceptual design efforts being developed by NASA field Centers.

In addition, the ESAS study touched only briefly on alternate deployment concepts for lunar outposts and concluded by supporting an “incremental build” strategy that integrates the lander and surface system deployment and functionality. With the Earth Orbit Rendezvous – Lunar Orbit Rendezvous (EOR-LOR) architecture now fixed, new studies can more fully explore options for deployment of a lunar outpost in pieces that can be packaged within this excess landed mass. This should be integrated with any lander reconfiguration study that contemplates leaving behind part of the habitable lander volume, airlock, etc.

Reference 4 provides the following lunar lander design requirements:

- Dual rendezvous mission mode (EOR+LOR)
 - Cargo Launch Vehicle (CaLV) Trans-Lunar Injection (TLI) capability from 296 km (160 nmi) circular orbit (assuming 20 mt CEV at TLI):
 - CaLV Shroud Diameter (meters [m]) Net Lander Payload to TLI (metric tons [mt])
- | | |
|------|------|
| 8.4 | 45.0 |
| 10.0 | 40.7 |
| 12.0 | 38.0 |
- Cargo mission (single launch) TLI mass: 53.6 mt

- Low-Impact Docking System (LIDS) docking system for CEV/LL interface
- Lander performs attitude control and Trajectory Correction Maneuvers during trans-lunar coast
- Lander 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 payload down to lunar surface
- 100 kg minimum payload return from lunar surface to Earth
- Surface airlock

In addition, the following are desired capabilities for the lander:

- 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
- “Green” propellants
- Capable of utilizing locally produced propellants using In-Situ Resource Utilization (ISRU)
- Unpressurized cargo stowage volume
- Ease of surface access for crew and cargo
- Extensibility to a dedicated cargo lander (see ESAS¹ report, section 4 for cargo mass data and descriptions)

B. Lunar Lander Structures Technology

The major mechanical/structural constraints on the lander are the mass delivery capability of the CaLV, the volume of the CaLV shroud, and the descent/ascent requirement of a pressurized volume for the crew. These constraints are further exacerbated by the harsh radiation, micrometeoroid, thermal and abrasive dust environment on the lunar surface.

A key component of the LL is the vehicle pressure vessel. The initial sortie missions are likely to utilize either a rigid metallic or polymer matrix composite (PMC) pressure shell. The material system selection is not based solely on mechanical and thermal loads, but also on MMOD and radiation considerations. NASA’s CEV Smart Buyer study (Ref. 5) also identified the mass savings of composites for the Crew Module pressure vessel. Efforts within NASA are now underway to develop a composite CM design and to assess the durability of composites that undergo hypervelocity (simulated MMOD) impacts. Section V provides additional discussion of rigid pressure vessels.

The Structures and Mechanisms project tasks A-H (section III) will be used to identify and develop low mass structural materials for the LL. Material systems and structural concept evaluations will be performed to identify low mass, low risk structural designs for the LL. The primary focus will be on the largest mass items such as the cryogenic tanks, the pressure vessel, and the landing support structure. The structural concepts will focus on modularity for reconfiguration and reuse in other surface systems such as the lunar rover.

Intermediate sortie missions may involve testing of inflatable pressure vessels for future outpost missions. The volume constraint of the launch shroud is likely to require higher packaging efficiency than is possible with rigid structures. (In this paper, packaging efficiency refers to the volume of the structure stowed for launch as compared to its volume once deployed and in operation.) The next section describes some candidate technologies and structural concepts for the outpost habitats

V. Advanced Structural Concepts for Lunar Habitation

Habitation on the lunar surface requires as a minimum a pressurized volume, ingress and egress capability, environmental protection, and life support systems. The volume of pressurized space is arguable with less space needed for sortie missions (4-7 days) and large volumes needed for outpost missions (~180 days). The volume requirement for longer duration missions increases due to physiological factors, increased need for resource storage

and utilization, and scientific support systems. Ingress and egress capability can be achieved with or without an airlock; however large volumes and sensitive systems will probably necessitate an airlock on all outpost missions. The probability of high radiation doses and micrometeoroid damage increases with mission duration. Hence, all outpost missions must mitigate the radiation and MMOD threat.

Figure 3 shows two extremes for the lunar habitat. The lunar sortie habitat is likely to be the crew module of the LL, much like the Apollo program used the lunar module as the habitable volume. The lunar outpost missions may begin by augmenting the LL crew volume with a connected module that provides increased volume and higher environmental protection. The outpost missions will also require various surface systems such as pressurized rovers and devices for in-situ resource utilization as shown in Fig. 3. Repeated outpost missions to the same lunar location will lead to a scientific base that will likely include both rigid and inflatable systems for habitation and laboratories as shown in Fig. 4. A discussion of the structures and materials for rigid and inflatable systems follows.

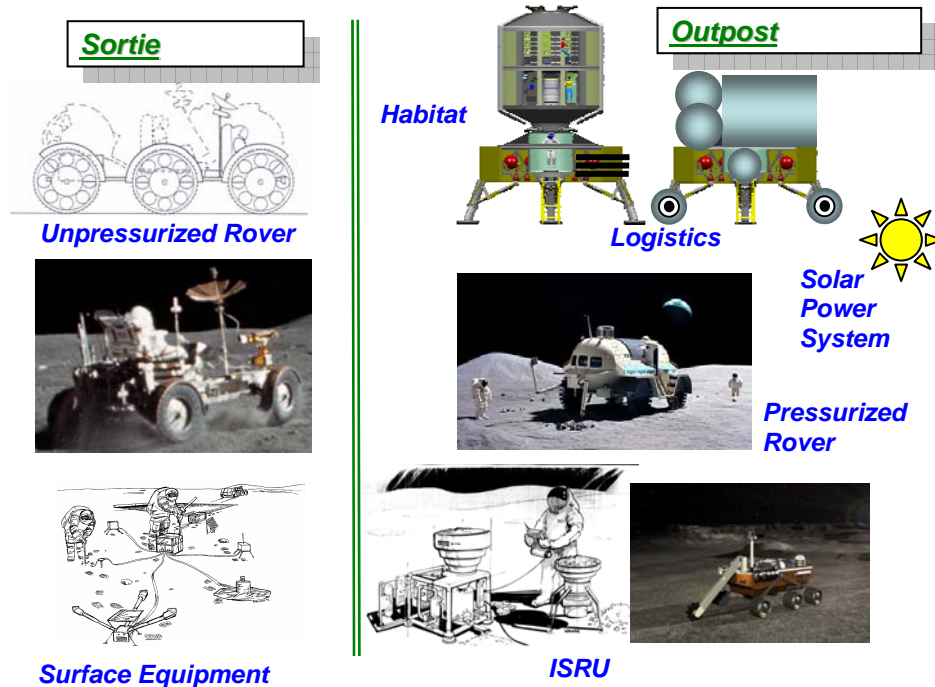


Fig. 3. Infrastructure for Lunar Sortie and Lunar Outpost/Base Missions

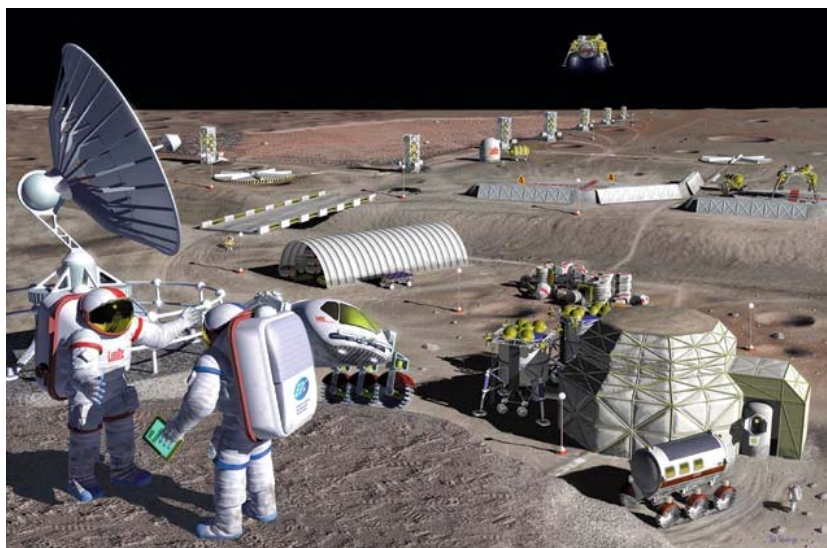


Fig. 4. Lunar Scientific Base – Rigid and Inflatable Structures

A. Rigid Habitat Systems

The Apollo program successfully used a metallic (aluminum alloy) rigid structure for the lunar module habitat. The crew compartment provided 6.7 m^3 of volume. The ascent stage structure, which is dominated by the pressure vessel and various equipment supports (secondary structure), weighed 1026⁶ lbs (465 Kg). This is 22.5 % of the ascent stage dry mass. MMOD shields and thermal insulation were recorded as part of the protection subsystem and not included in this structure subsystem mass.

The ESAS LL concept for the ascent stage (Fig. 5) provides nearly a five-fold increase in pressurized volume as compared to the Apollo LM. The LL pressure vessel is a horizontal short cylinder 3.0 m in diameter and 5.0 m long to provide 31.8 m^3 of pressurized volume for the crew during lunar operations. A nominal internal atmospheric pressure for the ascent stage of 65.5 kPa (9.5 psia) with a 30 percent oxygen composition has been assumed. The EVA strategy while on the lunar surface is daily EVA with all four crew members egressing the lunar lander simultaneously. Unlike the Apollo LM, the LL ascent stage crew cabin includes a bulkhead to partition a section of the pressurized volume for use as an internal airlock. Thus, crew members don their surface EVA suits in the airlock, depressurize the airlock, and egress the vehicle.

The CEV smart buyer study⁵ initiated an effort to determine the effect of various material systems on the pressurized Crew Module's dry weight. The pressure vessel skins would be driven by the pressure loading and their ultimate strength. For the relative low pressure for the LL, minimum gage skin thicknesses are probable. The minimum gauge constraints for composites would be included if applicable (8 plies minimum). It was assumed that the correct product form for each material system could be obtained, and that metals could be welded as needed. In addition, the best material properties available for each material system were assumed. The composite materials investigated were composite (IM7/5250-4) in two lay-ups: [0/+45/90] quasi-isotropic lay-ups for skins (Density = 0.057 pci, Modulus = 8.3 MSI, Ultimate (OHC) strength = 40.7 ksi) and an oriented [40% 0 / 40% +45 / 20% 90] lay-up for longerons and ring frames (Density = 0.057, Uni-axial Modulus = 10.7 MSI, Strain Compatible Strength = 53.5Ksi). For the longerons using the oriented lay-up, strain compatibility with the skin required that they be limited to the maximum strain allowed in the skin (at the OHC strength skin limit) so the strength value used for scaling the composite longerons was derived from the maximum skin strain and the longeron modulus. Two metals were investigated: a very high strength Titanium 551 (Density = 0.166 pci, Modulus = 17.4 MSI, Ultimate Strength = 210 Ksi), and the Shuttle Super-Lightweight External Tank alloy, Aluminum Lithium 2195 (Density = 0.095 pci, Modulus = 11 MSI, Ultimate Tensile Strength = 78 Ksi), and the baseline material used in the sizing was Aluminum 2024-T3 (Density = 0.1 pci, Modulus = 10.5 MSI, Ultimate Tensile Strength = 64 Ksi). The scaled finite-element derived weights were penalized for manufacturing and minimum gauge (in the case of composites) as was the baseline. The results of these approximate weight estimates showed that Aluminum-Lithium (2195) provided a 14% reduction, Titanium (551) a 24% reduction, and Polymer Matrix Composite (IM7.5250-4 BMI) a 26% reduction as compared to the baseline Aluminum (2024-T3) design.



Fig. 5. ESAS LL Ascent Stage

For the CEV CM design, composites showed the largest benefit overall, but the maximum benefit was in the ring frames due to the superior specific stiffness of the composite. In strength critical skin regions, the composite was largely minimum gauge limited which reduced the benefit obtainable. The most significant concern for composite is the hermeticity of the skins with loading and non-visible damage. For the metals, it is the formability, weldability and maintenance of properties in the desired product forms. These material systems and others will be further investigated for use on LL rigid habitats in tasks A, B, D, E, G, and H of the Structures and Mechanisms project.

B. Inflatable Habitat Systems

To achieve larger volumes for habitation in space, inflatable systems have been proposed to circumvent the limited diameter of launch vehicle shrouds.

Early NASA studies⁷ were focused on developing inflatable space structures ranging from space suits to habitats. These development programs included the manufacture and test of several large scale prototypes. Inflatable habitat structures have continued to be evaluated in studies conducted by NASA and industry under sponsorship of the Space Exploration Initiative (SEI)⁸ in the early 1990's. These studies were primarily concept designs with limited hardware evaluation. The exception to this was the TransHab⁹ inflatable structure technology effort.

TransHab was designed with a rigid core and inflatable walls for use on the ISS. The TransHab, with application to the International Space Station (ISS) shown in Fig. 6, was designed to provide increased volume for long duration missions such as a crewed mission to Mars. This multi-layered or laminate material system provided multifunctionality with separate membrane layers. In addition to providing vastly greater volume than other rigid habitat elements of the ISS, it also provided superior MMOD shielding as compared to rigid wall construction. Recently, Bigelow Aerospace has advanced this class of inflatable habitat technology and performed an on-orbit deployment of the Genesis 1 spacecraft¹⁰.

Another detailed inflatable system design for surface habitation was undertaken by ILC Dover¹¹ as shown in Fig. 7. Again a multilayer wall was designed to provide multiple functions. The Structures and Mechanisms project will continue development of inflatable concepts both at the material level and at the system level for structural functionality.

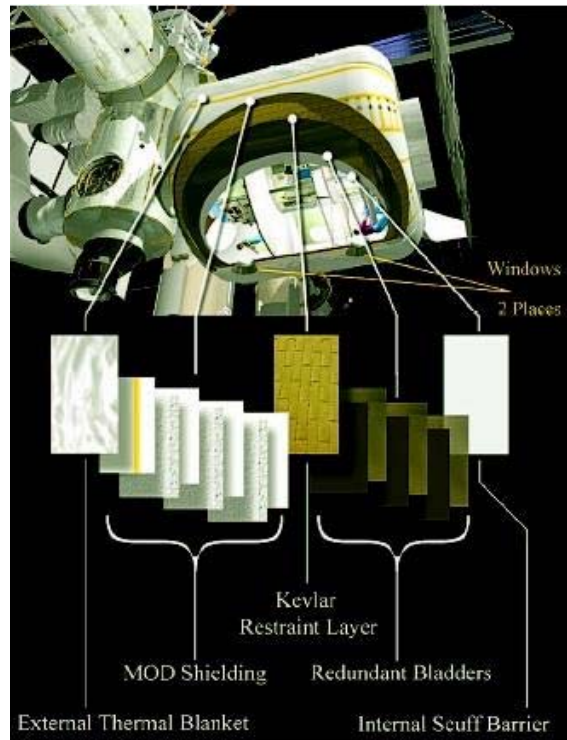


Fig. 6. Schematic of TransHab attached to the ISS

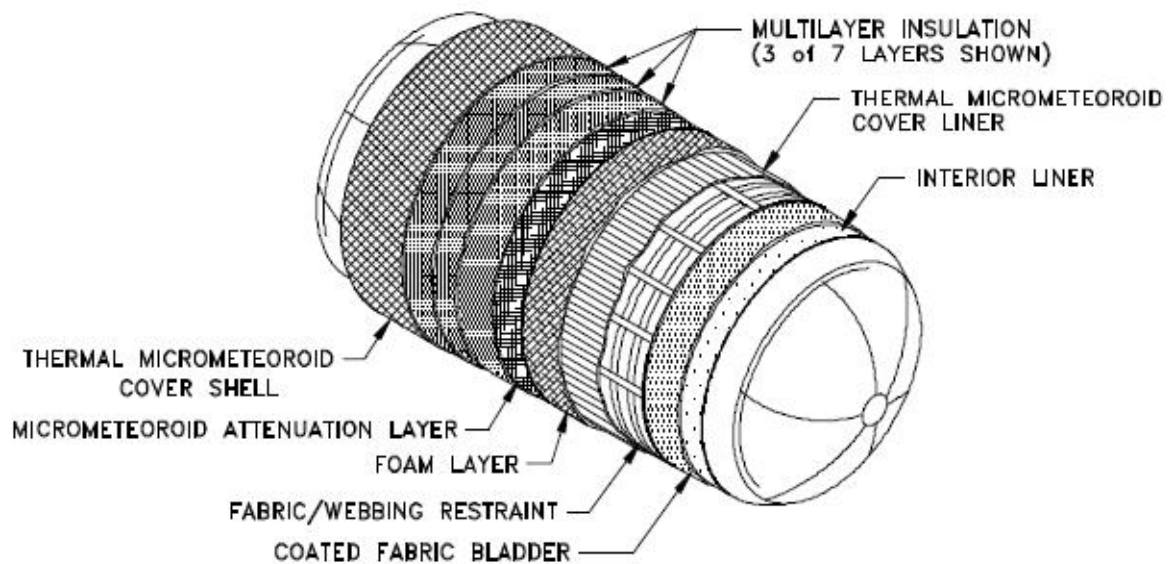


Fig. 7 ILC-Dover multilayer wall of an inflatable habitat

Inflatable habitat materials systems have not shown appreciable mass savings to date due to the large number of layers needed for hermeticity, durability, thermal management, GCR and SPE absorption and MMOD protection. While flexibility of the materials allows the structure to be packaged into a small volume for launch, advances in materials and load path concepts are needed to reduce the weight of these flexible material systems. Advanced flexible polymers and high strength fiber reinforcement should enable lower mass structures. Some promising design approaches for inflatable lunar habitats are discussed next.

C. Inflatable Habitat Concepts

Benaroya¹² correctly states that the level of design complexity for lunar habitats will increase with experience and mission duration. Fully outfitted habitat modules will serve as the first generation. These may be rigid and/or inflatable. Later, some fabrication and assembly of the habitats on the lunar surface is likely. Finally, the goal would be to utilize a majority of lunar resources to construct habitats either on or below the surface. The Structures and Mechanisms project will focus on the first generation habitats with some advanced concepts work in the more complex use of lunar resources.

Geometry of the habitats is a fundamental design variable. The literature is rich with “optimal” designs. A good example is the trade between a hemispherical habitat and a toroidal design¹³. Cylindrical and toroidal designs have advantages from a structural stress standpoint with the hoop and axial stresses being easily managed with some radial fiber reinforcement. Spherical designs have the advantage in that a uniform bi-axial stress state can be realized as in the Echo¹⁴ satellites. However, the geometry of a habitat is also highly dependent on its intended use, internal equipment layout, airlocks, and non-pneumatic loads. Thus, high performance structural habitat geometries may not lead to the best system habitat geometry.

Three lunar resources of interest for design of even first generation habitats are gravitational forces, surface reaction forces, and regolith. Forces due to gravity can be used to lower pressure induced stresses on the habitat wall. If the habitat wall is used to support equipment and other outpost systems, these inertial forces can be used to tailor the shape and internal loads of the habitat. Gravity forces also permit tensioned structure design using cables and other prestressed members to transmit loads within the habitat. A simple terrestrial example is the suspension bridge. Advanced habitat structural concepts that utilize gravity forces advantageously may result in non-intuitive geometries for pressurized habitats.

While all surface systems utilize the compressive force normal to the surface to react gravity, advanced habitat concepts may utilize more complex surface reaction forces. For example, shear forces and other three-dimensional forces can be reacted by the lunar surface using terrestrial technologies such as “flying buttresses” or simple tension elements anchored by “tent” stakes. Utilization of surface forces in the design of inflatable habitats may help reduce stress concentrations due to irregular geometries such as a dome or hemisphere.

Utilization of regolith on the roof and walls of a habitat to shield the internal volume from galactic cosmic radiation (GCR) particles is of high interest for long duration outpost missions. A thorough study of shielding using regolith is presented in Ref. 15. An average regolith density of 1.5 g/cm^3 is used to estimate the required depth of regolith needed for various levels of shielding. As indicated in Ref. 16, a 3 meter thick regolith shield produces a dead load of 8.3 KpA (1.2) psi. Again, this gravity load could be used to offset pressure induced loads for inflatable habitats if properly designed.

One inflatable structural concept that makes use of the above mentioned in-situ resources for a lunar habitat is the geodesic dome. The geodesic dome is an almost spherical structure based on a network of struts on the surface of a sphere. The geodesics intersect to form triangular elements that create local triangular rigidity and distribute the stress. Buckminster Fuller patented the Geodesic Tent¹⁷ concept shown in Fig. 8 in 1959. One lunar habitat concept is a “reverse tent”; a flexible network of struts tensioned by the internal pressure (tensioned net) in combination with a laminate membrane, to provide other functionalities (thermal management, MMOD protection, hermeticity, etc.). Surface reaction forces from the net/membrane structure could be managed at the habitat to surface interface. Regolith shielding could also be used if needed. While many other geometries are possible, the key to this concept is the high strength flexible net (pretensioned struts) that provides the primary load path to react the inflation pressure. (Pressure loading is critical for stability.) Another advantage of this concept is that the net intersections provide “hard” points for mounting of equipment and supplies within the habitat.

The Structures and Mechanisms project will utilize tasks A, B, D, E, G, and H to pursue development of near-term and long-term inflatable habitat technology. Emphasis will be placed on reducing the mass of current inflatable habitat designs through advances in material systems and structural concepts that take advantage of gravity and surface reaction forces. In addition, modular approaches to design and construction of outpost habitats will be pursued to enable incremental outpost buildup.



Fig. 8 Fuller Geodesic Tent (1959) (U.S PATENT - 2,914,074)

VI. Conclusion

Lightweight materials and structural systems are required to make the VSE possible. The Structures and Mechanisms project is a focused technology effort to reduce the mass (cost) and risk of future elements of the Constellation Program architecture. Both lunar lander and habitat applications of advanced metallic and composite structures are discussed.

For lunar landers, the structural design challenges for the pressure vessel are shown to include thermal management, MMOD protection, and radiation shielding. Advanced material systems have the potential to reduce pressure vessel mass by 26% based on the CEV command module studies as compared to Apollo era aluminum alloys. Detailed design will be required to assess the impact of minimum gage constraints on polymer matrix composites utilization and potential mass savings.

For lunar habitats, both rigid and flexible wall systems are discussed. Inflatable habitats show great promise due to their high packaging efficiency within the launch vehicle. However, state-of-the-art fiber reinforced, laminate membrane designs show minimal if any mass savings as compared to rigid wall pressure vessels. New inflatable habitat material systems coupled with advanced structural concepts are needed to realize the full potential of inflatable habitats. In particular, structural designs that take advantage of lunar resources (gravity and surface reaction forces) are needed to achieve low mass designs.

Project plans and goals for implementing a multi-year, multi-participant effort in lightweight structures technology development for NASA's Exploration Program are presented. All lunar systems must be low mass to achieve a viable space exploration architecture. Efforts to reduce cryotank and pressure vessel mass are of primary interest. Technology investments are also being made for risk reduction in mechanisms for lunar surface systems. The mass and risk reduction efforts of the Structures and Mechanisms project are crucial to the success of future lunar missions.

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