MORPHLAB: Modular Roving Planetary Habitat, Laboratory, and Base

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Abstract

On January 14, 2004, thirty-three years after the last Apollo mission, President Bush stated that a new and lasting human presence will return to the moon to explore and prepare for a manned mission to Mars. Through the Apollo missions, a large amount of lunar scientific data was gained; however, only a small portion of the moon itself was investigated. When developing a lunar base for long-term manned operations, traditional NASA design is a large permanent base with an extensive infrastructure. Such a design would tie a manned presence to one small area of the lunar surface.

The University of Maryland has designed an alternative solution to a permanent lunar base: MORPHLAB. MORPHLAB is composed of modules that assemble into a base, accommodating a crew of four for long-duration scientific exploration. Upon completion of a manned mission phase, MORPHLAB disassembles into modular components and drives across the lunar surface to the next site designated for human investigation. During this transit phase, MORPHLAB modules navigate and gather scientific data autonomously. Upon arrival at the new site, MORPHLAB reconfigures back into base mode and awaits the next crew. Operating in this manner, many different regions of the moon can be explored, yielding a greater amount of scientific data and an increased potential of scientific discovery while reusing base infrastructure.

1 – Introduction

1.1 –Description

Each MORPHLAB mission is divided into two distinct parts: a habitable phase and a transit phase. During the habitable phase of the mission MORPHLAB supports a crew of four who perform geological and life science experiments for three lunar day-night cycles, or months. During the unmanned transit phase of the mission, MORPHLAB components traverse up to 1000 km autonomously in three lunar day-night cycles, and can collect scientific information concurrently, increasing data collection capability.

MORPHLAB is a hybrid between a robotic and a manned exploration mission. The MORPHLAB design builds on the HABOT (Habitat Robot) concept developed by NASA engineers John Mankins and Neville Marzwell, which maximizes the utility of landed components while investigating a multitude of sites that hold scientific or technical interests. MORPHLAB is designed to utilize existing launch vehicles and to minimize total program costs. While the concept is designed specifically for lunar operations, the methods and technology developed can be applied to long-term goals such as the exploration of Mars.

1.2 - General Design Constraints

A set of externally applied design constraints were given for the MORPHLAB concept. The most significant design drivers are listed here:

- The MORPHLAB program will support a series of ten manned moon missions between 2015 and 2020.
- A manned mission shall consist of four crew members who inhabit the moon's surface for three lunar day/night cycles, or about three months.
- MORPHLAB components must be launched from the Delta IV Heavy or Atlas V Launch Vehicle. Specifics of the crew arrival and departure vehicle are not included in the scope of this program.
- MORPHLAB shall be designed such that it can accommodate the failure or loss of any single module at any time without significant disruption of nominal activities.
- Following the loss or failure of any two modules during a manned mission phase, MORPHLAB shall support the crew for a worst-case interval until a lunar launch window occurs and the crew can return.
- While designed for operation on the lunar surface, no design feature of MORPHLAB shall preclude its adaptation for use on the Martian surface.

- The design shall adhere to NASA STD-3000 specifications for crew systems.
- All system technologies shall be at a minimum NASA technology readiness level (TRL) of 3 on Jan. 1, 2005, and shall be capable of reaching a TRL of 6 by the technology cut-off date of Jan. 1, 2010.

2 - Revolutionary Design

2.1 - Modularity

By implementing modularity, the program may utilize existing launch vehicles. Multiple launches of smaller modules allow for landing the mass and volume necessary for a lunar base. In total, 16 modules will make up the main MORPHLAB infrastructure; one launch is necessary for each module. While each module provides a variety of functions, modules fall into three categories: habitable, chassis, and power. Habitable modules supply all the living space for the crew, chassis modules are wheeled drive trains that attach to the habitable modules and provide movement capabilities, and the power modules provide power to all modules. A MORPHLAB system is composed of six habitable modules, six chassis modules, and four power modules. By breaking down the MORPHLAB system in this fashion, a greater degree of redundancy and reliability is achieved compared to large infrastructure concepts. This design can withstand the loss of any one module without a significant reduction in system capability. The modules are also designed to take advantage of production learning curve cost savings.

The modularity of the MORPHLAB design can support different habitable phase and transit phase configurations. During the habitable phase of the mission, modules can be divided into two base structures in close proximity of one another in order to enhance exploration of the local mission site. During the transit phase of the mission, modules can travel in smaller, spread out groups with each group taking a slightly different route to the next base location. In this manner, more of the lunar surface can be explored.

2.2 - Systems Breakdown

Each module has its own designated launch and is designed to fit inside the dynamic envelope of the Delta IV Heavy launch vehicle. Following is a brief description of each module type.

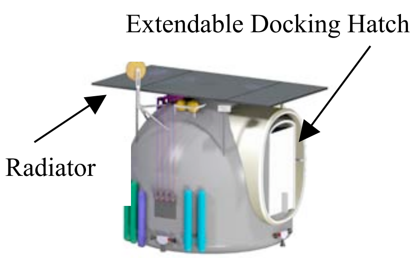


Fig. 1: Habitable Module

Habitable Module:

The dimensions of the habitable module are driven by the Delta IV Heavy payload shroud and by the life support habitable volume and floor space design constraints. To meet the minimum floor space of $61m^2$, there are six habitable modules having a 4m cylindrical diameter. Each has extendable docking hatches (see Fig. 1) to connect into a base. To save mass, the wheels and drive systems for these modules will be launched separately in a chassis module. The habitable module will land on legs, which will support it until the chassis module arrives.

Chassis Module:

The chassis module provides the wheels and drive system for the habitable modules. The chassis module positions itself below the habitable module. The habitable module then lowers and attaches itself to the chassis module. To fit inside the payload envelope, it employs a wheel structure expansion mechanism (see Fig. 2a and 2b). The wheels are stowed underneath the chassis during launch. After separating from the Delta IV, the wheels are deployed so that they stick out in the front and back. This larger wheel base allows for greater stability while traveling the lunar surface.

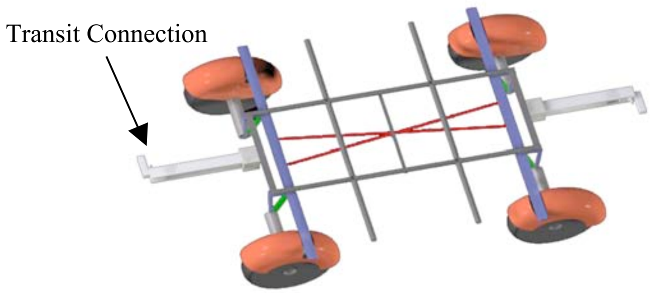


Fig. 2a: Chassis Expanded

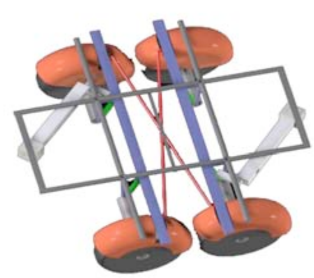


Fig. 2b: Chassis Collapsed

Power Module:

The main power supply used on Morphlab is a Dynamic Isotope Power System (DIPS). The DIPS generates electrical power from a radioactive heat source. To keep the radiation source away from the crew, the DIPS is placed on the uninhabited power module with a shadow shield. During base habitation, the power module is only connected by power and data cords and remains a safe distance away of 10m from inhabited modules. The power module has its own wheels, drive system, and avionics set. All obstacle avoidance and navigation control systems will be located in the power module. Each power module also has two robotic arms, based on the University of Maryland's (Space Systems Laboratory) Ranger technologies, capable of maintenance, gathering rock samples, and hardware manipulation. The module is also equipped to lift and carry the lunar rovers during transit.

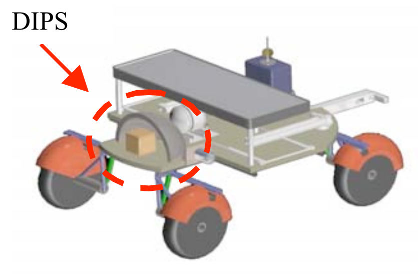


Fig. 3: Power Module

Vehicle Assembly (Transit Configuration):

For transit, modules configure into vehicle assemblies, which are connected via the transit connections on each chassis (see Fig. 2b). Each vehicle assembly consists of two habitable modules (each on its own chassis module) and a power module, resulting in three vehicle assemblies. The fourth power module drives on its own. The transit connections join power and data cords between modules. Each power module supplies enough electricity to power all three drive systems to which it is attached. Assemblies travel autonomously to the next base site, communicating through the transit connections inter-assembly and by short-range radio between assemblies.

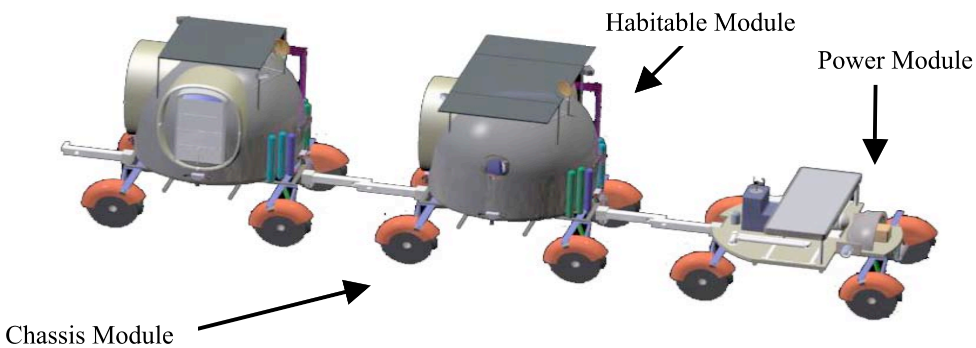


Fig. 4: Vehicle Assembly Transit Configuration

Base Assembly:

Upon arrival at the base site, the modules locate the best surface for base assembly. The transit connections disconnect from each other and modules reconfigure into the orientation best-suited for the science objectives of the next manned mission. Once positioned correctly relative to each other, the modules extend the docking mechanisms at each hatch door and set up airtight connections. Once those have been established, the modules pressurize the inflatable tunnel and move the walkways into place. The transit systems shut down and all inter-module computer systems are initialized to prepare for crew arrival.

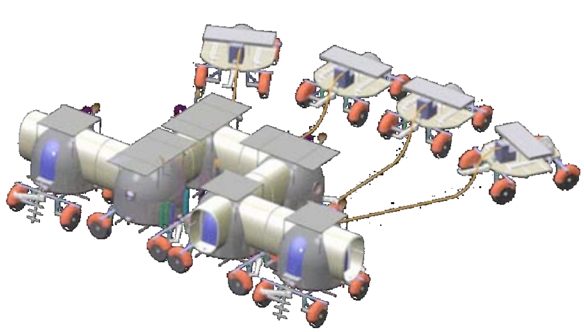


Fig. 5a: Base Assembly Configuration

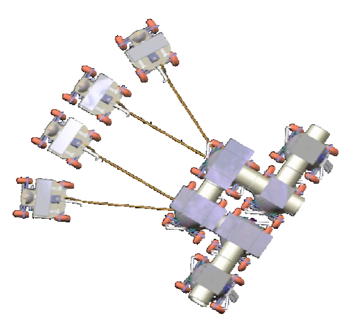


Fig. 5b: Base Assembly Top View

2.3 - Timeline

The MORPHLAB project begins in 2005 and must land humans beginning in the spring of 2015. This allows ten years to design, manufacture, test and launch modules. Looking back in history at the Apollo and Shuttle programs, an overall program timeline can be derived. The design and manufacturing phase for each of the previous programs was five years; MORPHLAB will be designed and manufactured from 2005-2010. Apollo tested for two years and the Shuttle tested for four years, therefore taking an average, three years has been approximated for the testing phase of MORPHLAB from 2010-2013. The modules will then be launched 2013-2014 and each will land at local lunar dawn. Starting in June 2015 the manned missions will begin.

In May 2015, the first MORPHLAB base will be fully assembled and ready to begin five years of manned missions. The first mission will begin with an unmanned phase lasting one month to fully test all systems followed by a manned phase lasting two months. All subsequent manned missions will last three months each, separated by three months for disassembly, transit, and reassembly. Initially, there will be ten manned missions with the ability to extend to the program further.

3 - Lunar Operations

3.1 - Geological Science Objectives

In a manned mission to the moon, much of the crews' time will be spent performing geological research, especially during EVAs. The geological goals of MORPHLAB can be divided into three main research objectives: volcanic and impact history, deep lunar composition, and water ice and ore deposits. Geological discoveries, along with existing information obtained from the Apollo program and recent satellite probes, will determine the program trajectory or path that MORPHLAB will follow along the surface of the moon.

Selection of the ten assembly sites was based on the following criteria: age of lunar structure (younger being more enticing), location of particular ore deposits, permanently shadowed regions near the poles (potential for water ice), interesting structures (lava tunnels for example), and former Apollo landing site possibilities. All potential assembly sites were put in a prioritized order, and ten were selected based on priority and distances. MORPHLAB's assembly sites can be seen in Table 1 and in Fig. 6.

The geological instruments utilized on MORPHLAB will be similar to those used for Apollo. The soil collection instruments will be the same, with few modifications. Because of the length of a mission, the crew will collect more rocks than were possible during Apollo. They will be trained to sort through collected rocks, and about 300kg will be sent back to Earth with the crew. There will also be small spectrometers onboard for preliminary analysis of geological specimen. This will allow for identification of soil samples to get a better understanding of the moon's volcanic and impact history. MORPHLAB is equipped with autonomous manipulators to gather soil samples during the transit phase while the crew is gone. Seismic instruments similar to the Apollo Lunar Surface Experiment Package (ASLEP) will be deployed across the lunar surface. Since MORPHLAB will cover more lunar surface than Apollo, it can cast a larger seismic "net" to get a better idea of deep lunar composition. The crew will also examine two Surveyor spacecraft to study the long-term effects of the lunar environment on equipment.

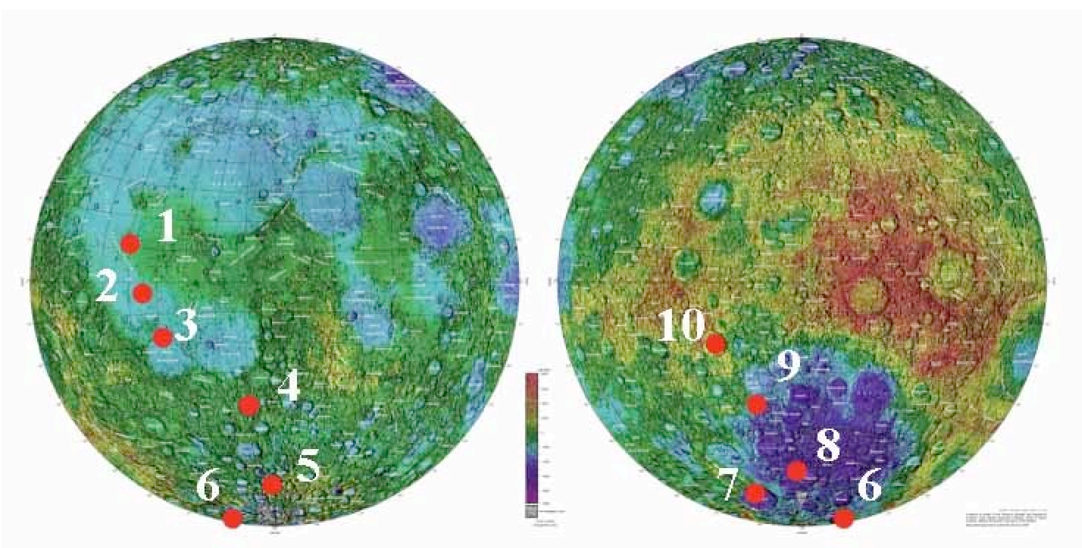


Fig. 6: Topographical Assembly Site Layout Map

Table 1 – Assembly Site Distances

Assembly Site	Distance To Next Site (km)	Driving Distance (km) (+ 30%)
1) Marius Hills	515	670
2) Flamsteed Crater P	479	623
3) Gassendi Crater	966	1256
4) Tycho Crater	911	1184
5) Moretus Crater	553	719
6) Drygalski Crater	212	276
(go through South Pole)	546	710
7) Schrodinger Crater	562	731
8) Minnaert Crater	822	1069
9) Mare Ingenii	539	701
10) Gagarin Crater		

3.2 - Life Science Objectives

Since MORPHLAB is designed for long duration missions, it is ideal for studying how the lunar environment affects life. These effects have been divided into 8 categories or objectives for study: radiation, skeletal system, cardiovascular system, muscle development, human performance, crew dynamics, nutrition, and plant/animal biology. Much analysis in these categories has already been performed in microgravity onboard the International Space Station (ISS), but very little data on 1/6th gravity exists. MORPHLAB intends to continue this type of research in the lunar environment, providing a broader insight into the effects of reduced gravity, perhaps paving the way to colonization of the moon. While on the moon for three months, the crew will undergo extensive tests in order to accomplish both MORPHLAB's science objectives and to monitor their health. From research on ISS, it is known that within 8 days 4-10% of muscle can decay, and actual bone loss in areas such as the lumbar spine and hip can be up to 1.5% per month without exercise. Further studies, on topics such as muscle atrophy and depletion of the skeletal system, will be performed onboard MORPHLAB to better understand the effects of long duration exposure to lunar gravity. Scientific experiments containing plants and animals will be under autonomous control during the transit phase to allow for studies of even longer exposure to the lunar environment.

The crew of MORPHLAB will stay on the moon for 3 months. It is projected that with exercise in lunar gravity muscle strength will decrease by approximately 17% and bone decay will be approximately 2%. Because the crew must stay healthy and physically fit during their stay on the moon, MORPHLAB will have a variety of equipment on board to maintain, monitor and protect the health of the crew. All life science equipment is stowed in three racks, one in each of the three habitable science modules. Each rack is equipped with its own workstation.

3.3 - Extra-Vehicular Activity

To accommodate the design constraints of daily EVAs the I-Suit will be used. The suit is designed to operate at 25.9kPa (3.75psi) to optimize mobility. The suit has an 8 hour air supply. The I-Suit is a soft suit, providing for easier repairs and smaller storage areas than a hard-bodied suit.

Design constraints also dictate that a rover is needed since the astronauts must be able to explore within a radius of 10km from the base. MORPHLAB will have two rovers, one to be used for each EVA and one to be left at the base as a backup. Each rover can carry two crewmembers to and from an EVA site, as well as transport soil and rock samples. They are also used to transport the astronauts and supplies from the landing vehicle to MORPHLAB. The rovers will be based on the Apollo Lunar Roving Vehicle (LRV), but modifications will have to be made to the rovers' communication and control equipment, as well as its batteries. The rovers will need sufficient communications arrays, cameras, and control equipment to be teleoperated from the modules. MORPHLAB has to allow for an 8-hour EVA each day during manned operations, so to accommodate this the rovers will use two rechargeable 36V lithium-ion batteries that can recharge from the power modules.

4 – Avionics

4.1 - Landing Autonomy

MORPHLAB will be capable of landing completely autonomously. High resolution maps as well as onboard sensors and cameras will enable the first module to touchdown within a 100m radius. Subsequent landings will be capable of higher accuracy due to infrastructure already on the surface assisting with the landing maneuvers.

In 2010, a mapping satellite will be launched into Low Lunar Orbit to gather high-resolution topographical maps of the lunar surface using high-resolution photography. The maps will be used to determine safe and unsafe landing zones, potential transit obstacles, and possible areas of further interest.

While on route to the moon, the modules will use an inertial mass unit (IMU) and a star tracker to determine orientation. Navigation will be managed from the ground prior to beginning the landing maneuver. During the descent phase, all navigation and guidance decisions will be determined using MORPHLAB's systems. The power modules will be the first to land, and will be equipped with a full landing sensor suite, comprised of three LIDAR systems, three video recorders, a star tracker, an IMU, a 10cm communications dish, and an omni-directional UHF antenna. LIDAR will be used to scan the surface for obstacles and gather altitude information. The video recorders will be used to determine horizontal velocity. Once landed, the power module will separate from the landing engines and proceed to generate obstacle maps of the terrain using the LIDAR systems. Subsequent landings will utilize this data to assist in their descent.

Once all four power modules have landed, they will deploy themselves into a diamond formation with 100m sides about a suitable landing area. This formation will be used to triangulate and provide guidance to future landings, because all other modules will be equipped with less advanced sensor packages. The chassis modules will land next, relying on real-time guidance from the power modules. After the safe landing of the chassis, a power module will drive to it, use the robotic arms to remove the landing engines, and establish a power connection. This connection will be accomplished within 24 hours before the chassis module's onboard batteries deplete.

The habitable modules will land using the same guidance concept as the chassis. A power module will then bring a chassis to the landing site. Its robotic arms will remove the landing engines, and the chassis will then position itself underneath the landed habitable module. Once in place, the habitable module will lower itself onto the chassis, the landing legs will be removed by pyrotechnics, and a permanent connection will be established. This process will also be accomplished within 24 hours.

4.2 - Transit Autonomy

Basic transit paths have been chosen from analysis of 1994 Clementine lunar mapping data (see Fig. 7 for an example). Before the first mission begins, data from the mapping satellites will be used to refine the planned course. Scientists on Earth will compare the "ease" of travel with the possible scientific gain of taking one route over another.

Primary control is left to MORPHLAB's computers to determine the exact course in real-time. The power module's on-board sensors will be monitoring the immediate terrain in front of the vehicle assembly, checking for unexpected obstacles that would require deviation from the pre-programmed path.

The power modules will use the same sensor suite used in landing operations to determine position and orientation of the entire vehicle assembly. Current LIDAR systems are sufficient for MORHPLAB, having a scanning range of 80x340 degrees and performing a full range scan once every 15 seconds.

Even though the vehicles will update the transit path autonomously, telemetry will be constantly streamed to Earth both for monitoring and for scientific reasons. In the event of an unforeseen obstacle, ground crews on Earth will be notified immediately. Ideally, onboard systems will be able to handle any situation that may arise, but in the event that a path modification is taking too long, the base will halt and wait for instructions from Earth before continuing.

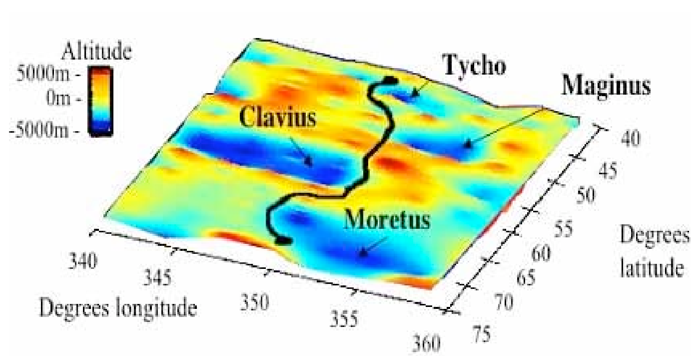


Fig. 7: Transit Path Selected for Fourth Traverse Based on Clementine Topographical Data

4.3 - Communications

Design constraints for the mission require two HDTV channels from, and one channel to MORPHLAB, in addition to a bidirectional data transmission rate of 10Mbps. Current bit-rates for a compressed HDTV channel are approximately 20Mbps; therefore, MORPHLAB will be able to send 55Mbps and receive 33Mbps. Surface communication between the rovers and modules requires bidirectional transmission of 5Mbps for control and sensor data with a single HDTV transmitted back to the base for visual monitoring: a total of 30Mbps.

Due to the large bit-rate requirements and long range, parabolic dishes will be used to communicate with Earth using high-frequency Ka-band. Short range, lower bit-rate communications between modules and rovers will be accomplished through omni-directional UHF antennas. On the near side of the moon a communications link will be established directly to DSN's 34m arrays. All sizing and power requirements are determined by far side communications. This is accomplished through relay satellites in halo orbits around the Earth-Moon L2 point. Each halo satellite will use a deployable, fully gimbaled antenna with a 5m diameter to communicate with the modules. A separate 30cm parabolic antenna will be used for relaying the communications back to Earth. This communication array will require less than 100W of power. Although only a single communications suite needs to be operational to fulfill the requirements, for redundancy and increased capacity each habitable module will use a 50cm dish, drawing 15W to provide the full communications capability. Each power module will have a 10cm parabolic dish drawing 15W, which provides only the bidirectional 10Mbps for control and sensor monitoring prior to the habitable modules' landing. The rovers' communications suites draw 45W, and will be equipped with an omni-directional UHF antenna as well as a 10cm dish in case of UHF communications loss with the main base.

5 - Module Details

5.1 – Habitable Module

Habitable modules provide the space where the crew will live and work while not out on EVA. Three of the six modules serve as living quarters and a galley-recreational area (habitable-living), while the other three modules are work areas that contain science equipment and EVA tools (habitable-science); this breakup allows minimal disruption if the astronauts have different sleeping schedules and restricts lunar dust to the EVA areas. Functions are distributed and redundant so that the failure of any one module will not disrupt normal activities.

***Sizing Requirements**:*

All crew interfaces are sized to accommodate 95th percentile American males to 5th percentile Japanese females. The basic body dimensions used were taken from relevant sections of the NASA-STD-3000 document. The size of the modules is bounded by the maximum size of the launch vehicle payload area – the interior diameter of the dynamic envelope in the payload area is 4.5m – and the minimum amount of room necessary for four people in the same module – 10.24m^2. Accounting for the wiring and pipes through the walls and the furnishings, while leaving enough space in the middle of the modules to move about and keeping the module mass reasonable, the habitable modules are 4.0m in diameter, which gives 12.56m^2 of floor space per module.

Pressure Hull:

The exterior module pressure hull is constructed out of 4mm thick aluminum 2014. This thickness was chosen based on pressure loads and micrometeoroid protection requirements. Using the micrometeoroid flux on the lunar surface, and a .999 probability of no penetration, the required skin thickness is 4mm. As will be described later in this section, the internal pressure is 57.2kPa, so for hoop stress on the upper cylindrical part of the module there is a safety margin of 4.7. However, the bottom of the module has a flattened curved shape, and the stresses are increased here. Based on finite element analysis, certain portions of the bottom exceed the maximum allowable stress of 164MPa. These sections will be reinforced with 2mm of aluminum, and FEA with a 6mm thickness shows that the maximum stress in this case would be 160MPa.

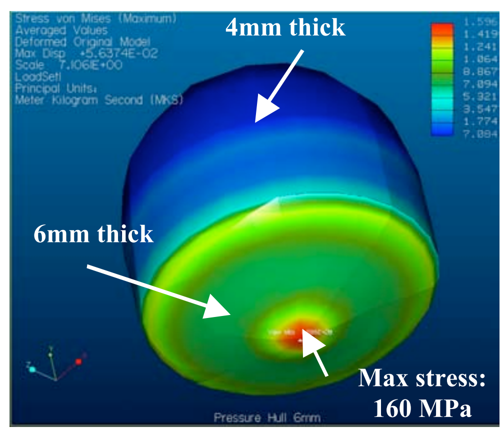


Fig. 8: Pressure Hull Finite Element Model

Stringers:

The Delta IV-H launch vehicle imparts on the payload 2.9 g's transverse acceleration and 9 g's axial acceleration. Six stringers secured to the pressure hull's interior carry these launch loads. The maximum stress applied to the stringers is 365MPa. In addition, a frame is positioned 0.35m above the floor space to increase the stringers' critical Euler buckling stress. The weight of the stringers and frame is 71kg, and the stringers' safety margins for axial and Euler buckling are zero.

Landing Gear:

The landing gear for a habitable module consists of four frames spread around the module at 90° intervals. Each strut on the frame is connected to a stringer that delivers loads from the module to the legs. In addition, the struts contain crushable aluminum honeycomb to alleviate the landing loads. Design constraints for MORPHLAB demand capability of touchdowns on 10° slopes with 0.5m obstacles. In addition, the modules may have a residual horizontal velocity of 1m/s and a residual vertical velocity of 0.5m/s. These requirements were applied to the design of the landing legs to assure the stability and structural integrity of the module and the legs at touchdown. Table 3 lists the critical design loads, masses and safety factors for each strut in the frame. Furthermore, each frame is equipped with pyrotechnic mechanisms that allow the legs to jettison after the habitable module has lowered itself onto a chassis module.

Fig. 9: Habitable Module Landing Gear

Docking Mechanisms:

The pathways between modules consist of sliding hatch doors, a folding walkway, and a telescoping tunnel (see Fig. 10b). When closed, the double sliding doors are flush with the hull and provide a seal from the outside vacuum. The hinged exterior door folds into a cantilever t-beam to provide a walkway for the crew (see Table 3 for structural analysis). Closed during transit, it acts as a dust cover to the interior sliding doors. The tunnel is an inflatable Kevlar material with an aluminum ring on the end and latches for connecting to another tunnel. The ring is supported by three telescoping rods, which can extend up to 1.5m from the habitable module. The telescoping rods also act as water pipes between modules. The size and structure of the tunnel can accommodate a 95th percentile American male.

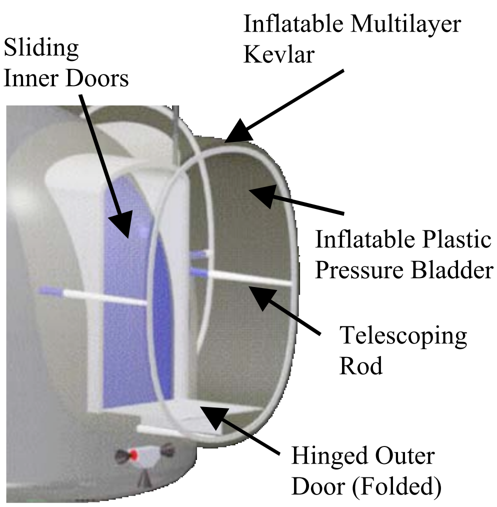


Fig. 10a: Docking Mechanism Cut-Away

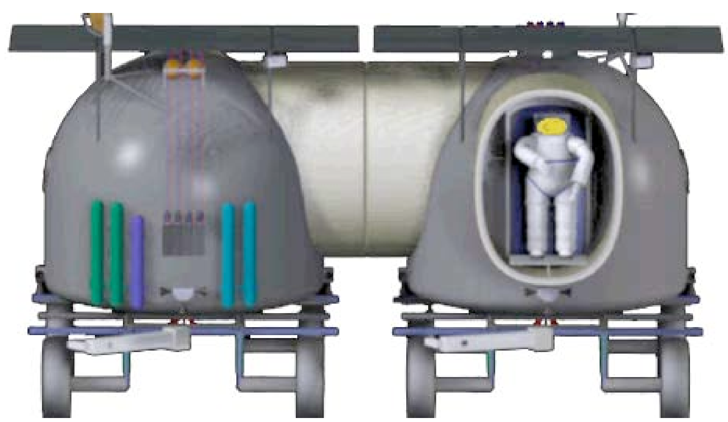


Fig. 10b: Tunnel Extended and Connected

Windows and Floor Panels:

Module windows are circular and designed to withstand the cabin pressure of the modules: hatch (0.5cm thick, 0.51kg, 20.32cm diameter), living module (1.24cm thick, 7.95kg, 50.8cm diameter), and science module (1.37cm thick, 10.6kg, 50.8cm diameter). The panes are made of Thermo-Sil® UHS fused silica. Each window has two pressure panes for redundancy and a sunshade. In-plane vertical loads are sustained by stringers attached to the window frame. The floor panels for the modules deflect less than 1cm under distributed loads of 0.28psi. Each floor panel is a composite sandwich made of Carbon fiber/epoxy skin 1mm thick and Alcore Commercial Grade Aluminum Honeycomb (CGH™) core 5mm thick and weighs 2kg.

Habitable-Living Module:

There are two subtypes of habitable-living modules: two crew quarters modules, and one galley module. Both types include radiation shelter sleeping areas in the basement level, under the floor, with ECLSS systems taking up the remaining space. Both types have two hatches that intersect the module in an L-shape (see Fig. 11a and 11b). The working level in the crew quarters includes a sanitation area, two changing areas, and a main area, which are all sectioned off by privacy curtains. The working level in the galley includes a lounge area, a food prep area, and an exercise area, which are all open to each other. The galley also has the capability to be transformed into crew quarters for redundancy. There is a partial bathroom behind a false wall and the food can be moved to another location so that the storage areas may be used for clothes.

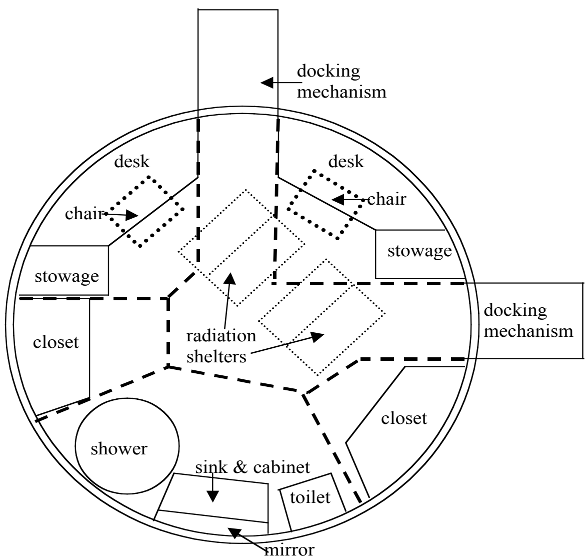


Fig. 11a: Habitable-Living, Crew Quarters (Top View)

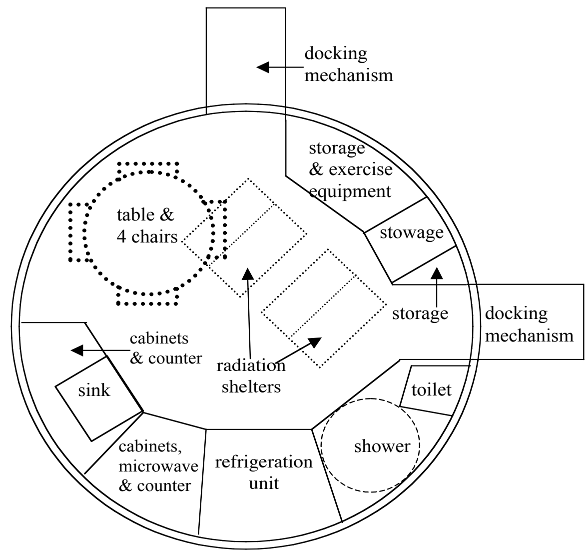


Fig. 11b: Habitable-Living, Galley (Top View)

Radiation Shelter Sleeping Areas:

Galactic cosmic radiation (GCR), a constant source of ionizing radiation, and solar particle events (SPEs), solar flares that give off large radiation bursts, can cause serious health problems if the proper shielding is not in place. Received radiation doses to the astronauts are designed to stay below the NASA set limits: 25rem to BFO (blood-forming organs) in 30 days and 50rem to BFO annually. The pressure hull, 4mm thick aluminum, serves as GCR shielding. The radiation shelter sleeping quarters, surrounded by 5.8cm of polyethylene shielding, protect against SPE events and lessen the GCR dose received during sleep. These quarters are built into the basement of the habitable-living modules. They are 1.9m long by 1.95m wide by 0.8m tall and can accommodate two people each. Two doors are built into the top; each door splits and opens downward into the sleeping quarters in two sections. The sleeping quarters are split in half by a noise-muffling curtain for privacy, so in the event of an emergency (if, for instance, one of the doors will not open) an astronaut may move the curtain aside and exit via the second door. In the event of an impending SPE, the astronauts will be informed by Mission Control and retreat to the shelter for the duration of the event. The crew will be able to maintain contact with Mission Control via their laptops, and they will have access to whatever libraries and amusements that they can download from NASA computers.

Habitable-Science Modules:

There are two subtypes of habitable-science modules: two EVA workspace modules, and one experiment area module. Both types include ECLSS systems in the basement level, with storage compartments for experiments and less-used tools taking up the remaining space. Both types have three exits that intersect the module in a T-shape (see Fig. 12a and 12b). The working level in the EVA workspace includes an EVA airlock at the base of the T-shape (replacing the normal door hatch) and scientific equipment. The EVA workspace also contains a lounge area, where the crew can take a break, monitor the EVA on the television screen, or gather during downtime. The EVA airlock protrudes into the working area of the module and is sealed off except when an astronaut is cycling through for an EVA. The working level in the experiment module includes a main work area and a small food prep area for redundancy of the galley module. This area also serves as a junction between the different parts of the base.

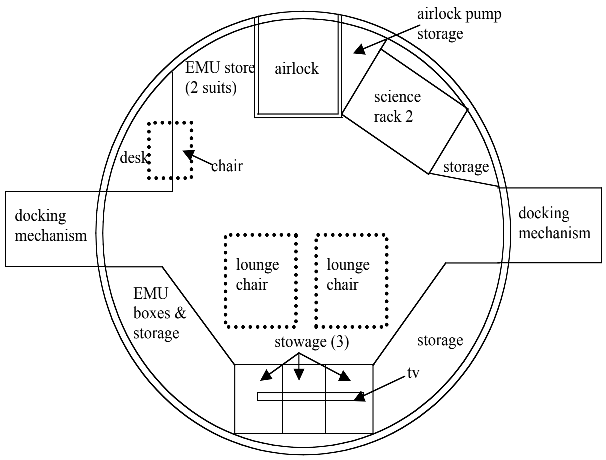


Fig. 12a: Habitable-Science, EVA Workspace (Top)

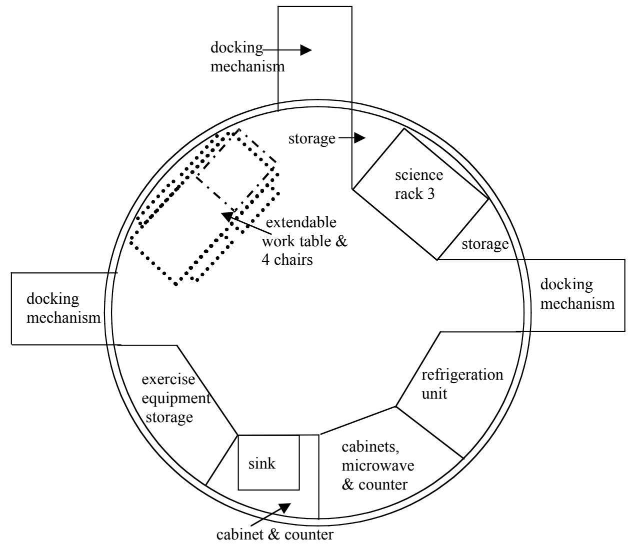


Fig. 12b: Habitable-Science, Experiment Area (Top)

Cabin Atmosphere Selection:

From the given design constraints, our design needs to allow for zero pre-breathe time for EVAs. Therefore, the ratio of the nitrogen partial pressure to the pressure of the suit R value must less then 1.6. The oxygen levels needed to be high enough to prevent hypoxia, but not too high as to cause hyperoxia. Finally the risk of a fire hazard needed to be considered. These requirements settled the internal atmosphere of the modules at 57.1kPa (8.3psi), with a mix of 40% O_2, 59% N_2, and 1% CO_2. This make-up gives us an R value of 1.3.

Environmental Control and Life Support Systems (ECLSS):

The ECLSS systems are divided between modules to reduce mass. This is done because the radiation shelter sleeping areas in the living modules are very massive, and an even mass distribution between the modules is desirable. The habitable-living modules house the two-person capable systems that process solid and liquid waste products: Super-Critical Waste Oxidation (SCWO) for solid waste disposal, Vapor Phase Catalytic Ammonia Removal (VPCAR) for urine processing, and Multifiltration for water-recovery. The habitable-science modules house the crew-capable systems that filter and maintain the cabin atmosphere and create water: Water Vapor Electrolysis (WVE) for O_2 generation, Trace Contaminant Control (TCC) for air filtration, Sabatier for water generation, and Electrochemical Depolarized Cells (EDC) for CO_2 removal. The ECLSS systems are integrated between modules through the docking mechanisms. Water is circulated via tubes running through the center of the telescoping rods (see Fig. 10b). Air fans circulate the air through the modules via the docking tunnel. Water, oxygen and nitrogen supplies are replenished before each manned mission by launch of a logistics depot.

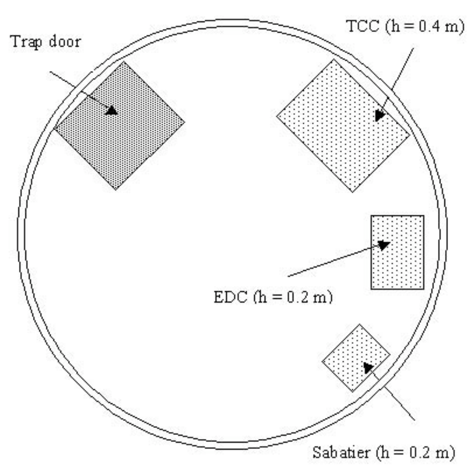


Fig. 13a: Habitable-Science Basement Level

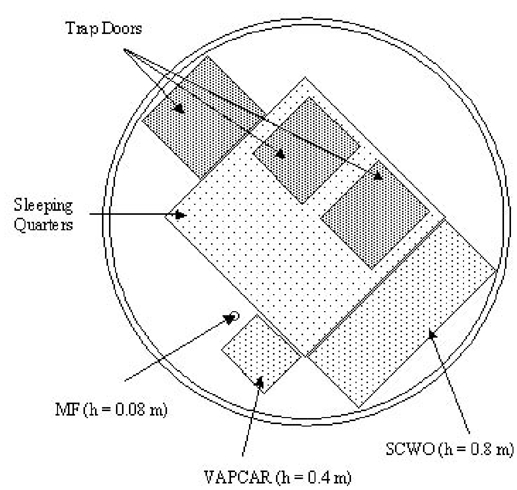


Fig. 13b: Habitable-Living Basement Level

Table 2: ECLSS Subsystem Details

	O_2 Generation	CO_2 Removal	CO_2 Reduction	Trace Cont. Control	Water Distillation	Water Filtration	Solid Waste
Subsystem	**WVE**	**EDC**	**Sabatier**	**TCC**	**VAPCAR**	**Multifiltration**	**SCWO**
Weight (kg)	144.00	44.40	17.90	100.00	68.00	3.9000	694.00
Volume (m^3)	20.0	0.07	0.04	0.30	0.24	0.0012	2.12
Power (kW)	1.60	0.15	0.05	0.15	0.10	0.0004	1.44

Logistics Depot:

Before each manned mission, it is necessary to re-supply the MORPHLAB system with food provisions and gas tanks that contain oxygen and nitrogen. This is accomplished by the launch of a logistics depot, which is the external hull of a habitable module with re-supplies in place of the internal equipment. In addition to normal provisions, the first logistics depot will contain two mobile Robonauts and two lunar rovers for use throughout the program. Robonaut has been demonstrated to function on wheels and will assist in loading supplies from the depot.

Food Storage:

Internal storage space is limited: the entire supply of food for three months cannot be stored indoors all-at-once. This is also impractical because the interior space where the food would be stored would slowly empty over time but would not become useable space. Therefore, the majority of the food supplies will be sent up in the logistics depot before every manned mission and stored there until needed. One of the EVA activities will be to replenish the food supplies every week-and-a-half.

Safety Systems:

Sensors for air and water composition, pressure levels, and system integrity are incorporated into the appropriate module systems. These sensors are all tied into a monitoring computer system (MCS), which tracks changes in the levels. If an optimal level is not met, the MCS issues commands to the appropriate to make adjustments. This system also communicates problems to the crew via yellow and red alert alarms when problems occur. Necessary fire prevention is minimal because of the atmospheric composition; when a fire does occur, fire extinguishers are present to put out small fires. Health monitoring occurs on a daily basis, and is part of the exercise routine for data collection on the effects of a low-gravity environment on the human physiology.

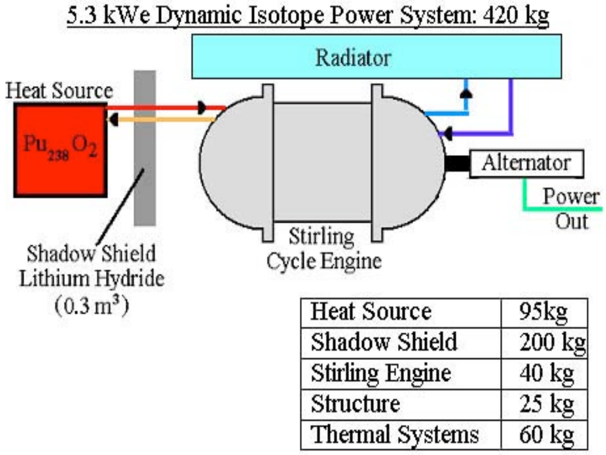
5.2 – Chassis Module*:*

The locomotion of a habitable module is provided by a chassis module. By separating this function from the habitable module, the mass of the wheels and drive system can be relocated to other subsystems. The chassis is able to land on its wheels. After locating its respective habitable module, the chassis drives beneath it. Onboard sensors line up four holes with pins on the habitable modules, after which the legs of the habitable module lower it onto the chassis. The chassis module wheels are spherical wheels with a diameter of 1m and a width of 0.4m. These dimensions allow the wheels to sink 4cm into the lunar soil. The 1m diameter wheels allow the chassis to drive over 0.5m obstacle and prevent the vehicle from bottoming out when going over a hill of with 30° incline uphill followed by 30° incline downhill. Furthermore, the wheels are constructed of 0.5mm aluminum 2014, and their margin of safety is 1 for a puncture load of 26kN applied over a 17cm arc.

5.3 – Power Module

The power module is designed as a modified chassis module with additional subsystems. The main purpose of the power modules is to house the DIPS (see Fig. 14 for DIPS schematic). Each power module has a 5.3kWe DIPS generator which is sized to meet vehicle assembly and base assembly power needs. A DIPS system (with shadow shield) has a specific power of 12.5W/kg, and offers advantages such as: constant power generation, ten year design life, low system maintenance, and a .9955 reliability of operation without a single point failure.

The DIPS design uses 95kg of Coated Particles Fuel Compacts (CPFC) for the general-purpose heat source. CPFC are composed of $^{238}PuO_2$ and offer a specific heat output of 214W/kg. With the 95kg of fuel, approximately 20kWt will be produced for transfer into the stirling cycle engine. System electrical power output is 5.3kWe, giving the DIPS an efficiency of 26.5% (RTGs have a efficiency 12%). To limit crew exposure to radiation, a lithium hydroxide shadow shield is placed in front of the fuel on the power module. To decrease needed system mass, the power module will remain 10m away from inhabited modules (see Fig. 15).



Heat Source	95kg
Shadow Shield	200 kg
Stirling Engine	40 kg
Structure	25 kg
Thermal Systems	60 kg

Figure 14: 5.3 kWe Dynamic Isotope Power System

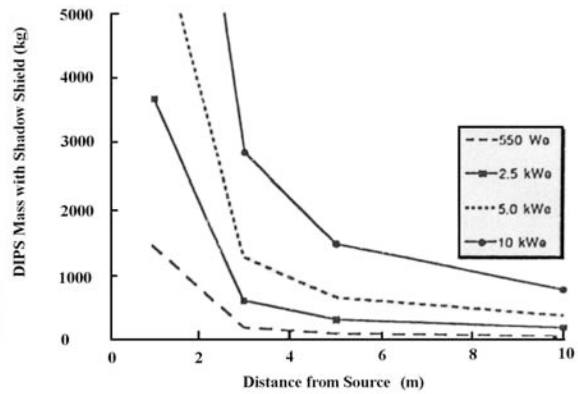


Fig. 15: DIPS System Mass vs. Distance from Source (.22 REM Over 90 Days)

5.4 – Power Usage*:*

The MORPHLAB power budget is dependant on the current phase of the mission (see Fig. 16a and 16b). The main power supply consists of 4 DIPS which are sized to meet system average power consumption. During transit phase, one DIPS can meet the average system needs of a vehicle assembly. Under higher loading conditions, the DIPS power output will be supplemented by a peak power system composed of rechargeable lithium-ion cells. The peak power supply system is broken up among the non power modules (44kg per chassis, 101kg per habitable modules) and can deliver 36kWhr to each vehicle assembly. In base configuration, three power modules can supply the average power consumption of the base. Peak power can be supplied by the 4th power module, or the combined charge stored in the lithium-ion battery bank. The total battery bank has a storage capacity of 108kWhr.

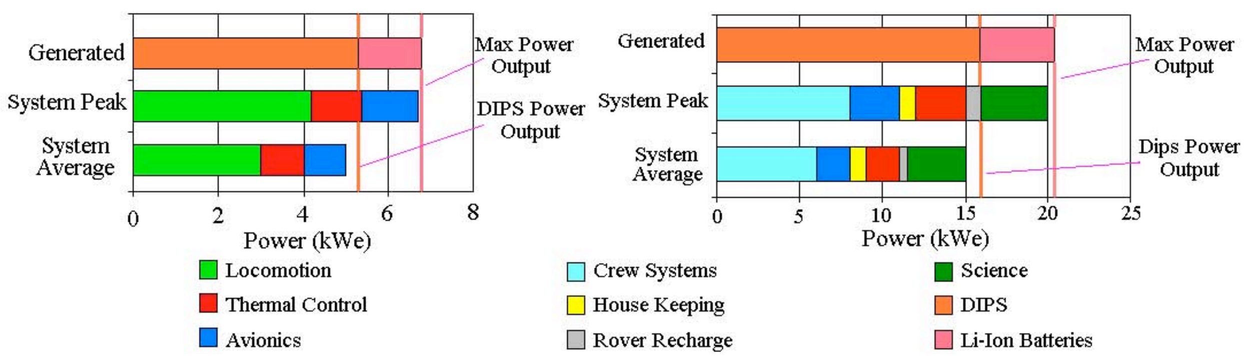


Figure 16a: Transit Power Generation / Budget **Figure 16b: Base Power Generation / Budget**

5.5 – Thermal Control Systems*:*

Thermal Control will utilize a passive system, which requires fewer moving parts, costs less, and is more robust than an active system. MORPHLAB's passive system involves YB-71 surface coating with an absorptivity of .12 and emissivity of .92 to minimize solar heating effects. It also consists of Multilayer Reflective Insulation (MLI) that allows the module to stay warmer at night with less required heat, and Carbon Aerogel for seams and heat leakage paths where the MLI will not suffice. The MLI is comprised of thin layers of metal-coated polymer that are separated by a vacuum. This insulation is assumed to keep the module at an ambient reference temperature of 298K during the lunar nighttime. Variable conducting ammonia-filled heat pipes will transfer the internal heat to the honeycomb-horizontal radiator with a surface absorptivity and emissivity of .08 and .92 respectively. The habitable-living module will have a radiator area of 13.3m^2 to dissipate 4kW of energy while the habitable-science module will have an area of 7.7m^2 to dissipation 2.3kW. Heat will flow through the radiator via ammonia-filled capillary heat loops. During lunar night and polar expeditions, parts of the radiator will be shut down to keep more heat in. The radiator lies horizontally so it always faces deep space and therefore "sees" 4K. Only the solar flux during daytime affects the thermal equilibrium. There is enough MLI on the bottom of the radiator to act adiabatically and protect it from reflected infrared radiation and lunar albedo. The habitable-living radiator is about 71kg while the habitable-science is about 40kg. The YB-71, MLI, and Carbon Aerogel mass is less than 10kg.

5.6 – Structural Analysis Summary

Table 3: Structural Safety Margins	Safety Factor	Applied Load	Margin of Safety	Failure Mode
Pressure Hull	3	57.2 kPa	2.8	Pressure
Stringers – Cylindrical Section of Hull	2	510 MPa	.078	Compression
Landing Leg – Primary Strut	2	984 MPa	.00576	Buckling
Landing Leg – Secondary Strut	2	460 MPa	.202	Buckling
Landing Leg – Foot Pad	2	238 MPa	1.31	Bending
Radiator Connectors	2	437 MPa	.257	Bending
Descent Engine Truss Structure	2	3500 N	.50	Bending
Docking Module Walkway	2	179 N	.01	Bending
Transit Connector	2	100 N	204	Shear stress

6 - Getting to the Moon

6.1 – Launch Vehicle, Thrust Structure, and Trajectory

One of the design constraints for MORPHLAB was that all components must designed for launch on either a Delta IV Heavy or an Atlas V launch vehicle. The goal of the MORPHLAB program was to perform no in-orbit rendezvous, so the launch vehicle decision was based entirely on Low Earth Orbit (LEO) mass. The Delta IV-H was chosen for MORPHLAB launches because it can place 25,800kg into LEO compared to the Atlas V-551's 20,000kg.

Fig. 17: Thrust Structure With Habitable Module

The trajectory determination was broken down into two components: first, getting from LEO to the Lunar Approach Orbit, and second, getting from Lunar Approach to Lunar Landing. The first part of the trajectory can be broken down into three burns. The first burn puts the MORPHLAB module into the Lunar Transfer Orbit. A burn of 3.14km/s is performed which puts the module into a Hohmann transfer with apogee being 50km above the surface of the far side of the moon. The second burn is performed at apogee. At the time of the burn the module has a hyperbolic excess velocity of .84km/s so the velocity at which the module appears to be moving relative to the moon is 2.51km/s. Therefore, to enter a circular low lunar orbit (LLO) of altitude 50km, a burn of .84km/s must be performed. The last burn to be performed in the Lunar Approach phase of the trajectory is the descent burn, .01km/s, that brings the module to an altitude of 10km and prepares it for landing.

Fortunately the difficult landing trajectory does not need to be calculated because the Apollo program had a 100% success rate with their approach, making it an obvious choice for MORPHLAB. The Apollo program split the landing maneuver into three separate components: Braking, Approach, and Landing. For MORPHLAB however, the landing maneuver will be broken into two components appropriately named Braking/Approach and Landing. The point at which the maneuver switches to the Landing portion will be Low Gate or approximately .15km moving with a velocity of 16m/s horizontal and 4.9m/s vertical relative to the surface of the moon. The burn required to reach Low Gate is 1.88km/s and the amount of ΔV remaining to hover and land the vehicle is 0.26km/s. Table 4 summarizes all of the burns required to travel from LEO to the surface of the moon.

Table 4 – Summary of Burns

Burn Number	**Burn Description**	**ΔV**
1	LEO to Lunar Transfer	3.14 km/s
2	Lunar Transfer to Low Lunar Orbit	0.84 km/s
3	Lunar Descent	0.01 km/s
4	Braking and Approach	1.88 km/s
5	Landing	0.26 km/s
TOTAL ΔV REQUIRED		**6.13 km/s**

6.2 - Rocket Engine Selection

Due to the limited amount of mass that can be launched into LEO it is very important that the propellants used to perform the necessary maneuvers are efficient. Therefore, the decision was made to go with cryogenic propellants because their specific impulse (Isp) values are generally 100s higher than storable propellants. The criteria considered when selecting an engine were Isp, mass, and technology readiness. The Pratt and Whitney RL-10B-2 engine was selected due to its high Isp (465s), low mass (277kg), its high TRL of nine, and its years of use. It will be modified to provide thrust throttle control so it is able to perform the Braking and Approach maneuvers.

One problem with the RL-10B-2 is the size of the engine. When the extendable nozzle is in the stored position the nozzle is just over 4 meters in length. With the nozzle extended, the length nearly doubles; this would cause a problem for landing. Therefore to bring the landed height of the module base down to below 2m a small landing stage would be necessary. For this stage two EADS S3K engine were chosen. These engines run off of storable MON3 and MMH. The engines produce 3500N of thrust each, sufficient for landing on the moon. The S3K engine will also need to be modified to provide throttle control. This stage will be activated at Low Gate or the beginning of the landing phase. This will allow the module to clear the jettisoned Lunar Transfer and Approach Stage and land safely. Table 5 summarizes the two stage masses and the mass for the Reaction Control System (RCS). If you subtract the sum of the masses in Table 5 from the LEO mass of 25,800kg, the available landed mass is approximately 3700kg.

Table 5: Launch System Masses

	Lunar Transfer and Approach Stage	**Landing Stage**	**RCS**
Engine	RL-10B-2 277 kg	S3K (2) 14.5 kg each	R-1E (32) 3.7 kg each
Propellant	LOX/LH2 18675 kg	MON3/MMH 330 kg	N_2O_4/MMH 45 kg
Tanks	1100 kg	130 kg	8 kg
Insulation	290 kg	0 kg	0 kg
Structure	920 kg	150 kg	20 kg

7 – Conclusion

7.1 – Cost Analysis

The MORPHLAB program was externally allocated a total budget of $51.5 billion (B) spread over the next 15 years, derived from NASA's projected spending on a lunar exploration program. Using an inert mass-based cost estimating relationship (CER) with a conservative learning curve of 80%, the nonrecurring, development, and production costs of the modules result in a total vehicle cost of $9.3B. Using the same CER for the launch structure and satellites, component costs come to $1.9B and $180M respectively. With a total of 26 Delta IV-Heavy launches for the modules and two ATLAS V-551 launches for the satellites, the program will have $4.5B in launch costs. Including $5.7B for wrap factor costs such as program support and management, and a reserve factor of 40%, the program will have a total cost of $36.2B. This is well below the given budget constraints (see Fig. 18), leaving a large spending margin.

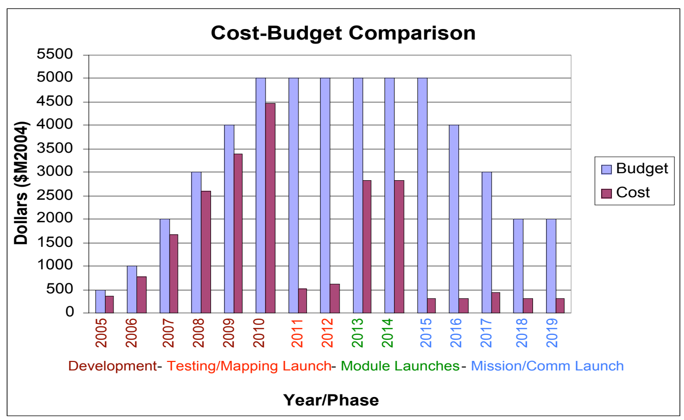


Figure 18: Program Budget Allocation

7.2 – Reliability

Based on requirement 6 of NASA's Human-Rating Requirements document (JSC-28354), the overall reliability of MORPHLAB at the beginning of the missions must be a minimum of 0.99 for crew return. This reliability will be obtained through testing using technological capabilities of a minimum NASA technology readiness level (TRL) of 3 on January 1, 2005, and a TRL of 6 by the technology cut-off date of Jan. 1, 2010, prior to the first MORPHLAB mission. With a single Dynamic Isotope Power System (DIPS) reliability of 0.9955, the required program reliability of 0.99 gives a MORPHLAB power module reliability of 0.989, and a habitat-living system and habitat-science system reliability of 0.995 each. With this system reliability for habitat-living and habitat-science, each of MORPHLAB's six habitat-living and habitat-science modules will need to have a reliability of 0.930 since the ECLSS is split among both module types.

7.3 – Fault Tolerance

MORPHLAB's design constraints include that the design can accommodate the failure or loss of a single module at any time without significant disruption of nominal activities. Also, following the loss or failure of any two modules during an inhabited mission phase, MORPHLAB shall support the crew for a worst-case interval until a lunar launch window occurs. To meet those requirements, the modules are designed such that each module's single failure will still allow capabilities for a useful scientific mission to continue. However, if two modules fail (except for the 3 fault tolerant power module), the crew shuts down the base, performs an EVA to the return vehicle, and heads back to earth. In the event of a single module failure and a malfunction of the return vehicle, all normal operations are suspended and the crew then can wait out a rescue mission for up to 180 days on a subsistence diet.

7.4 – Future Studies

Further design detail regarding sensor systems and exterior lighting is necessary. Interior layout of subsystems within modules will undergo revisions as trade studies are performed regarding crew environment and performance. Lastly, detailed analysis of Robonaut's functions and capabilities in base configuration shall be done.

7.5 – Public Outreach

In an effort to educate the public about lunar exploration and habitation, all MORPHLAB design reviews are open to the public. At our Trade Study Review, February 12, and our Preliminary Design Review, March 1, we introduced MORPHLAB to the faculty and students at the University of Maryland (UMD). At our Critical Design Review on April 19, the final design was presented not only to UMD faculty and students, but also to representatives from NASA and major engineering companies. On April 24, UMD sponsors Maryland Day, where 30,000 people from around the country annually come to UMD to be exposed to everything the University has to offer. Our team had a table set up at UMD's Space Systems Laboratory with a poster presentation and team members present. Through these activities, MORPHLAB hopefully sparked an interest in lunar exploration and colonization.

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