# Project Magellan:
# First Human Circumnavigation of the Moon

University of Maryland, College Park
Department of Aerospace Engineering Undergraduate Program

Jhason Abuan, Jorge Aviles, Ryan Dickson, Oscar Hsu, Michael Kessler, Mehdi Khoali, Daniel Maloney, Karen Mitchell, Nicholas Patregnani, Peter Pawlowski, Lisa Policastri, Jonathan Quigg, Robert Reed, Molly Simmons, Diane Thies, Paul Timko, Kevin Turner, John Van Eepoel, Rommel Zara

Advisors: Dr. David L. Akin
Dr. Mary L. Bowden

## Abstract

This report summarizes a single-semester team design effort for human circumnavigation of the moon. The initial design constraints included the goal of performing this mission within a single local day to take advantage of solar power. Details are presented on the rover system, which was designed to support three humans for a 35 day mission around the moon with a 7 day contingency, traveling at an average velocity of 17.6 km/hr while stopping three hours/day to perform extravehicular surface science. The final rover design is 12 meters long by 5.2 meters in height, with a total mass of 10,000 kg. The power requirement of 35 kW for propulsion and life support is supplied by a 100 sq.m. solar array, articulated to track the sun within 30deg of the local vertical. Detailed analysis is presented in the areas of life support and habitability, power, propulsion, thermal analysis, avionics, structures and mechanisms, and systems integration. Scenarios are presented for building and deploying all systems to the lunar surface, with the goal of a complete surface navigation in 2009. The final cost of $12.2B is approximately 1/8 that of the Apollo program in constant dollars, while providing extended science investigations around the equator and including the first detailed exploration of the far side.

## 1 Introduction

December 2009. Two astronauts gaze across a flat white plain. Beyond, the earth hangs suspended in space like a glistening sapphire on a bed of black velvet. Much like the pioneers of the late 19th century that heeded the call of manifest destiny and opened up the uncharted regions of America's West, these astronauts take the next steps on mankind's quest to colonize the last great frontier: space.

The covered wagon of yesteryear becomes the lunar rover of the future. Project Magellan, an innovative, unprecedented mission, will take humans beyond the limits of any previous manned program. Like the explorer it is named after, our rover will circumnavigate a heavenly body. But unlike Magellan, who proved without a doubt that the Earth is round, we will circumnavigate the moon. No human being has ever set foot on the far side of the moon; what limited knowledge we currently have comes from thirty year old fly-by data. What follows is a detailed analysis of the Magellan Rover and its mission.

## 2 Surface Mission

### 2.1 Route Design

Feasibility of a lunar rover mission is a function of design constraints of an acceptable lunar route. The route (see figure 2-1) follows the following mission design requirements:

?? Land at lunar dawn
?? Remain as close to an equatorial profile as possible
?? Safe abort of the crew at any point enroute
?? Maintain visibility with the sun at all times
?? Daily 3-hour EVA (21 hours of driving time)
?? Maximum long-term[1] climbing slope of 20°
?? Circumnavigate the moon with a 4-day contingency

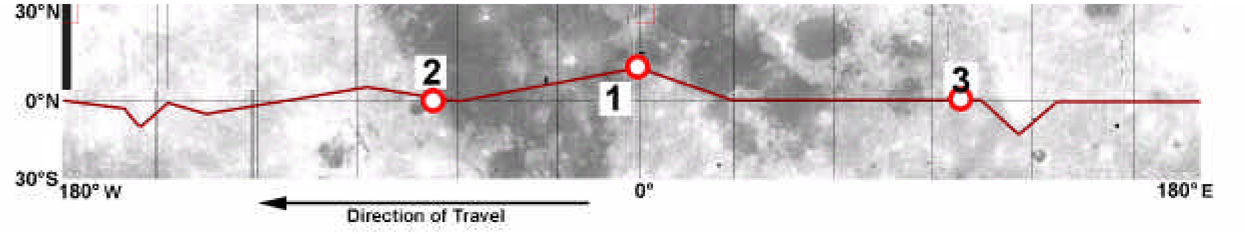


**Figure 2-1: Lunar Route. Point 1: Landing at 0°W,14°N. Point 2: Entrance into highlands (1.3° climbing slope for 150 km). Point 3: Exit from highlands (0.03° descending slope for 3000 km).**

Ideally the rover should travel at 17.6 kph to minimize changes in sun elevation through the entire route. However, power design constraints to climb from the mare to the highlands (a 1.3° long-term slope) as well as short-term[2] climbing slopes within the highlands forces the rover to travel at a maximum of 13 kph while on the far side of the Moon. To accommodate for the forced slower speed, a route velocity profile has been developed (see figure 2-2).

A result of the route velocity profile is the daily route sun elevation profile (see figure 2-3). While the sun is directly overhead (see figure 2-4) it will prove difficult to distinguish terrain features with the naked eye. This unavoidable situation requires the rover to be able to navigate via remote sensing.

The derived mission length as a function of the velocity profile is 38 days. This allows a full circumnavigation of the moon within 35 days. An initial 2-day period is allotted for the rover crew to become acclimated to the environment as well as maneuvering the rover. A final day is allotted for the crew to prepare for launch. This route design allows a 4-day contingency to complete the mission.

The current route design allows periods of deviation up to 14° latitude from the equator to avoid large known obstacles. Therefore, the contingency vehicle and launch vehicle that must dock with the Command Module in orbit needs to carry enough fuel to make a 0.4 km/s plane change delta-v.

The route consequently drives requirements for systems to operate the rover (see table 1). The systems that operate the rover abide by these driven requirements and prove that the circumnavigation of the moon by the Project Magellan rover with these set design constraints is feasible.

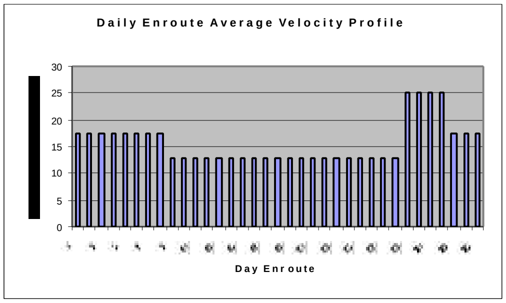


**Figure 2-2: Daily enroute average velocity to meet sun elevation requirements.**

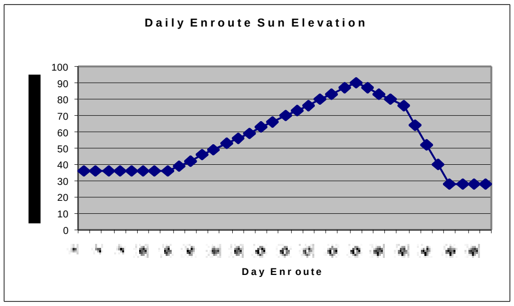


**Figure 2-3: Corresponding sun elevation during each mission day.**

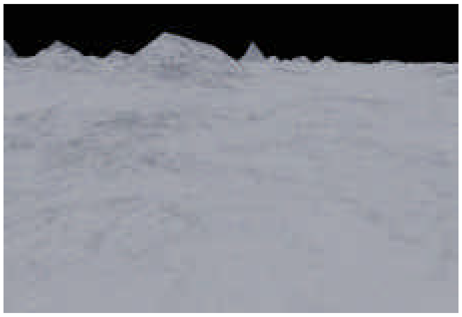


**Figure 2-4: Image generated with sun elevation at 90° showing total shadow washout.**

[1] Long-term climbing slope is a slope that the rover can climb with full power until the sun elevation changes to cause reduced power and force the rover to fail.

[2] Short-term climbing slope is an uncharted climbing slope expected to be no greater than 45°. The rover can climb these slopes, but only for finite time.

**Table 1: Affected requirements, features, and systems by route design.**

| Derived Requirement | Driven Feature | Driven Rover System |
|---|---|---|
| 1.3° climbing slope for 150km to enter highlands | Propulsion power | Power, Propulsion and Thermal |
| 0.03° descending slope for 3000km to exit highlands | Regenerative braking | Power, Propulsion and Thermal |
| 14° maximum deviation from equator enroute | Delta-V requirements to plane change | Contingency Vehicle |
| 90° periods of sun elevation | Navigation by remote sensing | Avionics |

### 2.2 Science

The unique advantage of Project Magellan is that it is a sustained, manned lunar mission. Never before has a manned lunar mission been capable of circumnavigating the moon. Previous lunar missions have been isolated to specific small regions near their landing site where geological sampling has been done and have only lasted for a few days. Therefore, it would only be obvious for the science during Project Magellan to focus on geological experiments.

The main purpose of geological sampling on the lunar surface is to more accurately develop a geological profile of the lunar surface. Invaluable data collected from the circumnavigation of the moon will be correlated with state-of-the-art Lunar Prospector and Clementine data. Due to equipment limitations of on-orbit remote sensing of the lunar surface, core samples will be taken at every EVA location to a depth greater than 0.5m. At six specified locations, a Lunar Surface Science Package (LSSP) will be deployed. The LSSP will be powered by a Radio-isotope Thermal Generator (RTG) so experiments can be conducted Earth-side without supervision by the rover crew. Experiments conducted by the LSSP include measurements of:

?? Lunar magnetic field
?? Suprathermal ions
?? Subsurface thermal temperatures
?? Lunar atmosphere
?? Gravity
?? Surface neutron flux
?? Each individual Apollo mission returned about 130 kg of lunar samples and one surface science package (isolated to a single landing site). Project Magellan will return 500 kg of core and rock samples and deploy six LSSPs about the entire lunar surface and not just a single location.

Even though in recent years, state of the art equipment has orbited the moon and done extensive surface mapping and scanning for water ice and elements, non-invasive science from orbit can only penetrate the surface so far. For example, the gamma-ray spectrometer on Lunar Prospector could only penetrate approximately 0.5 m beneath the regolith. This means that anything beneath this depth is completely undetected, and we may be missing important information about the elements on the moon. The only way to accurately determine what elements there are on the moon will be to go there on a sustained mission with Project Magellan.

## 3 Rover Overview

### 3.1 Launch Vehicle Selection

The Space Shuttle was selected as the launch vehicle because it has a payload capacity of 25000 kg, a payload bay dimension of 4.57 m diameter and 17 m length, and the assembly infrastructure is already present.

### 3.2 Locomotion Method

Two methods were considered: tracks and wheels. Other methods such as legs and hoppers, did not fit the mission requirements or were impractical for this environment.

Wheels have been used successfully on both Lunokhod and Apollo missions [1]. Wheels have a lower number of moving parts when compared to tracked vehicles, making maintenance easier. One primary concern with locomotion deals with conducting repairs while on the surface. It is easier to replace a wheel then it is service to a track while in an EVA suit. For these reasons, wheels were the logical choice.

### 3.3 Failure Mode Analyses

Two types of failure modes may occur. A Nose-In Failure (NIF) occurs when the front end of the vehicle makes contact with an obstacle. Based on the derived requirements of Mission Planning and Analysis (MP&A), the maximum slopes encountered on the route are no more than 30 degrees and maximum obstacle clearance of 1-meters. From this requirement, the maximum distance from the front end of the vehicle to the front wheels can be no greater than 1.1-meters.

The second failure mode, Hang-Up Failure (HUF), occurs when the underside of the vehicle makes contact with an obstacle. This can occur along the length of the vehicle (Longitudinal HUF) or along the width of the vehicle (Transverse HUF). To clear 1-meter obstacles, the distance between the ground and the underside of the vehicle must be greater than 1 meter. To prevent Longitudinal HUF, the distance between adjacent wheels cannot be greater than 4.8 meters; and to prevent Transverse HUF, the distance between pairs of wheels cannot exceed 4.3 meters.

Tipping will occur at 30 degrees if the center of mass is greater than 4.74 meters from the ground and sliding will occur at angles greater than 38.70 degrees assuming a coefficient of static friction of .8.

### 3.4 Steering Method

Two steering methods, Ackerman and Slip, were considered. Ackerman steering is used in automobiles and based on the premise that the inner tire turns more than the outer tire, the angle each tire makes is known as "Ackerman Geometry".

Slip steering, the wheels on the left side of the vehicle can run at different speeds and possibly different directions than the right side. This configuration imparts a lateral load to the wheels.

The method of choice is a modified Ackerman steering method. Ackerman steering is based on turning only one set of wheels, and the rover will be steering all wheels. A control law will have to be developed to determine the necessary angle each tire will need to steer and to determine what situations the wheels will need to be steered. High maneuverability/low speed situations will have all wheels steering. Higher speed situations may only require the front wheels to steer in order to achieve a heading change.

The turning radius of the vehicle is determined using geometry. Since the rover is using all-wheel steering, the turning radius is determined by the wheelbase between the outer set of wheels. The resulting turning radius is 7.1 meters for a single segment vehicle with a wheelbase between outer wheels of 8.25 m and a turning angle of 30 degrees.

### 3.5 Number of Wheels/Sizes

The number and size of wheels are constrained by several variables including wheel loading, wheel sinkage, size/shape of obstacles, and the size and shape of the launch vehicle. Based on the required obstacle clearing of 1-meter high boulders (from MP&A), the optimum diameter of each wheel is 2 meters. The 12-meter length of the rover bounds the number of wheels. Another factor taken into account is the towing resistance. Towing resistance, as defined by Dr. M.G. Bekker is the resistance in the direction opposite of the vehicle motion due to sinkage of the wheels [3]. From a graphical analysis, 4 wheels with a 4.3-meter diameter minimize the total towing resistance. However, from a practical standpoint, 4-meter wheels will increase the torque requirements on the motors. Therefore, 8 wheels at 2 meters in diameter is the best configuration.

# 4 Crew Systems

## 4.1 Crew Cabin

The driving force behind the crew cabin layout is usable floor space, because of the presence of one-sixth gravity. The design must have a clear vertical orientation, unlike the Orbiter. Areas that have high traffic should be kept accessible but out of the way. There are also comfort issues to consider; for example, keeping noisy machinery away from the beds and keeping the food and commode as far apart as possible. Taking all of this into consideration, the design has the steering controls in the front end-cap of the rover. Directly behind that is the sleeping area on one side and the food station on the other. Next to the food station is the ergometer for crew exercise and then on the end of that side is the personal hygiene station including the shower, commode and hand washing station. On the other side of the cabin next to the sleeping station is the storage area. In the storage area will be clothes, towels, personal effects, an extra space suit and spare parts for both the space suits and the mechanical units. Finally at the end of the cabin is the door to the airlock.

Due to the vibrations of driving, the interior environment is expected to be noisy. They must have protection for any noise above 85 dB but can go for 8 hours without protection if the noise is below 84 dB [5]. Types of noise that may be encountered are impulse noise, wide-band random noise, narrow band noise and tones, infrasonic, and ultrasonic noise. Taking all this into consideration, the crew is provided with two-way communication headsets that will allow them to speak with both each other and mission control. The headsets protect hearing up to 140 dB and are multi-channeled so they do not interfere with each other or any of the rover's systems. There is one window located in the navigation station, 1.5 meter long by 1.4 meter high. This window doubles as a last resort navigation window and as a viewing window. The window will be coated on the outside to protect the crew from infrared light and on the inside to reduce reflections and glare.

All navigation, steering, and communication controls are housed in the control station, as well as warning lights. In addition to these warning lights, warnings are sounded in the headsets. The navigation controls consist of a wheel, for steering, and a joystick to control speed, acceleration and braking. The driver will be able to lock in a speed, similar to an automobile cruise control.

Foods is shelf stable and does not require water reconstitution. There is enough food for three meals a day plus snacks per crewmember for 42 days (35 days of the mission and 7 contingency days). Each food locker holds 36-40 meals and weighs 6.4 kg empty and 24.5 kg full, and there is a forced air convection oven for heating food. Beverages are provided in pre-packaged, single serving containers. The crew will choose food and beverages from the basic NASA food list, provided the chosen options meet all the nutritional and caloric requirements of 11.720 MJ per person per day (for an average person of about 70 kg). Nutrition requirements can be supplemented with vitamins.

For personal hygiene a shower, commode and hand washing stations similar to ones found on the space shuttle are provided. Because of the vibrations while driving the crew will need restraints and handles to keep them still while cleaning or using the commode. Cleaning products are provided with low-sudsing, non-toxic, and non-staining properties and. Dry, wet, detergent, and biocidal wipes are also provided. Garbage is stored in two containers: one for wet trash (stored underneath the floor in airtight bags) and one for dry trash (stored in empty lockers in Velcro sealed bags). The waste from the commode is connected to a waste collection system that deals with gas, solid, and liquid waste individually. The gas is sent to filters to remove odor and bacteria, and then mixed with cabin air. Solid waste is stored and liquid waste is sent to the wastewater tank to be processed. There will be no dishwasher and no clothes washer because of their weight and water draw.

## 4.2 Life Support Systems

Every manned space flight mission has a need for some sort of Life Support System (LSS). Not only does a LSS must be life sustaining, it also must create a working environment that is conducive to high moral and work productivity. A number of factors, such as mission requirements, duration, number of crew, mass and cost constraints determine the type of LSS to be implemented. In this case, the driving constraints were mass and power consumption.

An open loop system capable of sustaining a crew of 3 requires an extraordinary amount of consumables, 2100 kg, mostly from water. Water can be reclaimed from a number of different sources such as urine waste, hygiene waste, and respiration/perspiration from the crew. Figure 4-1 shows the water usage per crewmember on the rover for the preferred closed-loop system.

Water reclamation is done using a multifiltration (MF) Unibed ® for hygiene wastewater, and Vapor Phase Catalytic Ammonia Removal (VAPCAR) for urine wastewater. Both devices output potable water for the crew, eliminating the need for separate hygiene and potable water loops.

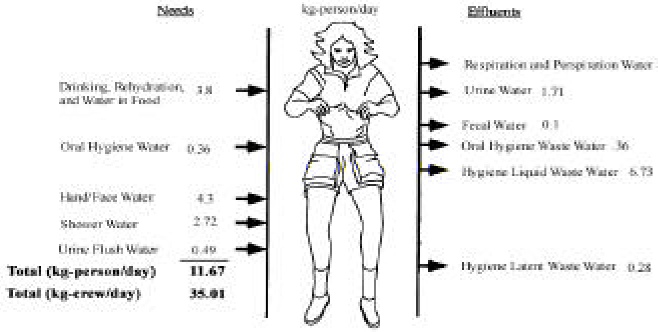


**Figure 4-1: Water Usage for the Rover**
Adapted From: Wiseland, P., "Designing for Human Presence in Space", NASA RP-1324, pg. 6, 1994

The crew cabin atmosphere is maintained at a pressure of 55 kPa (8 psi). The pressure was chosen to reduce leakage, exert less stress on the pressurized vessel structure, and to eliminate EVA pre-breathes. At 55 kPa, the $O_2$ concentration must be adjusted to 40% to maintain unimpaired performance and to avoid hypoxia and hyperoxia. $CO_2$ levels must be maintained at levels as low are reasonable achievable (ALARA), with a maximum concentration no greater than 1.25%.

A 2 Bed Molecular Sieve comprising of a bed of carbon fiber will be used to extract $CO_2$ from the atmosphere. $O_2$ and $N_2$ will be generated from high-pressure vessels located outside of the pressurize volume. The high pressure at which these gases will be contained at will serve as the means of controlling the associated partial pressures of each of these gases.

The expected 2009 launch date may pose concerns over radiation exposure. Figure 4-2 shows that the launch date will be around a solar minimum. At solar minimum, the solar wind strength is weaker than at solar maximum. Therefore, the solar wind is not sufficient enough to "blow" away Galactic Cosmic Radiation (GCR). Thus, exposure to GCR will be much more profound during a solar minimum. Another type of hazardous radiation exposure are very powerful X-class solar flares (Solar Particle Events). Instead of adding additional mass to serve as radiation shielding, the interior layout places as much of the existing structure (piping, water tanks, etc.) on the ceiling. This design philosophy, along with coverage of the solar array provides sufficient shielding for the duration of the entire mission.

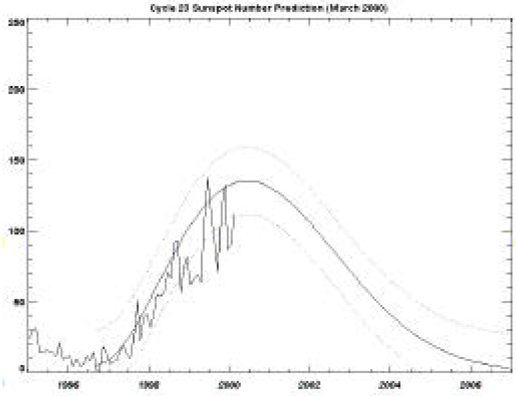


**Figure 4-2: Sunspot Number Predictions**
From: 2000, www.sunspotcycle.com

## 4.3 Interior Thermal Control System

The objective is to maintain an ideal cabin temperature of 20~21 C. The total heat generated inside the cabin is about 2000 W. This system consists of 2 condensing heat exchangers that will absorb excess heat and moisture and 2 radiators to dump the heat out. They will be placed on each side of the cabin. Whichever radiator is facing the sun will be turned off while the other radiator will be dumping heat to outer space. Two 60-cm diameter fans will be used to circulate the air around the cabin at a velocity of 0.20 m/s. Each heat exchanger is 2-m long and has eleven 2-cm pipes. Water is pumped at a temperature of 4 C and collects the excess heat from the atmosphere to reach room temperature of 20C. The mass flow rate of water is 0.3 kg/s. The size of each radiator is 6.5 $m^2$. We are going to use a high emissivity coating to maximize heat rejection: $Zn_2TiO_4$ pigment plus Potassium Silicate binder e=0.92 with an Aluminum plate of thickness 0.15cm. Two pumps of efficiency 0.7 requiring 9.3 W each are used to pump the water. The total mass of the system is 89 kg and the power requirement is 20 W.

The interior thermal control system maintains a cabin temperature of 20-21°C. The total heat generated inside the cabin is 2000 W. Two heat exchangers absorb excess heat and moisture; each is 2-m long with 11 2-cm diameter pipes. Water pumped at 4 °C flows through the exchangers and radiators at 0.3 kg/s. Two 60-cm fans circulate cabin air at a velocity of 0.20 m/s. Two exterior radiators, one on each side, radiate waste heat to space. If the radiator on one side is receiving too much incident solar energy, it can be turned off, therefore using the other radiator to dump heat. These radiators made of aluminum are 6.5 $m^2$, coated with YB-71 ($Zn_2TiO_4$ pigment plus Potassium Silicate binder) to raise emissivity to 0.92. Two pumps (70% efficient), complete the radiator system, each drawing 9.3 W. The total mass of the interior thermal control system is 89 kg with a total power requirement of 20 W.

## 4.4 Fire Detection and Suppressant System

Eleven detectors are used as part of the fire detection system. It is important that they be mounted away from solar radiation to avoid false alarms and from filters to avoid smoke being absorbed before reaching the detectors. Table 2 shows a list of the detectors that are used.

**Table 2: Fire Detection Systems**

| | |
|---|---|
| 3 Energy (flame) Detectors | -Detects visible, infrared and ultra-violet emissions.<br>-Detects flames at a distance of 10m<br>-Response time less than 150 milliseconds<br>-Location: Airlock |
| 4 Smoke Detectors | -Detects particles 0.3 microns or larger emitted from burning materials<br>-Detects smoke levels at concentrations of 2.5mg/$m^3$<br>-Response time less than 5 sec<br>-Location: 2 in the crew cabin and 2 in the airlock |
| 4 Ionization Detectors | -Detects burning particles 0.3 microns or smaller emitted from electrical fires<br>-Location: 2 in the navigation console and 2 in the crew cabin |

The rover carries 12 1-kg containers of Halon, two in the crew cabin and two in the airlock. Two bottles are manually activated and two bottles are automated and linked to an activation system within the detector. The suppressant delivery rate is 0.25lbm/sec (0.1134kg/sec) [2]. Also included are 6 cylinders of pressurized air (~0.081 kg of air in each bottle) to allow breathing for 45 minutes while fighting a fire. The Trace Contaminant Control System will remove any produced substance.

## 4.5 Trauma treatment [4]

-First aid kit: needles, syringes, local anesthesia, cotton, gauze, Band-Aids, ace bandages, splints, antiseptics (butadiene), ointments (eye patches), hemostatics medications (gel foam), strong pains medications (morphine), first aid for burns, gastro-intestinal medications (Lomotil)
-$O_2$ airways: Oropharyngeal and Nasopharyngeal airways, nasal canulas, nonrebreather mask to deliver high concentrations of $O_2$ and endotracheal tube for emergency situations.

## 4.6 Health monitoring [4]

Apply a small gadget to the index finger to control $O_2$ saturation. Pulse oximeter (80 beats/min), Holter monitor for heartbeats (60 to 90 beats/min), Sphygmomanometer for blood pressure (100-130mmHg systolic and 60-90mmHg diastolic), Thermometer for temperature (97.4 to 98.4 F) and for emergency situations like heart attack use Electrocardiogram and Defibrillator.

## 4.7 Sickness treatment [4]

Asthma reaction, allergic reaction, and anaphylactic shock: Benadryl 50mg, Cortisone IM or IV. Hypoxia (lack of Oxygen): use appropriate airway. Dehydration and to keep veins open: Dextrose-5-Water, Ringers Lactate. Symptomatic slow pulse: Atropine and Epinephrine IV. Symptomatic rapid pulse: Vagal maneuver and Adenosine. Hypotension: epinephrine 2 to 10 mg/min. Chest pain: Nitroglycerin 0.4mg. Seizure and convulsions: Valium 10mg or Dilantin 300mg. Heart attack: attach ECG monitor, pulse oximeter, blood pressure cuff, nitroglycerin 0.3mg/5min, morphine sulfate 3mg, aspirin.

### 4.8 Extravehicular Activity (EVA)

Only two crew members perform EVAs each day, the airlock has been sized for two unsuited astronauts, three suits, and additional space for the astronauts to move comfortably when suiting and unsuiting. Although the design only calls for room enough for the 95th percentile American male (~ 2.0 m tall), the height of the airlock is 2.5 m, for the comfort of the suited astronauts. The hatch from the airlock to the outside is sized for the comfort of the suited astronauts as well. When they exit the airlock hatch, there is a platform on which they will step. Then they proceed to walk on the platform, then down a deployable ladder to the lunar surface. This platform/ladder design is strategically sized and located to avoid contact with the rover wheels during a maximum vertical wheel deflection of .22 m while the wheels are turned inward at their maximum turning angle of 30 degrees. The ladder swings upward by means of a rope-pulley system and is latched to the horizontal stringer for storage. Due the size of this component, it must be installed in orbit.

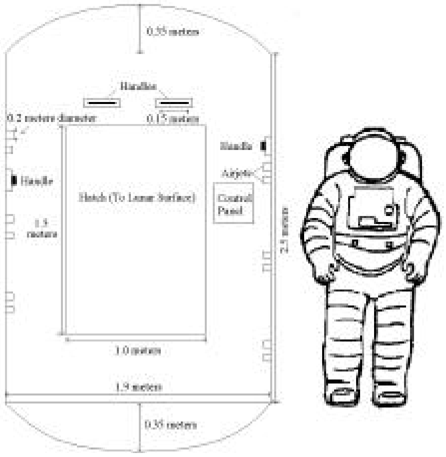


**Figure 4-3: Side view of Airlock**

The crew cabin pressure of 55 kPa and the airlock pressure of 27.8 kPa correspond to an R-value of approximately 1.2. Therefore, no pre-breathe is required before an EVA. The airlock will be depressurized from 55 kPa to 27.6 kPa and then from 27.6 kPa to 0 kPa. This procedure will take no less than 80 seconds for every 27.6 kPa pressure drop. The airlock will be repressurized in the same manner. The volume of the airlock will be approximately 8.1 cubic meters. The mass of oxygen needed in the airlock will be approximately 3 kg. The total amount of oxygen needed for the airlock for the entire mission will be close to 14 kilograms.

The airlock will also operate as an air shower. There will be 12 air jets throughout the airlock that will simultaneously pressurize the airlock and blast moon dust off the extravehicular mobility units (EMU). The air leaving the jets will be traveling at 20 m/s (45 m.p.h.). The dust will be collected using a circular HEPA filter 2.84 square meters with a thickness of 2 centimeters. It will hold a maximum of 1.2 kilograms and will need to be replaced twice during the mission. Figure 4-3 shows a side view of the airlock

The dimensions of the EMUs are 1.918 m high, 0.848 m wide, and 0.686 m thick, including the portable life support system [5]. Each EMU has a mass of 50 kilograms and will be stored in the airlock (3 total) [6]. A spare EMU is stowed in the crew cabin. The total mass of all the EMUs will be 200 kilograms. The EMUs carry a primary and secondary oxygen tank. The primary tank holds 0.55 kg of recyclable oxygen with a 70% efficiency rate. The secondary tank holds 1.19 kg of non-recyclable oxygen to be used in case of primary tank failure [7]. The total mass of oxygen needed for the EMUs is 20 kilograms. Potable water is also carried in the EMUs. Each astronaut is allotted 0.6 kilograms (~21 ounces) of water per EVA [6]. The total amount of water required for the EMUs for the duration of the mission will be around 42 kilograms.

Astronauts will have a variety of choices for entertainment. Some of the most popular forms of amusement are reading books, listening to music, looking out the window, and watching movies. The ergometer will also be provided as a form of entertainment, as exercise is not mandatory but highly recommended, for the mission.

## 5 Avionics

### 5.1 Communications

Having constant communication between the rover and the Deep Space Network (DSN) for the duration of the mission presents a challenge when the rover is on the far side of the moon. Different designs are analyzed to meet the 3 dB link margin while incorporating video signals as well as voice, data, and telemetry to broadcast to the DSN. This challenge is overcome by using a small constellation of satellites in orbit around the moon. The rover uploads data to a satellite in the constellation, which then relays the information around the constellation until there is a line of site with the Earth. An omni directional antenna is used on the rover to eliminate pointing errors from the rover to the constellation. The constellation, placed in a 3500 km circular orbit to keep power usage to a minimum for broadcasting from the rover. The constellation consists of four satellites spaced 90 degrees apart, with a period of 5 hours. Figure 5-1 shows the satellite orbital positions.

Each of the four satellites in orbit consists of two 0.3-meter parabolic dishes to transmit and receive communications through the constellation. A 1-meter parabolic dish is used to transmit and receive communications from the rover, while a 0.125-meter dish communicates with a 36-meter dish in the DSN. The largest consumption of power is used for transmitting from the rover to the constellation using 8 watts. Transmitting from the constellation to the rover consumes 5 watts, while all other communications require approximately 1 watt or less.

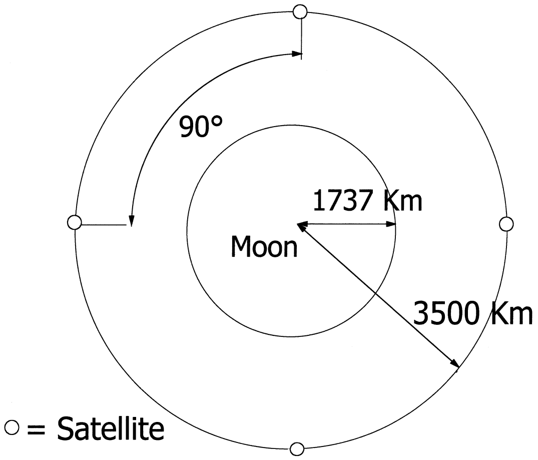


**Figure 5-1: Satellite Orbital Position**

Taking into account galactic and atmospheric noise, frequencies between 7.8 to 9.3 GHz are used. These frequencies leave ample room for bandwidth to incorporate the 1.2 Mbits/sec data rate required, with video being the largest consumption of the bandwidth.

## 5.2 Navigation Sensors

The Clementine satellite provides images to a resolution of only 500 meters. This fact, combined with the fact that the rover is only capable of navigating over a one-meter object, makes it a requirement that the rover have navigation sensors with better resolution. A synthetic aperture radar (SAR) system will be placed in orbit around the moon with the communication satellites. It will scan the surface of the moon and send the data back to earth for processing, via the satellites. This processed data provides the day-ahead route planning. The SAR system uses the RADARSAT-2 with an ultra-fine resolution of 3m x 3m. A Light Detection and Ranging (LIDAR) system will be used on the rover for near-range sensing. This system provides a one-meter resolution at a distance of 150 meters. A exterior front mounted camera system will provide the far-range sensing. The center camera will have a zoom lens with a field-of-view of 120? to 30? to resolve a one-meter object at a distance of 325 to 1300 meters. A camera will be located on either side at the front and back of the rover with a fixed field-of-view of 90? to provide a range of 650 meters. All five cameras will have two degrees of freedom and will also be used to watch the astronauts during EVAs. Figure 5-2 shows a relative camera layout

To assure that the rover's true path does not wander from the planned route, it is necessary to have an inertial navigation unit (INU) such as the OceanTools INS-06. This system drifts only about 0.08? after 21 hours of driving resulting in a change in latitude of 0.3 to 0.9 km (depending on driving speed). The system will be updated everyday during EVA using a high accuracy star tracker located on the top of the rover.

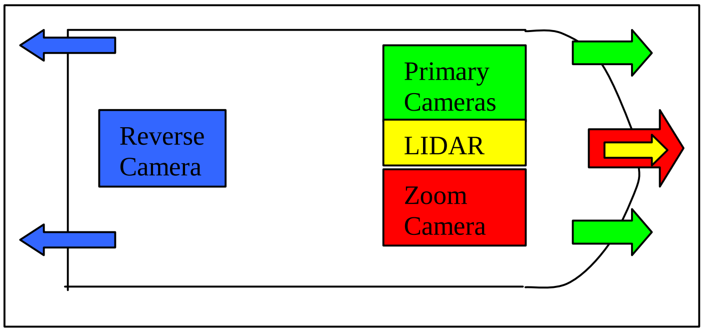


**Figure 5-2: Camera Layout**

Guidance during ascent and descent is provided by a radar system on the command module. At the initial landing site, there will be three radar beacons triangularly placed to guide the landing of the ascent vehicle. The rover will also carry a set of beacons in case of emergency evacuation.

## 5.3 Computer Design

In order to control the flow of telemetry and sensor data for the rover, a sophisticated yet simple and reliable computer processing system must be designed. Key system requirements dictate a 90% chance of mission success and a 99.9% chance of crew survival rate. To comply with these requirements the rover has six Litton LC-750EV general computers for monitoring crew sustaining systems and navigation. Each Litton 40 MHz computer is radiation hardened, weighs 9.09 kg and has a mean-time-between-failure of 4,000 hours proven in vehicles such as RAH-66 Comanche, V-22 Osprey, and the Clementine Spacecraft. The mean-time-between-failures provides a 77.8% reliability rate for our 42-day (1008 hour) mission. Four of these computers are redundantly designated to monitor and control primary mission critical systems and thus dubbed mission critical computers (MCC). The four MCC monitor all data separately. An average of all four signals are sent back to each computer and to the display screen. If there is more than a 5% deviation the computer ceases monitoring the set function until reset. The nominal reliability for the MCC are 99.7%.

The other two computers, mission-aiding computers (MAC), augment the capabilities of the MCC. They provide extra functions such as automatic driving modes like heading hold, speed control, limited autonomous travel, and data reduction for science and mapping without excessively increasing the weight of the system to maintain reliability. The nominal reliability of the two MAC system is 95.0%, however their ability to replace damaged MCC assure a total system a reliability above 99.9%. The computers will be spaced nominally .5 m apart axially and 3.0 m laterally to reduce the chance of single incidents failing multiple computers.

Backup mission critical software is stored on EEPROM Chips, with primary software and data is stored on a 40 GB radiation hardened hard drive specially designed with no moving parts for space environment. The hard drive stores data until it is compressed and transmitted. Compression follows MPEG-4 standards, compressing audio down to 50% and video down to 8% before it is relayed back to Earth via the lunar orbiting satellites. In case of hard drive failure or communication loss, data can be written to a digital optical disk, similar to a DVD, specially designed for the lunar environment. 20 disks are carried on the rover, each disk is able to interface with science equipment and stores 2 GB of data. This disk system increases the survivability of data in the event of a communications loss.

To reduce fatigue and boredom, several driving aids can be implemented. Heading hold can be engaged to hold the rover on a nominal heading. It relies on a computer feedback loop with the gyrocompasses and is automatically disengaged when the LIDAR sensor on the rover detects a 1 m obstacle within 30 m of its direct path. A speed control function maintains a preset speed by monitoring the motor speed and the accelerometers. This mode will be disengaged when either a 1 m object is detected within 30 m directly ahead of the rover or when the motor increase rate is too high (indicative of excessive slipping). Automatic disengaging of each of these modes will cause the rover to sound an alarm and engage in braking unless the driver intervenes. An autonomous mode allows a limited preplanned course input into the computer to be executed similar to robotic control. This mode uses both heading hold and speed control and is disengaged by any of their failure criteria.

# 6 Power, Propulsion, Thermal

## 6.1 Power System

The final power system configuration is composed of solar cells, regenerative fuel cells and batteries, and is designed such that the loss of the main system allows for 24-hours of emergency life support.

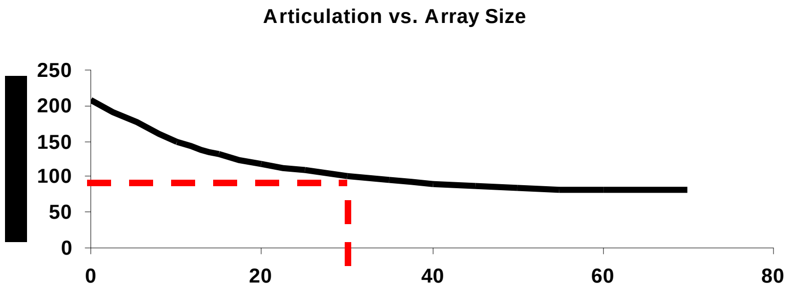


**Figure 6-1**

As a safety factor, the solar cells must be able to produce 35 kW of power when the sun angle is at it's lowest projected point in the sky of 25 degrees. By plotting the size of the solar array vs. the amount of articulation (figure 5-1) is generated.

From figure 6-1 it is clear that 30 degrees of articulation is the optimum articulation, which can be realized with an area of 100 m^2. The solar cells used for the array are 32% efficient and should be developed in the near term by Spectrolab Inc. [8].

The tracking accuracy required for the array is minimal when the sun is high in the sky; the sun can be at plus or minus 35 degree from perpendicular to the solar array to produce the needed 35 kW. The solar array is actually capable of a 45 kW output maximum, which is 20% more than is needed. This allows for damage to occur to the solar array, and a decrease in efficiency due to dust while still meeting the power needs of Magellan. Tracking is accomplished using power output feedback, inertial feedback, and manual input and corrections. This allows for automation of the system without being completely dependant on computer controlled.

For energy storage a mixture of regenerative fuel cells and batteries will be used. There must be enough energy stored at all times to 24 hours of life support; however since the energy stored will also be used to provide power boosts there should actually be enough energy stored to provide 48 hours of full life support. The regenerative fuel cells that used are Unitized Regenerative Fuel Cell System (URFCS) [9]. There will be 500 cells, allowing a discharge of 12.8 kW for a maximum of 75.5 kW-hr of stored energy. The battery storage system will be composed of Li-Ion Polymer batteries that can store 0.175 kW-hr/kg. This technology is a future technology however given the development of batteries and the need for improvements in industry it is worth while to develop these batteries. The batteries will be sized such that they can provide enough power storage to run minimal life support for 17 hours. With the addition 7 hours of life support from the space suit, 24 hours of life support is provided to the astronauts. This will bring the mass of the batteries to 100 kg.

## 6.2 Locomotion System

Having determined that the best choice of motion is a wheeled vehicle, the dynamics and loading of such a system must be developed in order to determine how to drive those wheels. Once a model of the forces on the system is developed and analyzed, a system can be designed.

The forces developed on a wheeled vehicle under motion consist of a loading from the Lunar regolith due to the vehicle penetrating the soil, a frictional force, an acceleration force, and a loading from obstacle traversing. Cases considered in designing the system were:

- ?? Driving on a straight and level surface
- ?? Climbing up an incline
- ?? Traversing an obstacle while on an incline

Attached to each of these is the variation of adding acceleration or simply considering constant velocity. At first glance, the last case would appear to be the limiting case for the motors, but the motors must also be able to operate continuously if the vehicle is climbing. From a development of the soil model [3] and dynamics of a rolling wheel, figure 6-2 was generated showing how the power required by the system varies with inclination and acceleration.

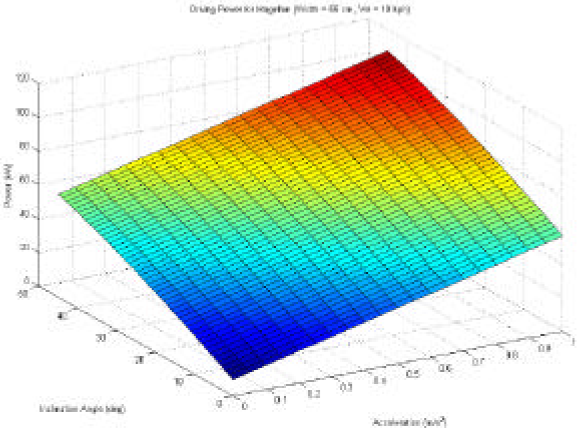


**Figure 6-2: Locomotion System Power**

From this, in order to remain within the power requirement of 28 kW for continuous operation, the maximum sustained slope was set at 10?, at an acceleration of 0.25 $^{m}/_{s}{}^{2}$, and the velocity was held constant at 13 kph as set from Mission Planning and Analysis.

From the analysis of climbing up a hill, a peak torque was determined for a worst-case obstacle of 1 m in height with a 45? slope. This value was 4800 N-m, and allowed sizing of the Kollmorgen Direct Drive Motors and disc brakes.

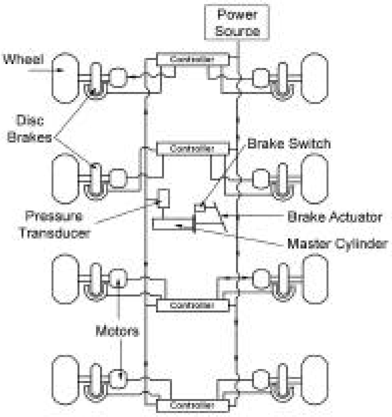


**Figure 6-3: Locomotion System Schematic**

The system will make use of regenerative braking technology by having the motors act as generators. This involves a more complex control system, but will return 10W-h nominally, and approximately 90 W-h when traveling down a slope. A schematic of the system is shown in figure 6-3 and a parts drawing is shown in figure 6-4. The steering mechanism was developed to articulate the wheel +/- 30?. Using a ball and socket joint at the point where the strut joins the rod, and a pin connection on the arm from the motor case that slides up and down. With that structure, the entire mass of the locomotion system, not including the tire, is 950 kg for 8 wheels.

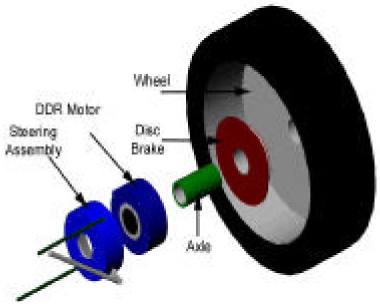


**Figure 6-4: Locomotion**

## 6.3 Exterior Thermal Control Systems (ETCS)

The challenge of designing a cooling system in an environment without an atmosphere may seem daunting at first. Common everyday solutions such as fans and air-conditioning are completely unfeasible. However, radiative transfer alone governs heat transfer in such an environment. Systems using radiative cooling are much simpler and lighter than those utilizing convection or conduction. In addition, only one equation is necessary to size such systems: $q = A??(T_s^4 - T_a^4)$, where q is the emitted energy, A the surface area, ? is material's surface emissivity, ? the Boltzmann constant, $T_s$ the absolute surface temperature, and $T_a$ the absolute ambient temperature.

The ETCS for this project utilizes both active and passive thermal control. Thermal blankets, properly known as multilayer insulation (MLI), make up the passive control system. The entire surface of the rover and airlock, 63 square meters, is swathed in MLI, as are all science packages, exterior avionics, pressure tanks, and batteries. Composed of ten layers of aluminized mylar alternated with ten layers of Dacron fabric, the MLI has a protective top layer of Kapton with an emissivity of 0.02. Total surface area of MLI is 198 square meters, and the total weight of is 368 kg.

The active thermal control system encompasses two cooling methods: radiators and heat pipes. The motors, being 90% efficient, have sufficient surface area to dissipate 500 Watts of waste heat each. The fuel cells must be kept at 4 ?C during regeneration. The most logical choice for this application is a radiator. With a thermostat, the radiator system will be turned on only when needed.

Two coolant loops run through the radiator (color coded green and red). The interior separation of the tubes is 0.1 m. The purpose of this double loop design is to add reliability to the system. If for some reason one of the internal loops suffers a puncture, the damaged loop can be sealed off and the second loop can then handle cooling load. Under normal operation, however, coolant will flow through both loops. The radiator is coated with a compound known as YB-71 ($Zn_2TiO_4$ pigment with potassium silicate as a binder), a coating noted for its excellent radiative properties. Use of this coating raises the emissivity of the radiators to 0.92.

Aluminum honeycomb face plating separated by 5/16" diameter aluminum tubing comprises the radiator. The feed tubes are ¼" diameter aluminum tubing. A water/glycol mix is the coolant fluid. The total amount of coolant needed here is approximately 15 liters (7.5 liters of glycol and 7.5 liters of water). The total weight of the radiator system, including pump, is 127 kg.

Heat pipes service the avionics heat sinks. Each of the five exterior cameras has a heat sink maintained at 35 ?C. The cameras utilize thermoelectric coolers to dissipate the 19-26 Watts emitted by each. The heat from these coolers is stored in heat sinks. Heat pipes are an extremely simple, yet effective means of radiating heat. The weight of the heat pipes is approximately 5 kg.

# 7 Structures

The primary goal of the structural design of the rover is to protect the well being of the crew while maintaining maximum functionality. The first step in designing a viable structure is to establish the safety constraints in the form of specific factors of safety for different types of structure. Identification of the loads and where they will act is the logical second step in the design process. As an external design requirement, the rover must also be able to fit in the payload bay of the space shuttle and the structural components must be less than 3000 kg.

To ensure the safety of the crew and the successful completion of the mission, all systems must be designed to provide a non-negative margin of safety for worst-case loading conditions. All systems must also incorporate the factors of safety listed in table 3.

**Table 3: Factors of Safety**

| Factors of Safety | |
|---|---|
| Structure | F.S. |
| Primary Structure | 2.0 |
| Secondary Structure | 1.5 |
| Pressure Lines | 4.0 |
| Pressure Tanks | 3.0 |

The structural design of the rover is divided into three main sections: crew cabin and airlock, loads cage, and suspension system. The crew cabin and airlock are pressure vessels designed to house the crew and their equipment. Surrounding the crew cabin and airlock is the loads cage, a rib/stringer structure designed to divert and absorb the driving loads transmitted by the suspension system. Additionally, attached to the loads cage are support struts for the solar arrays. The struts are positioned so that the solar array can articulate 30⁇ in both the pitch and roll axes. Finally, there is a suspension system that absorbs the driving loads of the rover. A listing of the primary structures, the source of their respective critical loading, and their margins of safety can be found in Table 4. The launch loads, although they are the most massive load on the vehicle (15.2g, 9.6g, and 15.2g respective to the x, y and z axes after incorporating the applicable factor of safety), are not listed as critical loads on the table. Instead of directly absorbing these extremely high loads, the rover will rest on a cradle (design pending) that takes a majority of the launch loads.

**Table 4: Primary Structure and Associated Loads**

| Component | Critical loading | Source of Critical Loading | Design Factor of Safety | Margin of Safety | Mass (kg) |
|---|---|---|---|---|---|
| Crew Pressure Vessel | 55.2 kPa | Internal Pressure | 2 | 27 | 753 |
| Suspension System | 8000 N | Start-up Torque | 2 | 1 | 163 |
| Solar Array Struts (6 ) | 11.375 kN | Dynamic Braking | 2 | 1 | 16 |
| Airlock | 55.2 kPa | Internal Pressure | 2 | 37 | 167 |
| Pressurized Storage Tanks | 20.68 MPa | Internal Pressure | 3 | 2 | Variable |

## 7.1 Crew Cabin & Airlock

The crew cabin (figure 7-1) encompasses 63 $m^3$ of total volume. 51 $m^3$ is assigned as living space for the crew; the remaining 12 m3 being used for storage space. The inner shell of both the crew cabin and the airlock are made of 1.25 mm of graphite/epoxy in a quasi-isotropic lay-up. Both are also covered with 18 mm of composite impact shielding to protect against micrometeoroid impacts and collisions with lunar obstacles. The impact shielding consists of alternate layers of Ensolite foam, graphite facesheet, aluminum mesh and another graphite facesheet. It is a thinner, lighter version of the shells developed and tested by the White Sands Test Facility [10].

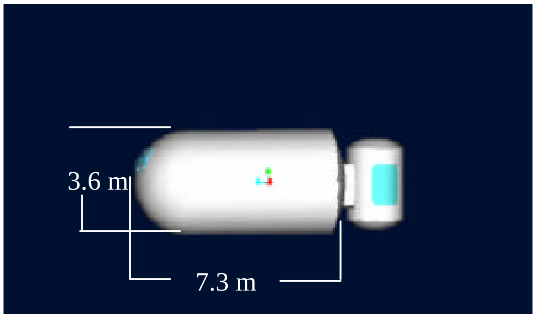


**Figure 7-1: Side View of Crew Cabin**

The main section of the crew cabin is cylindrical with a length of 5 m and a radius of 1.8 m. The front hemispherical section also has a radius of 1.8. The rear endcap has a radius of curvature of 3.48 m resulting in a length of 0.5 m from the intersection plane. The total length of the cabin section is 7.3 m. A navigation window of dimensions 1.4 m high by 1.5 m wide is located on the front hemisphere.

The airlock is a vertical cylinder with a total height of 3.2 m. The cylindrical section is 2.5 m in height with a radius of 0.95 m. The endcaps each have a vertical height of 0.35 m. Both the hatch into the crew cabin and the hatch to the surface are 1.5 m tall and 1 m wide.

The inside of the crew cabin is designed to promote functionality. Ribs are mounted to the interior of the crew cabin wall to provide mounting points for high strength, plastic isogrid structures. The isogrid “walls” will then be used to mount equipment and enclose storage areas. The floor is also an isogrid structure, manufactured of a low density, high strength material. The main advantage of the isogrid design is that objects and people can be attached to the floor and still be mobile. Video footage from the Apollo missions illustrates that objects under impulse loading have a tendency to float before returning to the lunar surface. The lunar terrain will produce a vibration laden ride making attachments for people and internal structures important to prevent constant floating of objects in the crew cabin. Ensolite foam coats the inner wall of the structure to protect against accidental impacts.

The primary loading for the crew cabin and the airlock comes from the internal pressure. A stress analysis determined the maximum hoop and membrane stresses due to the internal pressure load. The maximum hoop and membrane stresses (and the corresponding factors of safety) for the crew cabin are 79.5 MPa (F.S.=28) and 76.8 MPa (29) respectively. In comparison, the numbers for the airlock are significantly less: the hoop stress is 39.9 MPa (57) and the membrane stress is 52.1 MPa (38.) The radial deflection of the shells is not a problem as the maximum deflections were 1mm for the cabin section and 0.3 mm for the airlock. Fatigue loading is not a factor for either structure given the low number of cycles and low stresses.

The maximum bending and torsion loads that the crew cabin could withstand were also calculated should one of the primary load bearing members get damaged. The maximum shear stress the crew cabin can undergo is 1.77 MPa, corresponding to a tangential load of 25.2 kN. The maximum bending stress of the cabin is 719 MPa, corresponding to a bending load of 9.2 kN.

A large percentage of the mass of the structure is attributed to the impact shielding. The crew cabin and airlock without any additional protection mass 154 kg and 34 kg respectively. However, the impact shielding will mass an estimated 580 kg. A twenty percent mass margin was also added to account for additional structure around hatched, windows, and punctures of the crew cabin from piping. The total mass of the crew cabin and airlock section then becomes 920 kg.

## 7.2 Ribs and Stringers

The loads cage is a rib/stringer structure designed to absorb the bending and torsion loads from the suspension system. It also has a secondary purpose in that it provides mounting points for external equipment such as radiators. Given the unfavorable behavior of graphite structures to mechanical fasteners, both the ribs and stringers are constructed of thin walled aluminum I-beams for ease of fastening. Also, for preliminary analysis, the beams are assumed to have identical cross sections that are uniform for the length of the beam. Attached to the loads cage are the struts that support the solar array. These struts have a telescoping mechanism that allows the solar array to articulate. The struts were designed using aluminum also, mainly for the fastening reasons stated above, although a graphite/aluminum hybrid beam may be introduced later to take advantage of graphite's stiffness properties.

## 7.3 Suspension System

Modeled the rover as an idealized block, spring, and damper system. To complete the model, need to pick spring constant and damping constant. Damping constant is not a factor as can be set to a required value by using active damping. Spring constant is chosen by the maximum strut deflection (discussed later)

Rover suspension system consists of two struts, one connected to the top of the wheel motor casing, one connected to the bottom. A spring-damper connects the top strut to the rib of the rover. To size, the spring constant, the maximum deflection of the top strut must be calculated. This depends on the angle the struts make with the horizontal when the rover is just sitting there. I prefer that the struts are parallel to the ground when the rover is just sitting there. In that case, the maximum deflection of the top strut before it hits the rover body is about 5 degrees. Put in a margin of safety and the spring constant that you need is around 52 kN/m. If you choose to orient the struts at a different angle, then you can obviously change this number.

Vertical Loads: $F_{static}$ = 2043.75 N; $F_{dynamic}$ = 4087.5 N; F dbl = 7285 N. Looking at $F_{dbl}$ as a design load, we find that the spring force Fs = 7668N, the reaction force, Fr = 383N, and the maximum moment in the strut is 727.7 Nm.

Horizontal Loads: Start up torque happens to be greatest load. Doing analysis shows that the reaction force, Fr = 8000 N and the maximum moment in the strut is 16000 Nm. This is the design load for the strut. Sizing the strut as a thin walled circular cylinder yields a strut of .2 m in diameter and a thickness of 3 mm. Each strut is made out of aluminum and weighs about 6.4 kg.

The Keel Beam is the beam that runs under the Rover. Its design is driven purely by geometric considerations. If it were sized to the loads, it would be extremely this and not very big. The keel beam is also made out of aluminum and is 11.25 m in length. The flange and web thickness are 1/8 of an inch. It is .7m high and .2 m wide. It weighs, at most, 60.7 kg. Holes can be cut out of this beam to make way for cables or other accessories that need to go in that general area.

## 8 Final Rover Layout

The final rover layout is shown in figure 8-1 through 8-3.

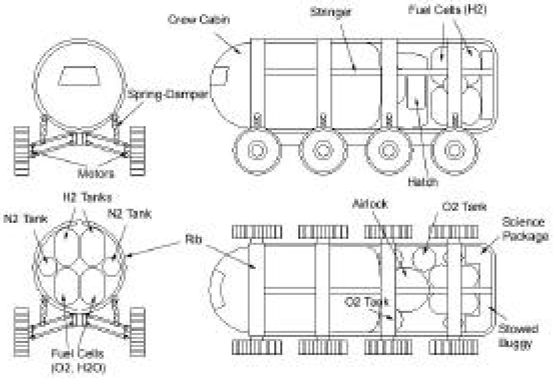


Figure 8-1: Rover Layout without Solar Arrays or Radiators

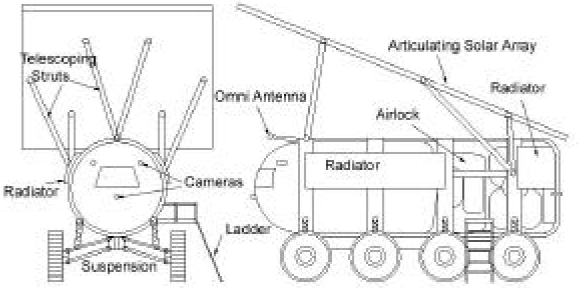


Figure 8-2: Rover Layout with Solar Arrays and Radiators

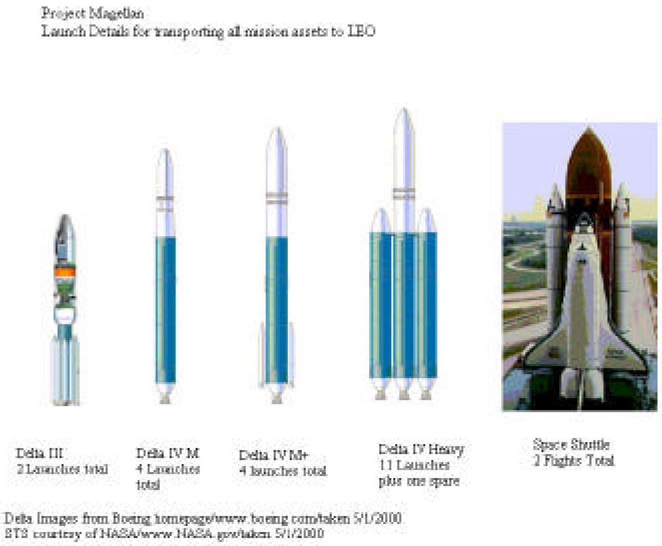
## 9 Support Vehicles

The centerpiece of this phase of the project is the surface rover system. However, one of the few things that it can't do is fly. Therefore, this system requires an assembly of spacecraft in support of its mission. These vehicles fall into two broad categories; near Moon and trans orbital spacecraft.

A variety of different scenarios were envisioned that were each capable of successfully completing the mission as outlined. Each scenario is based around a limited number of trans orbital transport sorties, between the Earth and the Moon, that precede the crew in order to assemble all of the mission assets in a Low Lunar parking Orbit (LLO). These plans differ in the number and configuration of the Lunar Shuttle Vehicles (LSV) used to transfer the crews from LLO to the surface, the configuration of the Lunar Cargo Lander (LCL), and the type of crew extraction method used to satisfy the external requirement that the crew enjoy an unaided means of abort to orbit anywhere along the route. Each of these configurations was compared in a trade study using the same performance envelope. The results of this parametric analysis were compared on the basis of total system mass, system costs, payload to structural mass ratio optimization and the probability of surface mission survival. Although the results of this study identified two high value scenarios, in terms of their basis for comparison, the least expensive of these cost nearly 14 billion dollars. Since these cost estimates were based on performance figures developed through the parametric analysis, and did not include any design margins or provisions for testing and development, economic concerns sent us back to the drawing board.

The outgrowth of this study led to a concept called the Unified Lunar Flight Vehicle system (ULFV). In order to satisfy the mission goals 3 LSVs and one LCL comprise this package. The LCL transports the rover system to the primary landing site followed by the crew in an LSV. The other two LSVs remain on orbit for emergency crew extraction en route. Initially, this system was based around a common descent stage for the LCL and LSV variants. Later, the ascent stages that carry the crew back to LLO was also standardized. Since the two LSVs remaining on orbit would have the greatest delta V requirement and hence require the greatest propellant mass for both stages all of the design work was based on these performance points. Simply put, the LCL and LSV used for the primary landings would be these same craft with less than a full propellant load.

The ULFV system provides several important benefits to the overall mission. First among these are the reduced expenses realized by the common stage designs. Necessarily, previous scenarios had suffered higher non-recurring costs due to the mission specific optimization of each flight vehicle type. This savings more than offsets the increased vehicle operating costs. ULFV system also frees the rover from carrying a piggy-back flight vehicle along its surface journey, the plan that had previously been envisioned in response to the aforementioned external requirement, since it allows for an extra on orbit contingency vehicle. Serendipitously, this had the effect of reducing rover's power requirements for locomotion and associated subsystems which ultimately reduced the overall system mass. A further benefit of sizing the system to the emergency flight envelope is an additional 900 kg payload mass margin, above the specified 10000 kg, for the LCL that could be used for extra structure that can help the rover withstand specified landing loads.


Project Magellan
Launch Details for transporting all mission assets to LEO

Delta Images from Boeing homepage/www.boeing.com/taken 5/1/2000
STS courtesy of NASA/www.NASA.gov/taken 5/1/2000

Figure 9-1: Launch Vehicles

ULFV is a modular system that is designed to be placed into Low Earth Orbit (LEO) using currently available and near future launch vehicles. The ascent stages are launched complete with full propellant loads. The components of the descent stages are packed for launch. Once on orbit, the basic platform unfolds like a carrier fighter's wings and the modular propellant tanks and landing gear subassemblies are mated to the platform. Then either an LSV ascent stage or the surface rover system is mounted to the complete platform. All of the vehicle components are placed at a rendezvous point in a LEO parking orbit. Then, a Shuttle mission is flown transporting the rover to LEO. The shuttle crew will perform minor assembly work to the rover as well as assemble the ULFV flight vehicles. As versatile as ULFV system is, it is still a near Moon flight system and just as with the rover, requires transport from Earth to Moon. This is the job of the Orbit-to-Orbit Transfer Vehicle (OOTV).

OOTV is an autonomous or remotely piloted vehicle designed to transport the ULFV system from LEO to LLO. Three different approaches to this mission have been considered. One concept involves linking all of the assembled ULFV vehicles together as one assembly, including the crew and command module (the trans orbital crew habitat), and propelling this assembly to the Moon. Only command Module would return to Earth under this plan. The other two approaches involve flying each vehicle, in a series of sorties, between the parking orbits. The difference in these approaches is one employs a reusable spacecraft with a robotic arm that refuels itself by trading empty fuel tanks for pre-charged ones launched into the parking orbit. The other utilizes one-way, expendable transfer stages that are assembled on orbit at the same time as the ULFV flight systems. Although the one-shot and expendable transfer vehicle approach saves total fuel mass consumed, the reusable OOTV concept allows for very low cost subsequent Lunar Missions.

# 10 Program Schedule, Costs, & Budgets

## 10.1 Program Schedule

Figure 10-1 shows the program development schedule.

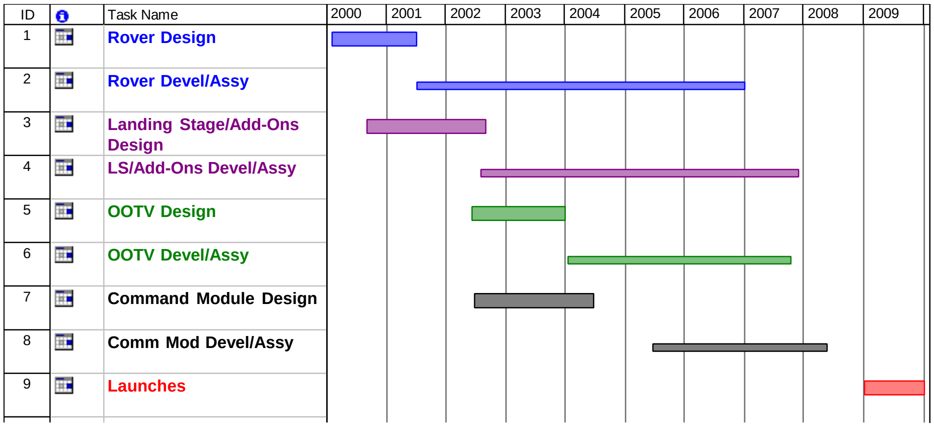


**Figure 10-1: Program Schedule**

## 10.2 Rover System Mass Breakdown

To ensure that the total mass of the rover does not exceed 10,000 kg, a 9,000 kg mass budget was created. The decision to design to a 9,000 kg rover increases the chance that the rover will meet the 10,000 kg requirement, allowing for a 10 % margin. The mass budget breakdown is illustrated below in Figure 10-2. From this current actual mass breakdown, it is clear that the 10,000-kg rover requirement will be met.

## 10.3 Rover System Power Budget

The power budget divides up the available power of 35 kW amongst various systems that are in need of it. It is representative of the power needed for driving the rover on a continuous route during normal daily operations, which allows for a long-term sustained climbing angle of 15 degrees. Currently, the actual total power required for each system is actually under the budget goal, totaling 31.7 kW. This budget, shown below in figure 10-3, illustrates both the goal and actual power for each system; however, it does not directly include a margin.

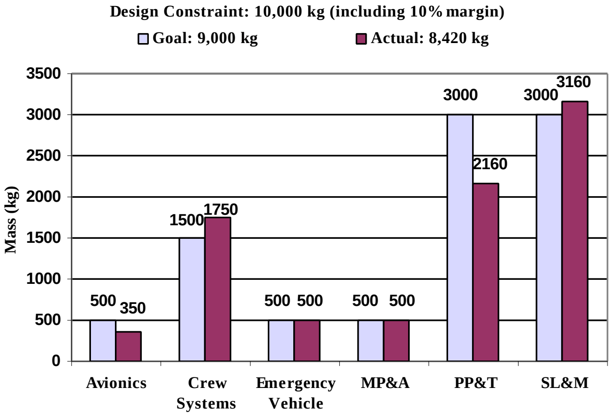


**Figure 10-2: Rover Mass Budget**

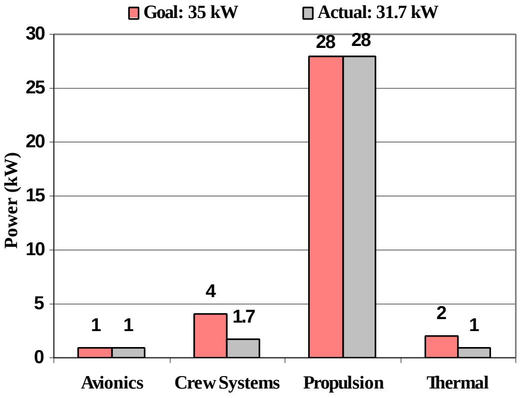


**Figure 10-3: Daily Continuous Operation Power Budget**

## 10.4 Program Cost Estimation

The cost estimating relations provided by Johnson Space Center projected the total Magellan Project cost to total $12.22 Billion. Table 6 lists the non-recurring and production costs of each of the vehicles, as well as the cost for satellites and launches. The number of each vehicle produced exceeds the number of vehicles needed for the mission for most cases. These extra vehicles were included in the cost budget to allow for pre-flight testing purposes. Additionally, the non-recurring cost of this program accounts for 65% of the total program cost and the total cost for satellites and launches accounts for another 20%. Leaving only 15% of the cost for producing the vehicles concludes that producing the additional vehicles for pre-flight testing purposes barely increases the cost (see Figure 10-4). In fact, if only the number of vehicles needed for the mission were produced, the total program cost would only be $11.38 Billion. On another note, the projected program cost of $12.22 Billion is not all that expensive when it is compared to the Apollo Missions, which in 1967 dollars cost $23.19 Billion. In year 2000 dollars, the Apollo Missions would have totaled $97.65 Billion.

**Table 6: Program Cost Estimate**

| Vehicle | Mass Per Unit (kg) | Non-Recurring Cost ($M) | Number Needed for Mission | Number Produced | Production Cost ($M) | Additional Costs per Item ($M) | Total Cost ($M) |
|---|---|---|---|---|---|---|---|
| Lunar Rover + Buggy | 10000 | $2,862.32 | 1 | 3 | $663.12 | | $3,525.44 |
| Landing Stage (Descent) | 2338 | $507.75 | 4 | 6 | $134.84 | | $642.59 |
| LSV Flight Cabin | 2000 | $1,181.09 | 3 | 5 | $351.16 | | $1,532.26 |
| Ascent Stage Add-on | 795 | $711.08 | 3 | 5 | $190.67 | | $901.75 |
| Orbit to Orbit Transfer Vehicle | 10000 | $1,129.24 | 1 | 1 | $75.28 | | $1,204.51 |
| Command Module | 3500 | $1,606.78 | 1 | 3 | $330.95 | | $1,937.73 |
| Satellites | | | 4 | | | $45.00 | $180.00 |
| Shuttle Launches | | | 1 | | | $400.00 | $400.00 |
| Delta Launches | | | 19 | | | $100.00 | $1,900.00 |
| **TOTAL ($Billion)** | | **$8.00** | | | **$1.75** | | **$12.22** |

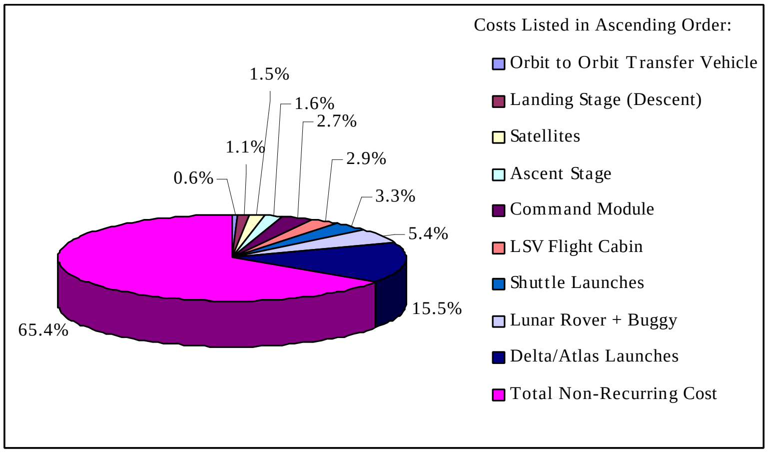


**Figure 10-4: Total Program Cost Estimate**

## 11 Outreach

As with any project it is important to provide a link to the community in which the idea was fostered in. The class held formal Preliminary and Critical Design Reviews that were open to the University community and interested outsiders. For example, over 100 invitations were extended for the Critical Design Review. The audience included University of Maryland faculty, graduate students, and undergraduates, professionals from NASA and the Naval Research Laboratories, and students from Eleanor Roosevelt High School. It was important to not only include the community of the University of Maryland but also the aerospace industry in the surrounding Washington D.C. area. The presentation provided the opportunity for the mixing of industry and education in a setting that was electrified with the need for increased planetary exploration.

## 12 Conclusion

Just as the Lewis and Clark expedition opened the West to settlers, the Magellan expedition will open the moon to colonization as well. And those lunar settlers will turn their eyes to the next big unknown: Mars. For in the grand scheme of things, as momentous as this lunar circumnavigation is, it is only one step in a far more ambitious goal: the circumnavigation and colonization of Mars. And from there, the cosmos awaits.

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