Project Endurance:
Six 90-day Missions on the Lunar Surface

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

Theresa Battaglia, James Clark, Michael Collins, Suneal Gupta, Todd Herrmann, Drew Hykin, Mark Kimball, Brian Kujawa, Benjamin Lee, Yan Lui, Kajal Pancholi, Matthew Schnaubelt, Joseph Simons, Troy Sookdeo, Joseph Stecher

Advisors: Dr. David Akin, Dr. Mary Bowden

Abstract
In the hopes of paving the way for a permanently inhabited moon base, a six-mission program was designed, with missions being flown yearly from 2013 to 2018. Each mission will consist of a "habitat module" and an "ascent/descent module." These modules will be launched on a Delta IV rocket and a Space Shuttle, and will then connect with booster stages in LEO before finally reaching the moon. Throughout each mission, four crew members will explore the lunar surface in detail, conducting various scientific experiments over their 90-day stay, with the goal of expanding knowledge of the lunar environment. Missions will explore both the near and far sides of the moon, with communication satellites providing a link to far side missions.

Introduction
In the early 1900s, Antarctica was a vast and virtually unexplored region of the world. Sir Ernest Shackleton decided that he would be the first person to cross the barren continent, and so in 1914, he set sail on the ship Endurance. During his voyage, however, his ship became trapped in ice and was destroyed. Shackleton and his crew miraculously survived the long winter night on Elephant Island and a perilous open boat crossing of the Antarctic Ocean. Though Shackleton did not succeed in his endeavor, his brave voyage paved the way for future explorations of the continent.

His story is the basis for Project Endurance. Just as Shackleton's voyage opened the door for future Antarctic explorers, so did the Apollo program open the door for the detailed lunar exploration of Project Endurance. This series of six missions will pick up where the Apollo program left off, 40 years later, and hopefully lead the way for the first permanently inhabited moon base.

Site Selection
The six sites chosen were selected to provide the greatest scientific and exploratory return. Each site needed to have a 500-meter-wide portion of terrain, with slopes of less than 15 degrees, to allow for safe landing. Geological features, mineral concentration, the possibility of studying the formation of the moon, unique terrain, and possible ice deposits were some of the criteria considered in the site selection process. All sites also had to be within certain bounds in order to maintain constant communication with Earth. The sites chosen are as follows: Copernicus Crater (2013), Tycho Crater (2014), Korolev Crater (2015), Aitken Basin (2016), Apollo Crater (2017) and Mare Imbrium (2018).

Mission Architecture
Each mission will consist of a habitat module with seven boosters and an ascent/descent (A/D) module with four boosters. The A/D module will leave a trans-Earth injection (TEI) stage with a heat shield in low lunar orbit (LLO) when it descends to the Moon. Throughout the 90-day mission, the crew will live and work in the habitat module. They will use lunar rovers to travel and collect samples. At the end of the 90 days, the crew will ascend in the A/D vehicle to dock with the TEI in LLO, leaving the habitat module, lunar rovers, and descent stage on the lunar surface, and will then return to Earth.

Trajectories

The approximate _V's for the mission are summarized in the following table:

Path	_V (m/s)
LEO to LS	6247
LS to ES	2890
LEO to LLO	3844
LLO to ES	837
LLO to LS	2706
LS to LLO	2334

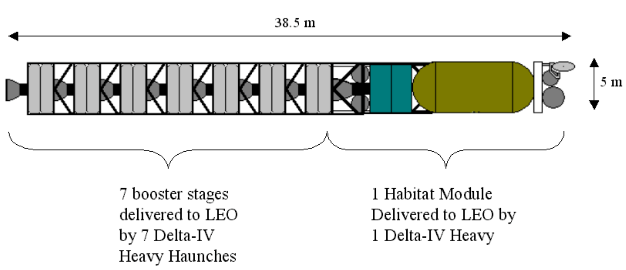
**LEO: Low Earth Orbit, LLO: Low Lunar Orbit,
LS: Lunar Surface, ES: Earth Surface**

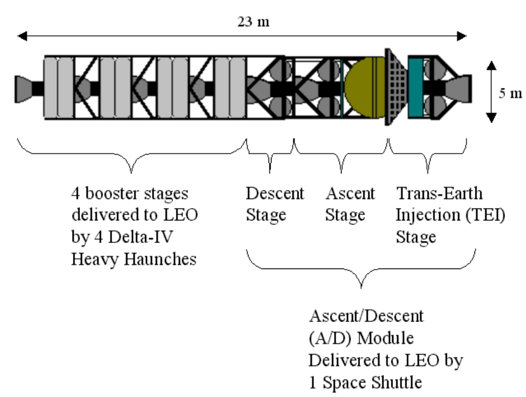
The chosen transfer method from low earth orbit to lunar orbit is a one-tangent burn with a transfer time of approximately 3.46 days. This method was chosen because it provides a relatively short transfer time at a small _V cost.

Attitude Control

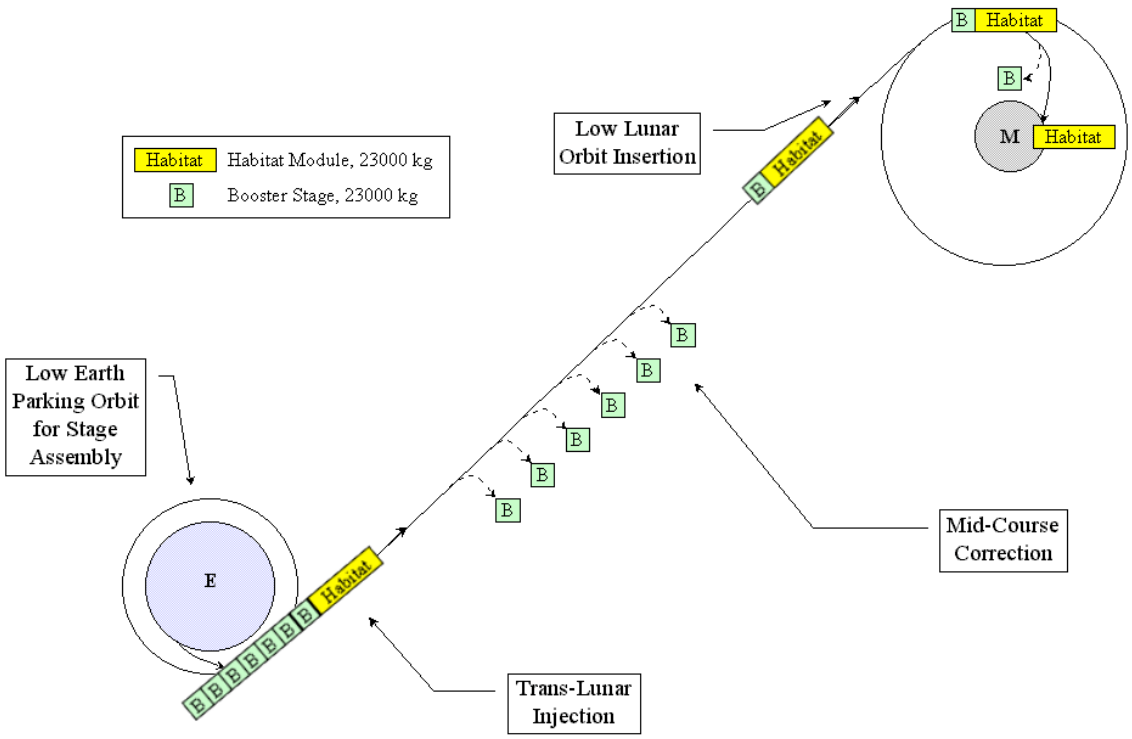
The habitat module, ascent stage, and TEI stage each have 16 attitude control thrusters for all-axis rotational control. Each booster stage will also have at least 16 thrusters. The first 3 boosters launched into LEO, however, will contain 32 thrusters, in order to provide extra maneuvering ability to compensate for their prolonged exposure to atmospheric drag.

Boost Sequence & Staging

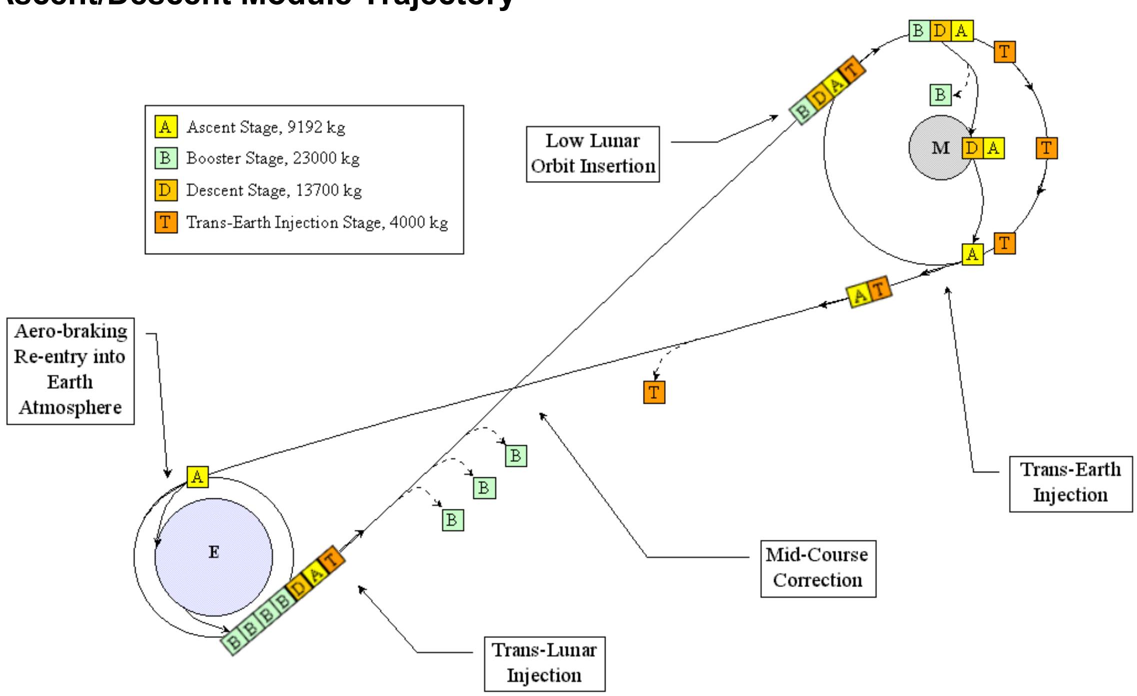




Habitat Module Trajectory



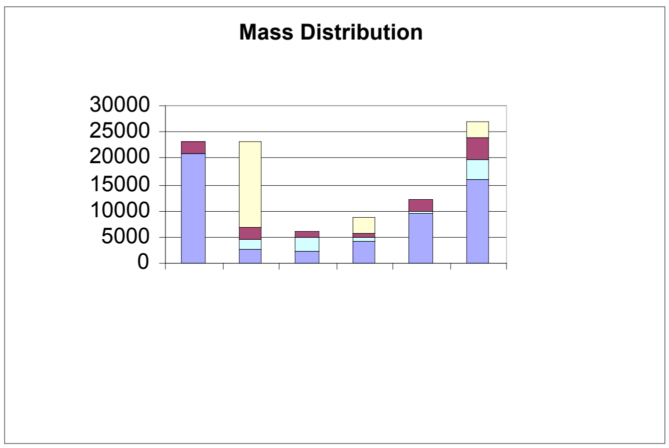
Ascent/Descent Module Trajectory



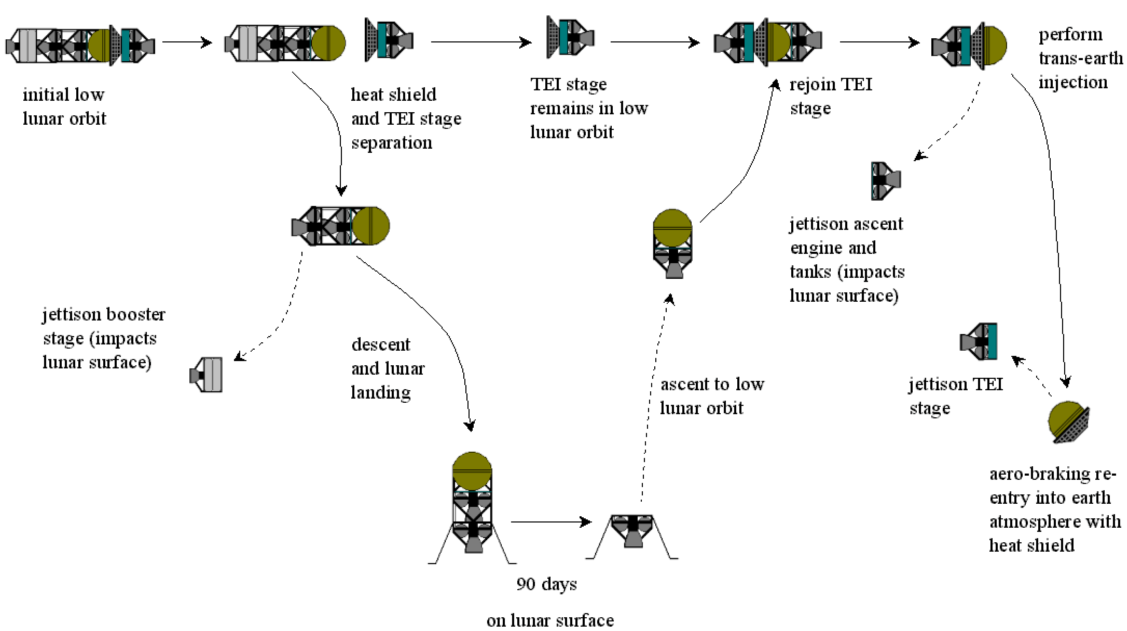
Payloads & Landed Masses

A breakdown of the total mass by vehicle component is shown in the following figures: (all masses in kg)

	Payload	Inert	Propellant	Residual	Total
Booster Stage	-	2300	20700	0	23000
Habitat Module	16000	2300	2617	2083	23000
Ascent/Descent Module					
TEI Stage	-	1000	2386	2614	6000
Ascent Stage	3000	868	4168	648	8684
Descent Stage	-	2300	9305	710	12315
Total	3000	4168	15859	3972	26999



Return Scenario



Abort Scenarios

The TEI stage has been designed with a good deal of residual propellant, so that in the worst-case scenario, where its orbit has rotated 180° from the landing site, it can perform the needed inclination-changing burn. Once re-aligned with the landing site, the ascent module can rejoin it and return to earth.

Attitude Control

There are four main types of disturbance torques: gravity gradient, solar radiation, magnetic field, and aerodynamic. While each booster stage waits in orbit for docking with the other stages and the habitat or ascent/descent module, the relative weakness of solar radiation makes its presence almost negligible. As the spacecrafts leave low earth orbit, the solar radiation torque becomes more prominent since the other three are dependent upon orbital altitude (aerodynamic torque and magnetic torque disappear the quickest).

In order to maintain the proper attitude while in low earth orbit (it is important to avoid exposing a large cross-section to drag and losing too much altitude before rendezvous), extra attitude thrusters are required. This depends on how long each booster stage remains in orbit. The attitudes of some boosters may be intentionally changed to a non-optimal configuration in order to meet up with boosters that have a slightly lower orbit.

The habitat module will be landing first and requires a radar system to avoid any obstacles larger than one meter. This is a derived requirement from another: that the spacecraft be able to land on a 15 degree slope with a 1-meter obstacle. Since they are not designed to handle anything greater from a structural point of view, a collision avoidance system is necessary to ensure crew safety.

Once the ascent/descent module is within 15 miles of the habitat module, the states of both will have to be known very accurately by the ascent/descent module's onboard navigation system. In order to obtain the proper degree of accuracy, rendezvous radar measurements (range and range rate) will be taken from an altitude of 15 miles, until the crew can spot the habitat module. The attitude control engine chosen for all these applications is the DMT-600.

Docking Operations

The docking procedure will be fully automatic, and will closely resemble the current Kurs system. Automatic docking allows for greater flexibility in the launch windows of the boost stages, which is necessary as the period between Delta IV flights is restricted. The general operations for the docking procedure are outlined in the following table:

Time Before Docking (mins)	Operation
440	Radio rendezvous systems are activated on approaching vehicle
425	Transponder on target vehicle is activated
300	Distance closed to approx. 2.5 km
240	Distance closed to approx. 0.6 km
200	"Flyaround," the alignment process between the two docking ring antennas, begins
120	Flyaround complete, distance closed to 0.2 km
10	Probe deployed on approaching vehicle
0	Docking complete

Note that while this setup is similar to the Kurs system, it takes place over four times as long of a period. This is done to reduce the magnitudes of the relative velocities over final approach, which results in smaller docking loads than Kurs.

Landing Legs

The landing system is one of the most critical systems for each vehicle. In order to reduce the forces on the craft at landing, aluminum honeycomb shock absorbers will be used. The shock absorbers chosen are the Alcore Spiral-Grid with a crush strength of 9000 psi. Normally, the force on each leg at landing would be so high that the legs would have to be several hundred kilograms in order to avoid yielding. However, by placing a long section (~2 m) of Spiral-Grid in the load-bearing portion of the legs, the stress in that part is kept to only 9000 psi. The actual forces exerted on the legs, their corresponding accelerations, and several other values are summarized below.

Property	Habitat Module		Descent Module	
	Value	Units	Value	Units
Tread	7.0	m	7.0	m
Maximum Crush Length	1.469	m	1.304	m
Total honeycomb Length	2.099	m	1.863	m
Lower Leg Length	1.469	m	1.304	m
Spiral-Grid Crush Stress	62.1	Mpa	62.1	Mpa
Spiral-Grid Density	812.5	kg/m^3	812.5	kg/m^3
Sprial Grid Cross Section	0.001264	m^2	0.001086	m^2
Total Mass of One Leg	17.92	kg	14.69	kg
Mass of All Four Legs	71.68	kg	58.76	kg
Worst Case Force	313700	N	269700	N

Habitat Module Structure

The habitat module consists of a two-level pressurized living area, a power systems level, a cryogenic storage level, landing legs, and a 240-kN descent engine.

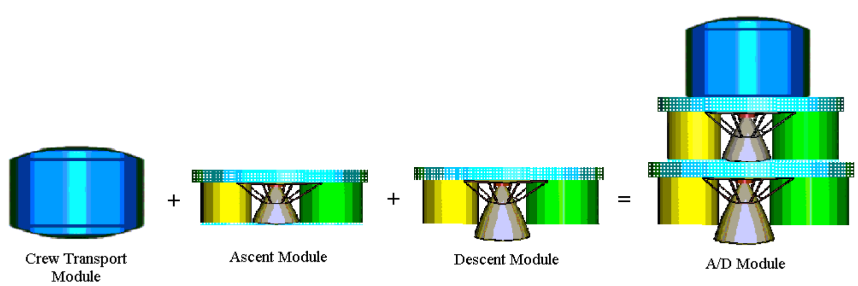
The habitat will experience launch accelerations of 4.5g vertically, with side loadings of 1.5g. Including dynamic loads such as vibration and staging shocks, the payload can experience combined loads of up to ± 3 g laterally, and from –2 to +6g vertically. The pressure hull will only support its own mass during launch, so pressure loads cause the critical stress. The worst-case loading situation would occur if the hull failed to depressurize as it ascended through the atmosphere after liftoff.

To prevent the pressure hull from buckling, ribs and stringers will be used to support the forces caused by the launch accelerations. The worst-case loading that may occur would be the combined load of +6 g acceleration axially and +2 g acceleration laterally. The stringers have an I-beam cross-section, with overall dimensions of 8 cm by 8 cm, and web and flange thickness of 3.5 mm.

	Stress (kPa)	Load Condition	FOS	Margin
Pressure Hull - walls	126.3	Internal pressure	3.0	+0.10
- bulkhead	86.7	Internal pressure	3.0	+0.59
Stringers	79.3×10^3	Launch loads	2.0	+0.29

Ascent/Descent Module Structures

The ascent/descent module consists of three separate modules joined together; they are the crew transport module, the ascent module, and the descent module.



The specifications for the crew transport module are as follows: a 2-mm-thick, 2-meter-high cylindrical tube with a radius of 2 meters is attached to a 2-mm-thick hemispheric shell with a height of 0.5 meters and a curvature radius of 4.25 meters. Inside the pressure shell will be a structural cage that will support and distribute loads throughout the shell. The cage's structural members work by acting as stiffeners, and increasing the moment of inertia at different locations. The structural cage will also be used to attach life support and other vital equipment to the transport module. The descent module is the second structure of the A/D module. Its purpose is to land the A/D module after it enters lunar orbit.

To allow for a controlled landing, the descent engine must be able to throttle and rotate. This requires a thrust structure designed to hold and transfer its loads onto the ascent docking module and the transport module. The thrust structure must be designed not just to handle vertical loads, but also angular loads.

The ascent module is a structure whose purpose is to launch the crew back into orbit to meet with the orbiting TEI stage. It carries a smaller engine along with its fuel, and will separate via pyrotechnics. After separation, the ascent module's engine will ignite, sending the module back into lunar orbit. The ascent module's thrust structure is similar to the descent module's, but is smaller because it holds a smaller engine, and is only designed to transmit vertical loads.

Structures	Loads Source	Safety factor	Margin of Safety
Pressure Shell	Atmosphere	3.0	.3
Cage + Shell	Reentry/Landing	2.0	.1
Floors	Equipment/Crew/Landing	2.0	.16 and .2
Thrust structures	Launch	2.0	.2
Landing legs	Landing	2	1.08

Air Revitalization

Atmosphere must be generated or supplied on the lunar surface. This makes atmosphere generation and revitalization a necessity. Through water electrolysis, hydrogen and oxygen can be recovered through dissociation of water molecules. Point-eight-four kilograms of oxygen per person per day, along with stored nitrogen, can be vented into a pressure vessel, similar to filling a balloon. One kilogram of carbon dioxide per person per day can be removed from the atmosphere, before displacing vital oxygen, through regenerative carbon dioxide removal systems. An earth-like atmosphere can be maintained for maximum comfort.

Using the ideal gas equation, $PV=nRT$, one can calculate the critical elements inside the pressure vessel. By maintaining 57.6 kg O_2 at 32 kPa and 70.2 kg N_2 at 30 kPa, a stable, habitable, and ultimately viable atmosphere is achieved. This is agreeable for EVAs, fire containment, and overall mission fluidity.

Food

Nutritional standards will be met by using the foods available to Apollo astronauts, including: beverages, breakfast items, cubes and candy, desserts, salads and soups, sandwich spreads and bread, and meats. The crew will maintain a healthy and balanced diet that is pre-selected prior to mission launch.

Each crewmember receives up to 1.8 kg of dehydrated food per day. Rehydration is accomplished through a water dispenser that pierces the rubber septum on the food bag or, "spoonbowl," and inserts the desired amount of water for rehydration. Available are two meals per person per day with 24-hour access to nutritionally-selected snacks and candies. There is enough food to support 99 days of lunar exploration for a four-person crew, thus meeting the mission requirements.

Water Reclamation

The water reclamation subsystem consists of three main components: storage tanks, water use items, and a filtration subsystem. Water is used for drinking, food preparation and hygiene. The first table below summarizes water uses. The main components of the filtration subsystem are a vapor-phased catalytic ammonia removal (VPCAR) distiller and a multifiltration bed. The VPCAR system is redundant, and a reverse osmosis filter acts as a backup to the VPCAR system. Before the cleaned water flows into the potable water storage tank, a quality control station for contaminants checks the water. The second table below shows the entire system mass and power breakdown.

Input	kg
Water in food	0.23
Food Prep Water	1.68
Drink	1.62
Metabolized Water	0.35
Hand/Face wash water	4.09
Shower Water	2.73
Urinal Flush	0.50
Clothes Wash Water	4.18
Dish Wash Water	0.00
Water needed per person/day	15.30

System Summary			
Water Savings Per Person	15	kg per person, per day	
Total Water Use	498	kg per day	
Equipment Mass	340	kg for entire mission	
Power Use	1.3	kW Continuous	
System Mass	837	kg total	
Water Usage	Mass (kg)	Power (W)	Vol (m^3)
Toilet (2)	40	72	0.523
Sink (3)	48	0	0.432
Shower (1)	22	0	1.52
Hot Water Heater	20	522	0.05
Washer / Dryer	91	1400	0.33
Plumbing	100	0	0.005

A/D Crew Systems

The A/D module crew systems are 100% re-supplyable. The A/D module carries enough atmosphere and water for four astronauts to survive twelve days, three to the moon, three to earth, and six emergency. Its cabin is pressurized at 62 kPa with the exact same partial pressures as the crew habitat module. Carbon dioxide is scrubbed using non-regenerative four-bed molecular sieves. Water available constitutes water used in drinking, hygiene, and urine flushing.

There is no airlock, only a hatch. The atmosphere is completely vented during EVA from the A/D module, and must be resupplied. The module carries enough atmosphere to depressurize and re-pressurize three times (once upon landing and two emergency, in-flight depressurizations). The g-couches are stored on the ceiling and a safe distance from the radioactive DIPS power system onboard.

Radiation Remediation

For long-term interplanetary missions, the dangers of radiation exposure become a major limiting factor. Adequate amounts of shielding are needed to prevent harmful doses accumulated over the course of the mission and large short-term doses in the event of solar flares. For each mission, each astronaut will be subjected to a maximum radiation dose of 50 rem. To keep the dosage at this level, shielding must be present during all phases of the mission.

Shielding on the ascent/descent module provides protection while passing through the Van Allen radiation belts during transit to and from the moon. A total of 10 % of the entire mission radiation dose is accumulated during transit. Once on the surface of the moon, the astronauts spend their time in one of three places: crew habitat module, sleeping/storm shelter area, and on EVA. Combined, 30 % of the entire mission radiation dose is incurred during the lunar surface stay. The remaining 60 % is reserved in the event of two large solar flares in which each astronaut is exposed to a 15 rem short-term dose per flare in the polyethylene storm shelter.

Fire Protection

Fire detection and suppression systems are in place on both the ascent/descent module and habitat module. The systems are comprised of smoke detectors, visual and audible alarms, portable breathing apparatus, portable fire extinguishers, and suppression ports located throughout the modules. Each system has a 99.9 % probability of working in the event of a fire.

Medical Supplies

The habitat module is equipped with an extensive medical supply. The inventory consists of diagnostic and laboratory equipment as well as therapeutic and resuscitative medications and equipment. The two main kits in the medical supply are the Medications and Bandage Kit (MBK) and the Emergency Medical Kit (EMK). The MBK consists of oral medications, bandaging materials for minor abrasions, and topical medications. The EMK consists of intravenous medications, diagnostic items, and instruments to perform minor surgery. Medical supplies in the ascent/descent module are scaled-down versions of those aboard the habitat module and are designed to provide adequate treatment until reaching the habitat module or returning to earth.

Data Management

The computer systems in the habitat will be required to run many, if not all, of the habitat's life critical systems. These systems will include all equipment that is essential to keeping the crew of the mission intact and fully functioning. They will also include the systems that can help the crew to successfully leave the habitat and arrive back to Earth or any space station for rescue. These life-critical systems also pertain to all sensors inside and outside the habitat such as air, temperature, pressure, human biological, radiation, and communication sensors.

Along with the main computer system, each crew member will have a laptop for their individual use on research experiments they are conducting. These laptop systems can be connected to the main computer system through Ethernet connections, allowing the crew members to have access to data being acquired by the main computer system.

Sensor Systems

Sensor systems are located throughout the habitat and A/D module inside and out. Sensors are used for signifying the tolerable and intolerable levels of the system being monitored. Each system is being monitored to make sure that it is operating at a nominal, safe level, or a level that is suitable to the crewmembers. These systems monitor the critical systems for the mission and are composed of primary and secondary systems, which are key elements to crew safety and mission success. These systems include pressure, temperature, oxygen level, water reclamation, radiation, audio and video communication, controls, navigation, and guidance.

Thermal Control Systems

The two most important requirements of the thermal control system will be to minimize the heat flow out of the habitat module and to dissipate the excess heat generated by the humans and electronics onboard. This electronics include the computer, laptops, and the crew systems equipment. In minimizing this heat flow, this thermal control system must account for a number of external heat sources, including solar heat and the albedo effect and infrared heat from the Moon's surface. Also, this thermal control system will be designed to protect the habitat module from micrometeoroid debris.

Project Endurance will utilize multilayer insulation as its only form of a passive thermal control system. Multilayer insulation is a type of high-performance insulator, which uses multiple radiation heat transfer barriers to retard the flow of energy. After consideration of many different types of outer layers, a beta cloth was chosen to be draped around the outside of the entire structure of the habitat module. On the inside of the structure, next to the pressure vessels, will be placed 20 alternating layers of reflector and separator layers. The materials chosen for these layers are goldized Kapton and Dacron netting, respectively.

An active thermal control system (ATCS) is used in addition to a PTCS when the latter is inadequate, as is the case in manned missions. In addition to blocking out the damaging effects from the outside, a system is also needed to maintain a comfortable temperature level within the modules, in order for the crew and all of the electrical equipment to function properly. For Project Endurance, the inside cabin of the habitat module will be maintained at a temperature range of 16 – 24 °C (60 – 75 °F). The total amount of heat generated, by the astronauts, water reclamation system, oxygen generation assembly, computer and laptops is 4060 watts. In order to dissipate all this heat that is generated, multiple components, which are outlined below, must be utilized.

Cooling plates will be mounted on the water reclamation system, the oxygen generation assembly and the computers. There will be a total of 12 cooling plates used around the habitat module, and will be placed as follows:

- 4 – 1 on each of the computers
- 3 on the water reclamation system
- 4 on the oxygen generation assembly
- 1 utilized for the air cooling system

In order to dissipate the rest of the heat, generated by the humans and the laptops a duct will be placed on the floor of the bottom level, and will contain a cooling plate. Air will be directed over this cooling plate, and will then be transferred to the top of the habitat module.

The types of pumped loop systems utilized by Project Endurance are water and ammonia coolant loops. The water loop uses cold water that is pumped through pipes located in the walls of the module. These loops will surround the crew cabin, and run through the cooling plates, including the one used for the air-cooling system. This loop will then transport the heat to an ammonia loop at a heat exchanger. Heat exchangers are used to transfer thermal energy between two or more fluids at different temperatures. Only one heat exchanger will be needed for the entire habitat module.

Radiators are heat-dissipating equipment that will be located on the outer surface of the habitat module. The size of the radiators will depend on both the heat loads that are to be expelled, and the temperature that is to be maintained inside the module. A thermal balance analysis was used to determine that the total surface area needed for the radiators is 7.95 m^2.

Should emergency cooling be required in the habitat module, the pumped-looped systems and the air-cooling system will simply operate at a faster rate. On the other hand, should emergency heating be required in the habitat module, the entire cooling system will be turned off.

The thermal system requirements for the Ascent / Descent Module are the same as those for the habitat module. Such a system should be capable of essentially maintaining the temperature within the module at a range where everything will function properly. Since the total surface area of this module is smaller, less multilayer insulation will be required. Also, since the total amount of heat generated is only 600 watts, the ascent / descent module will only require 2 cooling plates to fulfill the thermal requirements: 1 will be placed on the main computer, and 1 will be utilized for the air-cooling system. Due to this lowered amount of heat that needs to be dissipated, the radiators will only need to be 3.01 m^2. The emergency system will function the same as it does in the habitat module.

Communications

The communications requirement states that the surface spacecraft must be capable of continuously transmitting four channels of compressed high-definition television both to and from Earth. For four channels of HDTV, 180 Mbps of bandwidth will be needed. This large bandwidth drives the design of most of the communications system.

Communicating with missions on the near side of the moon is a relatively simple task. Since the moon is tidally locked to the Earth, a constant line of sight is always available. All communications with Earth will take place over NASA's Deep Space Network. A number of 34-m antennas located around the globe will provide constant communication with the two Endurance spacecraft. The table below gives the important parameters for various communication links with near side missions.

Link	Data Rate	Dish Diameter	Frequency Band
A/D Module to Earth	90 Mbps	0.5 m	Ku (14/12 GHz)
Habitat Module to Earth	180 Mbps	1.0 m	Ku (14/12 GHz)
Rover to Habitat Module	45 Mbps	0.5 m	S (4/2 GHz)
Rover to Earth	45 Mbps	0.5 m	S (4/2 GHz)
Suit to Habitat Module	80 kbps	0.05 m	UHF (470-890 MHz)

The missions to the far side of the moon present an interesting problem for communications. Since a direct line of sight to Earth is never available, the signals from the surface of the moon must be relayed somehow. It was determined that the best solution to this problem is to place two satellites in a halo orbit about the Earth-Moon L2 point, a feat never before attempted.

These satellites would have two antennas, a large one pointing at Earth, and a smaller one pointing at the moon. Though they provide great access to the far side, the size of their orbit did constrain the location of certain landing sites. A mission to Mare Orientale was eliminated because the site was in not in view of the satellites at all times. The table below gives the important parameters for links with the far side of the moon.

Link	Data Rate	Dish Diameter	Frequency Band
A/D Module to Earth	90 Mbps	0.5 m	Ku (14/12 GHz)
A/D Module to Satellite	90 Mbps	0.5 m	Ku (14/12 GHz)
Satellite to Earth	180 Mbps	1.0 m	Ku (14/12 GHz)
Habitat Module to Satellite	180 Mbps	1.0 m	Ku (14/12 GHz)
Rover to Habitat Module	45 Mbps	0.5 m	S (4/2 GHz)
Rover to Satellite	45 Mbps	0.5 m	S (4/2 GHz)
Suit to Habitat Module	80 kbps	0.05 m	UHF (470-890 MHz)

Power Systems

The Endurance missions' power system architecture involves multiple power systems for generation and storage. The primary energy source will supply the crew module with 20kW of power during the lunar day and 17kW of power during the lunar night. This power will provide for life support and daily activities once on the lunar surface. Separate mobile 2-2.5kW power systems will provide the astronauts with adequate power for lunar transportation and scientific exploration.

The mission will require multiple independently powered boosters, as well as a lunar habitat module and an ascent/descent module for crew transport. Each spacecraft will require a compact, long duration energy source for in-flight operations and systems monitoring and maintenance. To meet these requirements, photovoltaic array/rechargeable battery combination systems as well as the nuclear-based Dynamic Isotope Power Source will be utilized. The primary power source will be an independent system on the crew module functioning to provide for air revitalization, water reclamation, communications, science applications and various periodic loads once on the lunar surface. It will require subsystems for power generation and energy storage.

The power generation subsystem will operate during the day providing electricity via the Sun's radiant energy and storing energy for the lunar night. The energy will be stored in the form of hydrogen and oxygen chemical bonds. During the lunar night, hydrogen/oxygen regenerative fuel cells will supply all required power. During the day, the total power requirement will be provided by Gallium Arsenide (GaAs) photovoltaic arrays in the form of 27 individual sun tracking panels totaling $135m^2$ cell arrays. Two electrically-powered rovers will provide lunar transportation. They will have small, compact chemical battery power systems that will provide a safe, reusable power source.

Experiments

The driving force behind the six lunar missions is the science that will be conducted there. The experiments to be conducted include mineralogy, very low frequency array observations, and physiological experiments. Mineralogy experiments conducted on the lunar surface will help scientists learn more about Earth's only natural satellite. By collecting geological samples, much can be learned about the development of the moon, including its age and composition. Samples from different geological formations such as mountain peaks, plateaus, craters and volcanic formations will be analyzed and compared. It will be important to notice trends in the moon's development, such as periods of intense volcanic activity and periods of frequent meteor strikes. Slices of rock and core samples will be taken to limit the mass of samples transported back to Earth. Also, as reported by the Lunar Prospector and Clementine, there is ice in the polar regions of the moon. Core samples will be taken from Aitken Basin to determine if this ice is evidence of water existing on the Moon or the remnants of a comet.

Due to absorption of radio waves by the Earth's ionosphere, there is very little known of the radio sky beyond 10 m wavelengths. If these observations were taken from the lunar surface, much more could be learned about radio wavelengths beyond 10 m. A very low frequency (VLF) radio astronomy observatory, consisting of a large array of wire antennas equipped with an amplifier and digitizer connected to a computer, could make observations of wavelengths from 10 ~ 100 m with high resolution and observations of wavelengths from 100 ~ 1000 m with low resolution. Another important scientific factor to consider is the effect of a 90-day mission, with frequent EVAs, on the human body. The following physiological observations will be carefully monitored for each of the crewmembers: cardiovascular activity, bone and muscle loss, exercise and nutrition, immunology, and behavior and performance.

Airlock

The operational procedure for the airlock involves, first, suiting up outside the airlock. Next, the pair of astronauts would enter the airlock, close the inner hatch, and begin depressurization. Once the pressure inside the airlock has reached 5.75 torr by the vacuum pumps, the air release valves would be opened to finish the depressurization process. After the airlock has been fully depressurized, the outer hatch is opened and the astronauts climb down the ladder to perform their EVA. The airlock is left depressurized, and the outer hatch open, while the EVA is in progress, so as to minimize the chance of the astronauts being trapped outside the airlock. When the astronauts return from their EVA, the outer hatch is closed and the inner air release valves pressurize the airlock.

EVA

The suit chosen for lunar surface activities is ILC Dover's I-Suit. The I-Suit possesses several unique qualities such as: totally fabric construction for increased mobility, operability in a dusty environment, and a light weight due to the lack of massive solid pieces. The I-Suit is pressurized at 29 kPa 100% O_2. This is important when calculating the ratio between the suit pressure and the partial pressure of nitrogen in the cabin atmosphere. This value, represented as R, symbolizes the probability of side effects due to nitrogen bubbles formed during transit to the suit. In using the I-Suit, an R-value of 1.03 is maintained, requiring zero prebreathe before suit transit. This reduces the chances of dramatic side effects such as "the bends." In addition, it decreases the time necessary to transit between suit and cabin, and vice versa.

EVAs on the lunar terrain will require additional technology. This includes rovers and tools, which are stored externally, allowing easy access while on an EVA. They are placed directly in the bilge of crew habitat module, which helps to minimize dust contamination of the cabin. The suits, however, are stored internally on the first floor of the crew module in a storage bay. This allows quick access during emergencies and close proximity to the airlock.

To meet all mission requirements and to conduct experiments, the astronauts are required to make daily EVAs for almost the entire mission. EVAs in the beginning of the mission will be used to deploy the lunar rovers from the habitat module and to set up experiments such as the VLF array. Later EVAs will involve exploring the lunar landscape, taking samples, and conducting maintenance on the lunar rovers. The lunar rovers will be similar to those used on Apollo, and will run on two 36-volt rechargeable batteries. Two rovers will be taken on each mission, with one serving as a backup in case astronauts on EVA encounter an emergency situation. All EVAs will use the buddy system, meaning two astronauts will go on EVA, while two remain in the habitat, supporting the EVA and conducting their own experiments.

Reentry

Maximum entry accelerations are limited to 9 g's. A Matlab program was used to analyze lifting and nonlifting earth entries. The reentry corridor for the vehicle is approximately 0.5°. For a heat shield with a radius of 500 ft, stagnation point temperatures approach 3600°K and maximum total heating loads approach $1*10^9$ J/m^2. A simple Chapman heating model is used with a blunt entry vehicle.

Testing Scenarios

Three precursor flights to the moon will take place from 2010 to 2012 prior to the annual missions from 2013 to 2018. The first flight test with an unmanned A/D Module is necessary to make sure that a fully functional system exists to safely ferry the crews to and from Earth. The second flight test sends a Habitat Module to the lunar surface one week prior to the astronauts' arrival on another A/D Module. The astronauts spend two weeks on the lunar surface in final checkout of the Habitat and Ascent/Descent Modules and then return to Earth.

Overall Timeline

First, research and development starts in 2002 and ends in 2006. Vehicle production starts in 2005 for the precursor missions; the final vehicle is completed in 2015. Next, testing and validation of flight hardware begins one year after production starts and finishes a year after all production ends. As indicated above, flight testing runs from 2010 to 2012. Finally, the six 90-day missions fly to the moon from 2013 to 2018.

Cost Analysis

Project Endurance, beginning in 2002 and ending in 2018, costs an estimated total of $25.5 billion in Y2002 dollars. The price of research and development is approximately $5.3 billion (Y2002). Production of all spacecraft for all missions will cost $2.9 billion (Y2002). Launch costs for all missions sum up to over $17.1 billion (Y2002). Operations throughout the life of the program will cost over $304 million (Y2002).

Conclusion

Project Endurance will continue the efforts of the Apollo program. Through six lunar missions, beginning in 2013 and ending in 2018, humanity will vastly expand its knowledge of our closest neighbor. Advancements made during these missions will aid in future space exploration endeavors.

References

"A Mission Radiation Calculation Program for Analysis of Lunar and Interplanetary Missions". NASA TP-3211, May 1992.

Akin, David. "ENAE483 Course Notes", University of Maryland, 2001.

Anderson, John D. "An Engineering Survey of Some Radiating Shock Layers". AIAA Journal Volume 7, Number 9 September 1969.

Burke, Bernard. "Astronomical Interferometry on the Moon". Lunar Bases and Space Activities of the 21st Century. 1985.

Chin, Derek, and Hermans, Mike. "A Flight to The Moon". <http://webhome.idirect.com/~viking/themoon.html>.

Cintala, Mark and Paul Spudis and B. Ray Hawke. "Advanced Geologic Exploration Supported by a Lunar Base: A Traverse Across the Imbrium-Procellarum Region of the Moon". Lunar Bases and Space Activities of the 21st Century. 1985.

Delta IV Payload Planners Guide, The Boeing Company, 1999.

Douglas, James and Harlan Smith. "A Very Low Frequency Radio Astronomy Observatory on the Moon". Lunar Bases and Space Activities of the 21st Century. 1985.

Finckenor, M. M. "Multilayer Insulation Material Guidelines." NASA/TP 1999-20923. April 1999.

Greenberg, H. Stanley. Aerospace Structural Systems: Preliminary Design Techniques. Los Angeles: UCLA Department of Engineering, 1990.

Hamilton Sundstrand. Electrochemical Energy Systems: Water Electrolysis and Natural Gas. March 10, 2002. United Technologies Company. <http://www.hsssi.com/Applications/SpaceHabitat>.

Hibbler, R.C. Mechanics of Materials 3rd Ed. Upper Saddle River: Prentice Hall, 1997.

Hoffman, David. "Station-keeping at the Collinear Equilibrium Points of the Earth-Moon System." NASA JSC-26189. January 1993.

Horz, Friedrich. "Mass Extinctions and Cosmic Collisions: A Lunar Test". Lunar Bases and Space Activities of the 21st Century. 1985.

Leondes, C.T., and Vance, R. W. 1964. Lunar Missions and Exploration. New York: John Wiley & Sons.

Marcus, Martin. "The Efficiency of Computers and Optimizations in Performing Finite Element Computation". U.S. Naval Research Laboratory. May 17, 2001.

"Monitoring Bone Loss in Astronauts", Space Daily. <http://www.spacedaily.com/news/spacemedicine-01a.html>.

Shuttle Orbiter/Cargo Standard Interfaces (Core) ICD 2-19001, Revision-L, Boeing North American, Inc. 1998. <http://www.unitedspacealliance.com/icd/core/contents.html>.

Sonntag, Richard and Claus Borgnakke. Fundamentals of Thermodynamics. John Wiley and Sons, New York, 1998.

Sutton, George P. Biblarz, Oscar. 2001. Rocket Propulsion Elements Seventh Edition. New York: John Wiley & Sons, Inc.

Taylor, Lawrence and Dong-Hwa Taylor. "Location of a Lunar Base: A Site Selection Strategy". Engineering, Construction and Operations in Space V: Proceedings of the Fifth International Conference on Space '96, 1996.

The Lagrangian Points. March 5, 2002. Castle Point Astronomy Club. < http://www.cpac.freeserve.co.uk/docs/lagrange.htm >.

Vallado, David A. 1997. Fundamentals of Astrodynamics and Applications. New York: McGraw Hill.

Wade, Mark. Encyclopedia Astronautica. <http://www.astronautix.com>.
Weiland, Paul O. Designing for Human Presence in Space: An Introduction to Environmental Control and Life Support Systems. NASA Reference Publication 1324 (1994).
Wilhelms, Don. To a Rocky Moon: A Geologist's History of Lunar Exploration., The University of Arizona Press, 1993.
Wydeven, Theodore; " A Survey Of Some Regenerative Physio-Chemical Life Support Technology". NASA Technical Memorandum 101004 (1988).
Whitaker, Alana. "Overview of ISS US Fire Detection and Suppression System", June 25, 2001. <http://spaceresearch.nasa.gov>.
Young, Warren, Roark's Formulas for Stress & Strain. 1989 McGraw-Hill.