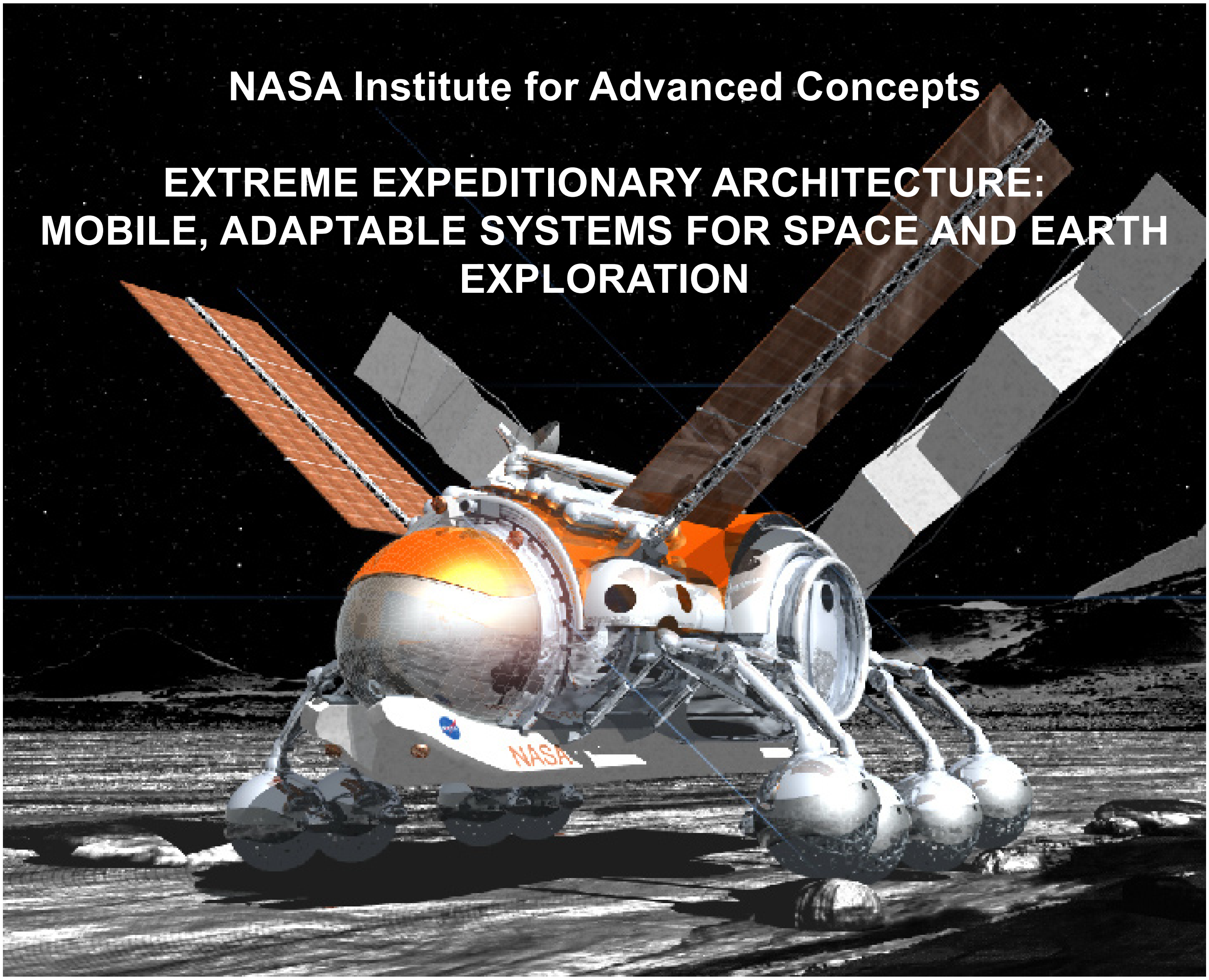

NIAC PHASE I FINAL REPORT

April 2007

Subcontract Agreement No. 07605-003-066

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TROTTI + ASSOCIATES, INC.

NIAC
NASA Institute for Advanced Concepts

Extreme Expeditionary Architecture (EXP–Arch): Mobile, Adaptable Systems for Space and Earth Exploration

Introduction

The Extreme Expeditionary Architecture (EXP–Arch) project developed an adaptable and mobile architecture capable of meeting a variety of space and earth missions. Earth exploration has demonstrated that mobility is fundamental to great discoveries. The EXP–Arch architecture proposes self-mobilizing, transformable systems combining robotics, inflatable and foldable lightweight structures, intelligent materials, and highly autonomous systems to revolutionize human and machine exploration. EXP–Arch is an adaptive exploration architecture for extreme environments (space and earth inaccessible locations) utilizing multi-functional, inflatable, and transforming system components. EXP–Arch attempts to better understand human-robotic synergies during exploration, and offers an educational initiative to merge design and engineering learning by engaging students at the Rhode Island School of Design (RISD) and the Massachusetts Institute of Technology (MIT).

EXP–Arch, offers a radical departure from conventional, evolutionary space systems mission planning. NASA's current mission architecture outlined in the Exploration Systems Architecture Study (ESAS) recommends an "incremental build" approach and "incrementally accumulating components" (NASA, 2005). In contrast, EXP–Arch provides an alternative, more creative approach, specifically, an adaptive exploration architecture for extreme environments (space and earth inaccessible locations) by embracing multi-functional modular, inflatable, and transforming system capabilities to foster self-sustaining human and robotic presence throughout the solar system.

The EXP–Arch concept directly ties in to long-term goals established by NASA's Exploration Systems Mission Directorate. Specifically, the 'Earth, Moon, Mars and Beyond' vision might truly be realized through creative, novel architectures that turn mission planning inside-out.

Contents

To help realize NASA's Vision for Space Exploration (NASA, 2004), we studied mathematical origami techniques and foldable structures for novel space and earth vehicle design that have not been previously envisioned. EXP–Arch developed a system of two larger rovers accompanied by two or more mini-rovers that operate independently or in groups to accomplish autonomous and crewed missions for four to eight astronauts.

The EXP–Arch contributes to NASA and NIAC in areas that are well aligned with the following Grand Visions (NIAC CP-06-01):
• Responsive, adaptive exploration architectures
• Lightweight construction systems with self-erecting capability
• Self-sustaining human presence throughout the solar system

This study also contributions to earth exploration and education by better understanding human adaptation; specifically human–robotic interaction and performance was studied. Symbiotic human-robotic capabilities for exploration expeditions must be achieved for future missions. Finally, the EXP–Arch educational initiative introduced Rhode Island School of Design (RISD) design students to the awe and challenges of space design in a semester-long studio (completely archived as an Appendix). In addition, EXP–Arch design lectures were given to MIT students to help synthesize their learning of design and engineering as holistic systems, rather than distinct disciplines. Overall, we strive to contribute in a small way to the national need of improving science, technology, engineering, and mathematics (STEM) education as outlined in the recent National Academies report. There is great concern that "the scientific and technical building blocks of US economic leadership are eroding" (National Academies, 2005).

A designer is an emerging synthesis of artist, inventor, mechanic, objective economist and evolutionary strategist.

– R. Buckminster Fuller

Extreme Expeditionary Architecture (EXP–Arch) Objectives and Vision

Trotti and Associates, Inc. (TAI) met the proposed objective to develop an adaptable and mobile exploration architecture and systems design concept capable of meeting a variety of space and earth missions. This revolutionary idea of Extreme Expeditionary architecture for planetary surfaces is in stark contrast to existing stationary base designs for lunar and Mars and most Earth Polar missions. A paradigm shift is possible in exploration by creating an architecture, or a suite of systems, which are highly mobile, quickly deployable, self shielding, and transformable to enable autonomous robotic and human exploration for short and long-term investigations at many diverse sites. Lunar exploration under the EXP-Arch concept is a stepping stone for Martian exploration with the goal of learning how to explore in a truly mobile way.

Light, agile transformers with self-assembly and repair capabilities should be realized in 10-25 years. Imagine mobile habitats, rovers and laboratories that transform from 1 m^3 while stowed or transported to 9.15 m^3 when fully deployed? This is the EXP–Arch vision.

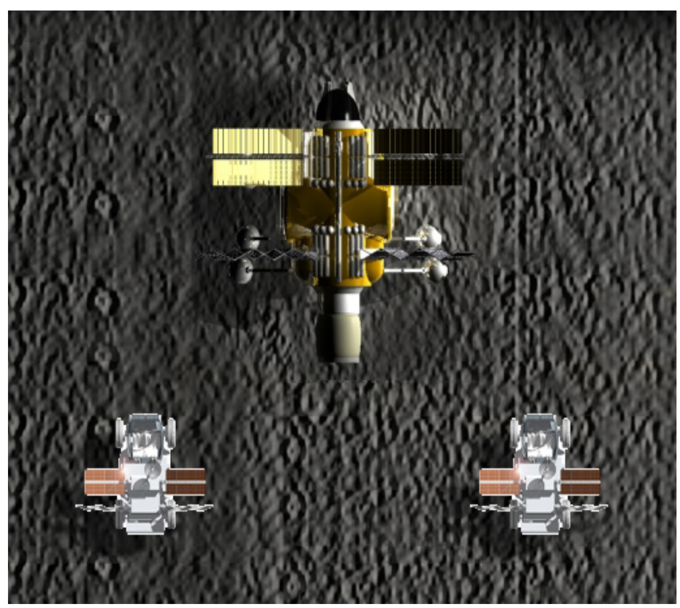


Figure 1. Initial Convoy of rovers to arrive on the Moon in the first launch.

Background

"The history of the human race is a continual struggle from darkness toward light. It is therefore to no purpose to discuss the use of knowledge. Humans wants to know, and when they cease to do so, he/she is no longer human." – Fridtjof Nansen, Norwegian scientist and explorer

Human and machine exploration on earth, sea and space are in our very nature, and exploring can help foster global citizenship and purpose, bring about creative solutions, and provide a symbiosis between technology, design, and the human spirit. Dick and Cowing pose three reasons why exploration is essential in a recent NASA publication (2005):

- Exploration is necessary for a creative society;
- Exploration requires clear goals despite its open-ended nature; and
- Risk is the inevitable companion of exploration.

What Is Revolutionary Exploration?
The EXP– Arch concept realizes mobile, self-erecting habitat, laboratory, and emergency shelter systems that demonstrate adaptive exploration architectures, which are responsive to their environments.

Future developments in intelligent materials, robotics, and autonomy enable the creation of new revolutionary systems that transform according to mission requirements by sensing, self-erecting, and self-propulsion. Imagine our EXP–Arch architectural system operating as a series of compact mobile vehicles that transport themselves to the next exploration site and then transform themselves into a habitable environment with laboratory facilities twice the original size for crew operations. The EXP–Arch design concepts include lightweight skins that are intelligent, give real-time data, and can self-adapt. The EXP–Arch fleet of transformers are networked and collaborate with each other to provide all the necessary facilities and capabilities for human-robotic exploration.

The highly qualified EXP–Arch team brings experience and creative ideas to study an adaptive exploration architecture where systems will sense and respond to their extreme environment. Architectural concepts for inflatable space structures can realize a 1:9 stowed to deployed volume increase.

On the moon or Mars, EXP-Arch transformers make nomadic exploration possible. An appropriate flexible architecture needs to meet many possible future scenarios, as outlined by NASA's Exploration Systems Mission Directorate for returning human presence to the moon and Mars, initially with 4 crew members during lunar sortie and outpost missions progressing to 6 crew members for design reference missions (NASA, ESAS, 2005).

For Earth missions the EXP–Arch concept can contribute to the needs for 1) Emergency shelter and rescue architectures in extreme inaccessible environments, especially due to global disasters (i.e., Hurricane Katrina that devastated New Orleans 2005, Asia's Tsunami that devastated Indonesia 2004, deadly earthquakes in Turkey, Japan and Mexico, etc.), and 2) Scientific study in inaccessible places (i.e., the ends of the earth: arctic, Antarctica and the harsh environment of the tropics).

Rapid deploying, lightweight structures with necessary life support facilities and laboratories can assist with urgent needs of humanity. We believe that the EXP–Arch discoveries and adaptive architecture concepts have great relevance to Earth exploration and disaster relief missions. EXP–Arch can be thought of as 'architecture on demand for human-robotic expeditions'.

We researched previously designed planetary rovers to learn from the various alternative designs and compare design requirements. We found that no habitable rovers were ever designed to operate autonomously and without dependence on a base for re-supply and shelter. During Phase I of the program we investigated many of the developments occurring today in the present revolution in the automotive industry. Particularly in the areas of new materials, wheel design, fuel cells, hydrogen storage, batteries, autonomy, biomimetics, navigation systems, and electrical motor propulsion. We think that it is time for a paradigm change in the way we think about planetary rover design and construction.

The EXP–Arch concept for adaptive exploration architecture targets scientific and commercial opportunities for space exploration and on earth by developing new concepts with the following capabilities for human-machine exploration:

- Self-building, self-repairing, and self-propelling
- Evolvable systems, structures and vehicles
- Concepts that can be recycled/reused for the Earth, Moon, Mars, and Beyond

The EXP–Arch architecture concept for lunar surface exploration offers a new approach compared to NASA's current lunar mission architecture of a single outpost, which requires extensive infrastructure at the south pole. The vision for EXP-Arch is to enable humans to become a "space faring species" and the EXP-Arch mission architecture focuses on realizing five exploration goals:

- To enhance the **human and robotic** experience during planetary exploration. Surface operations, self-sufficiency, and mars mission training should be demonstrated.
- EXP-Arch **technology testbeds** to demonstrate and gain experience with mining, construction, science, rapid excavation and regolith movement (for radiation protection), and systems testing.
- The lunar **surface exploration** includes investigating caves and lava tubes, and searching for water (ice).

Figure 2. Apollo Lunar Rover

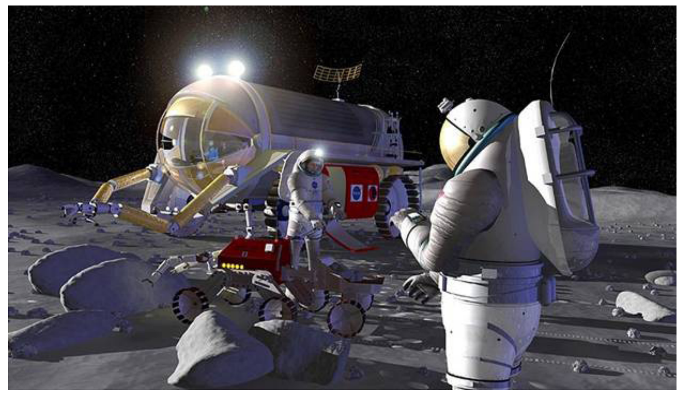


Figure 3. NASA Rover Concept

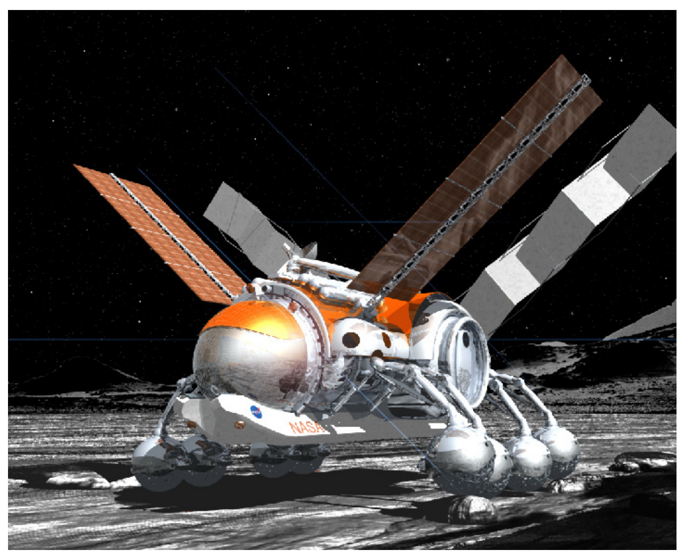


Figure 4. EXP-Arch Mother Ship Rover "Scorpion"

- EXP-Arch will enable **scientific research**, specifically, selenology, physics, astronomy, geology, chemistry, and life sciences.
- EXP-Arch offers extensive **public education and outreach** opportunities. By participating actively in rover operations we would like to facilitate a feeling by the public of "The People's Moon".

The Extreme Mission Architecture requires a Paradigm Shift in the way we envision planetary exploration. Exp-Arch is about total mobility and freedom to explore many diverse sites in all areas and latitudes of the Lunar or Martian surface. The focus of this study has been on designing a Lunar Architecture, however, we believe that this architecture is adaptable to Mars and extreme environments on Earth missions.

The basic architecture is composed of a suite of rovers or 'convoy' that allows a crew of 8 astronauts to explore the Moon. The total convoy is composed of 2 pressurized Mother Ship Rovers (MSR) and 4 un-pressurized small rovers or (Minis) that can travel on the Lunar surface autonomously, teleoperated, or manned. The total system can be landed with 2 landings from a Ares V type vehicle capable of landing 1 pressurized rover and 2 unpressurized rover in one Lander. The crews will be landed in different manned rated vehicles. The crews will be able to return on the same Lander or on a separate Lander at a different site where they are met buy a new crew. Each crew will bring the consumables and tools needed for their mission. The MSRs are equipped with all the necessary equipment to sustain the crew and they have the ability to expand to double their volume when stationary on a 'camp' mode.
In addition, they are design to dock with each other to again double the internal volume accessible to the crew. The Minis are in contrast unpressurized, they are highly mobile, they are mostly designed to carry cargo, tools, and assist the MSRs with route scouting, site preparation, and regolith movement. The principal role of the Minis is to transport the crew and supplies from the Lander to and from the MSRs. The minis will also transport and support some of the crew to remote sites during EVA explorations.

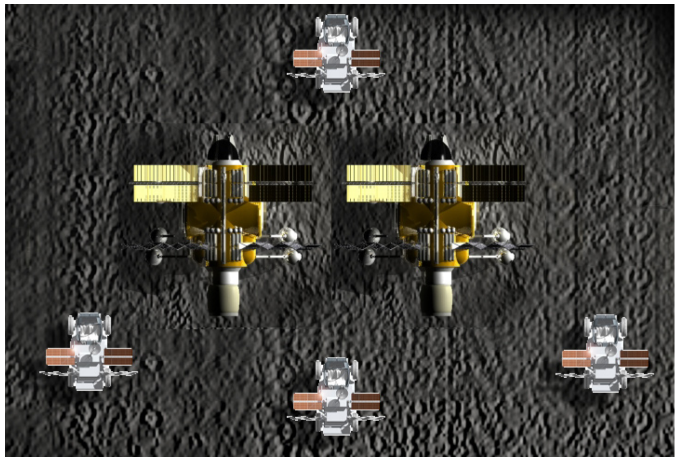


Figure 5.Total EXP-Arch architecture composed of a convoy of 2 MSRs and 4 Minis, delivered in two landers.

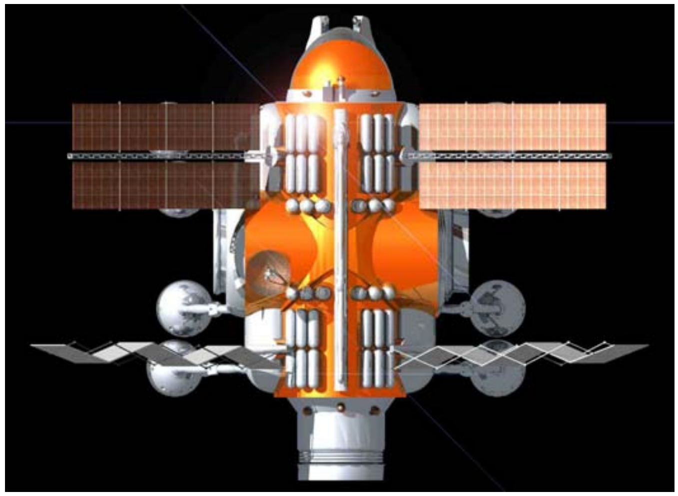


Figure 6. Top view of the pressurized Mother Ship Rover (MSR) capable of supporting a crew of 4 astronauts.

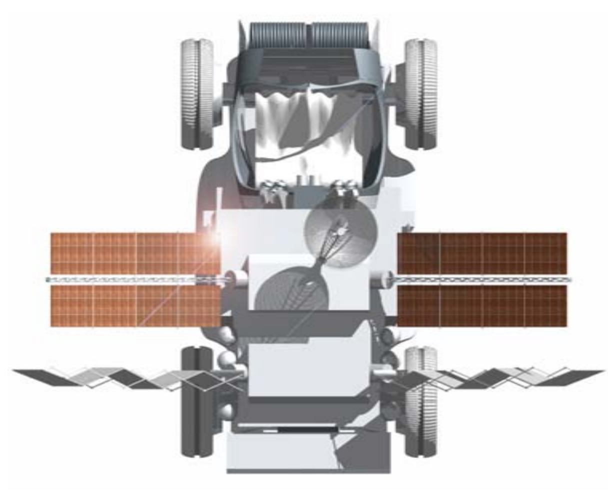


Figure 7. Top view of the small, agile, unpressurized, Mini Rover (Mini).

Mobility

If we study the way humans have explored the Earth, we will find that from the beginning when we humans started expanding our original territory from the Riff Valley in Africa first we walked/moved to explore and settle all the land masses around the planet. Eventually we developed technology to accelerate exploration through the invention of water vessels, airplanes and space vehicles. We firmly believe that the beginning of exploration of the Moon and Mars should be done with highly mobile rovers. Initially the rovers will be like the Mars rovers (although faster) and eventually they will be pressurized to be able to sustain human life. We strongly believe, and this report confirms, that there is no major technical 'showstopper' to allow us to design a highly mobile set of vehicles or 'convoy' to explore the Moon. These vehicles could be used eventually as the 'seed' infrastructure to the first Lunar outpost once we decide to establish a permanent base.

Historically, breakthrough exploration and discoveries have been accomplished by highly mobile systems, as in the Oceans surface and depths, the Antarctic, and many geologic sites. If we briefly study the " Scientific Context for the Exploration of the Moon" provided to the NASA administrator in 2006 by the Committee on the Scientific Context for the Exploration of the Moon, we will find that to accomplish many of the scientific goals set by the committee we will need access to many diverse sites across the moon and not one site satisfies all the scientific requirements.

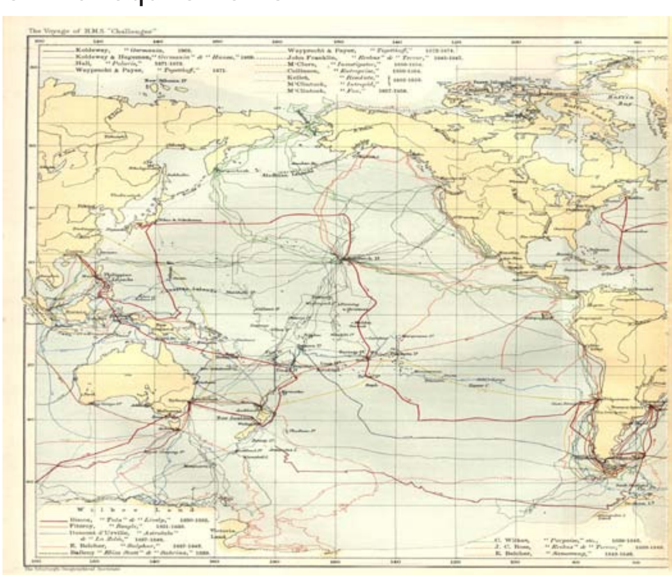


Figure 8. Map of thousands of miles explored by scientific expeditions just between the years of 1830-1874.

Figure 9. Examples of human and automated systems exploration

Figure 10. Convoy of habitat and laboratories exploring the Antarctic

"In spite of the opinions of certain narrow-minded people, who would shut up the human race upon this globe, as within some magic circle which it must never outstep, we shall one day travel to the moon, the planets, and the stars, with the same facility, rapidity, and certainty as we now make the voyage from Liverpool to New York."

Jules Verne, From the Earth to the Moon, 1865

Launch Considerations

Given the NASA plans to build a heavy launch vehicle to go back to the Moon. We have chosen the Ares V class launch vehicle as the principal carrier of the payloads to the Moon. The Ares V is capable of delivering over 20 mT to the Lunar surface. The payload configuration is composed of 1 MSR (12 mT) and 2 Minis (2 mT) per launch. The final surface configuration is envisioned to be a convoy of 2 MSRs and 4 Minis. This is accomplished in 2 launches. Human rated landers deliver the crews, consumables, tools, spare parts, etc. After the first launch is accomplished and the vehicles have been tested. The same lander that brought the crew returns to Earth with the same crew or a new lander arrives at a different site to bring an exchanged crew and pick up the first crew, lunar samples, lunar products, and scientific results to bring them back to Earth

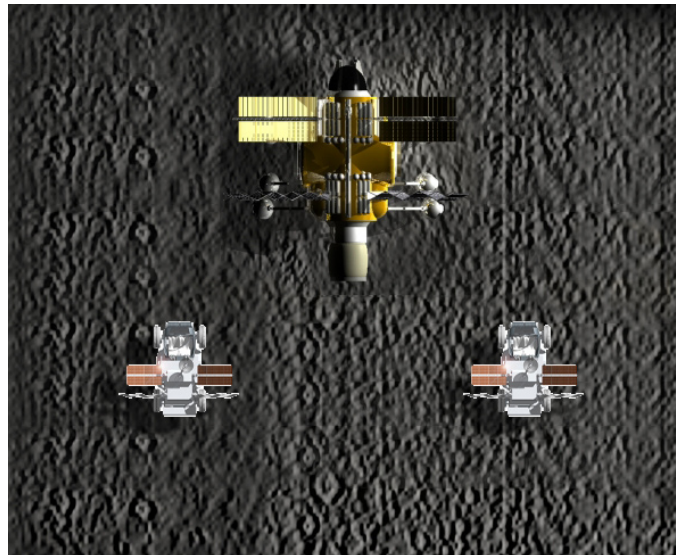


Figure 13. Initial launch configuration of 1 MSR and 2 support Mini Rovers.

Figure 11. Ares V on Launching Pad.

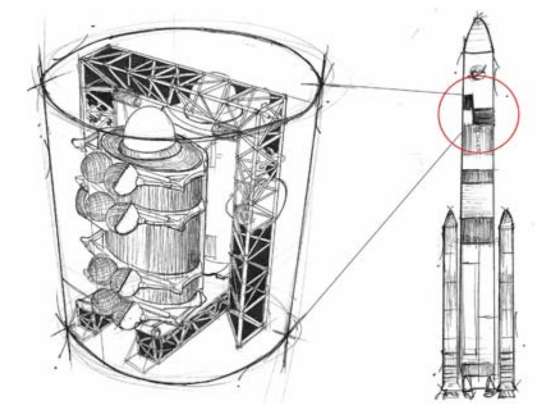


Figure 14. EXP-Arch payload configuration in the Ares V Launch vehicle.

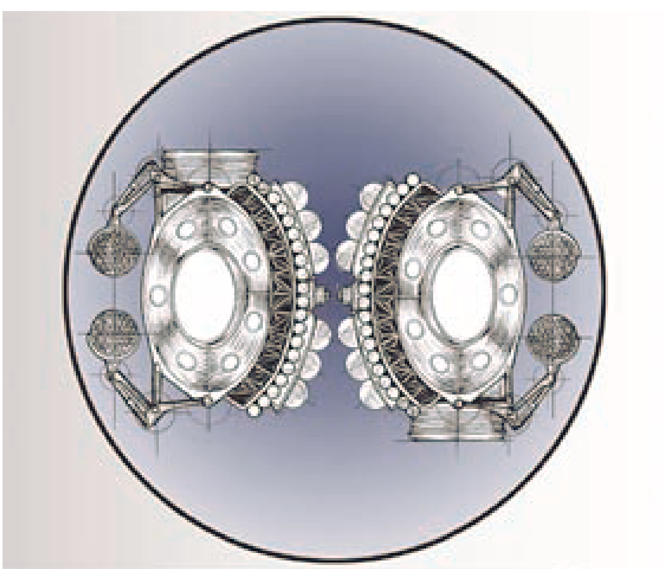


Figure 12. Ares V cross section showing possible launch configuration of 2 MSRs.

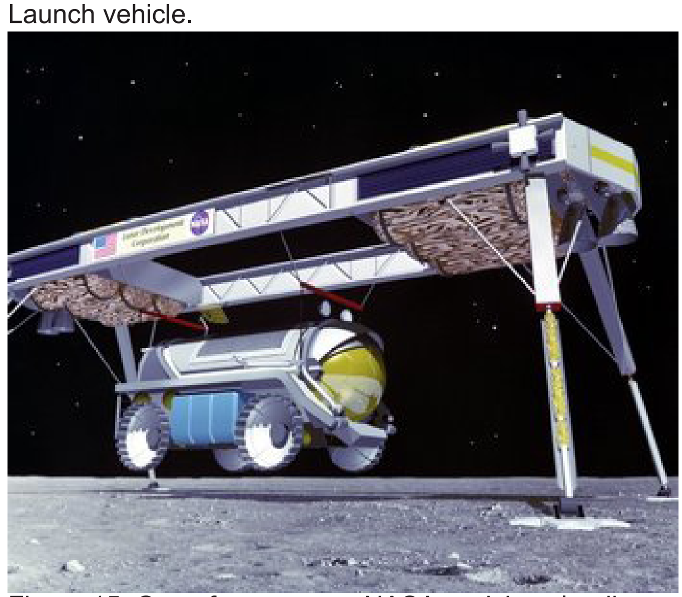


Figure 15. One of many ways NASA envisions landing large rovers or payloads on the Moon surface.

Design Criteria

From the conceptual mission architecture outline we produced a Design Criteria and a set of basic requirements for the MSR and the Mini Rovers. These served as the guide for decision making throughout the design process when we weighed the attributes and merits of each subsystem and design concept.

MSR and Mini Rover General Design Criteria
• All terrain omni-directional vehicle
• Modular design
• Hi Traction / contact patch
• Low dust pick up wheels
• Lightest possible structure
• Lunar Navigation (GPS-like capability)
• Video Cameras
• Night vision
• Highest degree of autonomy
• Teleoperation
• Topography detectors and sensors
• Navigational warning systems
• Re-supply of all consumables
• Self loading and unloading of consumables
• Solar and fuel cell powered
• Independent electric motor drives at each wheel

MSR Specific Design Criteria
• High exterior visibility
• Radiation Protection
• Micrometeorite shielding
• Crew of 4
• Re-supply of fuel, atmosphere, food, and water
• Experimental airlock / glove box
• Cockpit
• 'Dirt room' for space suit storage and repair
• Hygiene area with shower
• Sleeping area for all crew
• Galley
• Wardroom/ dinning/ videoconferencing
• Integral expandable environment
• 70 KPa (10.2 psi) atmospheric pressure
• Maximum Speed 15 km / hr
• Maximum mass 18 mT

"When I am working on a problem, I never think about beauty but when I have finished, if the solution is not beautiful, I know it is wrong."
– R. Buckminster Fuller

Mini Rover Specific Criteria
• Non Pressurized
• Crew of 4 in EVA suits
• Partial micrometeorite shielding
• Modular design
• Maximum speed 20 km / hr
• 2 mT load capacity
• Able to use various regolith moving tools such as plows, drills, shovels, backhoe and auger gun.

Bio-Inspired Design

Early in the design process we looked at various ways in which nature solves the problem of adaptability to different environments. The first analogy that we found (as per our original proposal) was that of the 'Puffer' fish which keeps its stream line body while moving and blows up when is in need of protection, we used this idea for the expansion of the inflatable environments and airlocks. In addition, we found several animals that provided us with inspiration for our design solutions such as: The armadillo for the micro meteorite shield, the scorpion for the 8 legs and the manipulator arm as a tool, birds and the protection of their chicks for the solar flare shelter, and the fly for the solar array and radiator wings.

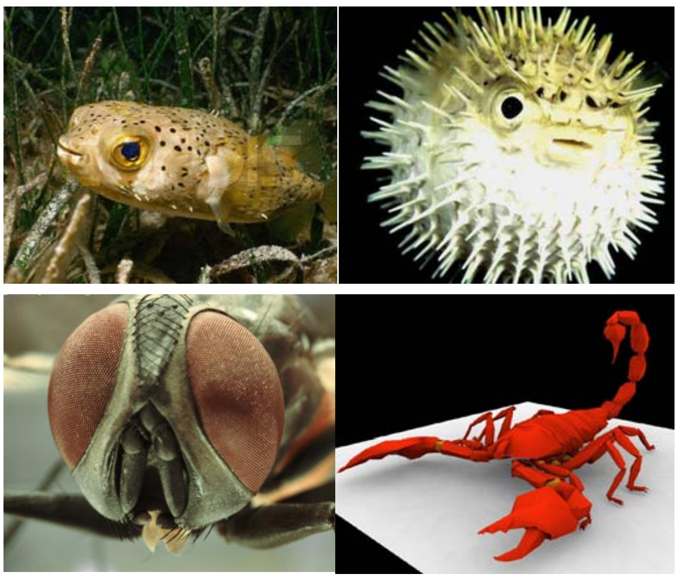


Figure 16. Examples of different animals that served as inspiration to the design team.

Vehicles Conceptual Design

After the initial conceptual design for the mission architecture was concluded we outlined the requirements for the types of vehicles that would be needed to accomplish the mission. From this exercise we determined that two classes of vehicles would meet all the requirements of the mission. Specifically, we designed 1) A large pressurized, transformable habitat type vehicle, and 2) A small very agile unpressurized vehicle.

After the two classes of vehicles were determined, we started conceptualizing through sketches, scale drawings, and models many design alternatives and configurations guided by the requirements. The ability to quickly sketch in three dimensions all the features, and alternative designs allowed the team to make decisions on the best alternatives to meet the design requirements. Here we show a few of these initial concepts as an example of the type of concept sketches produced during this period.

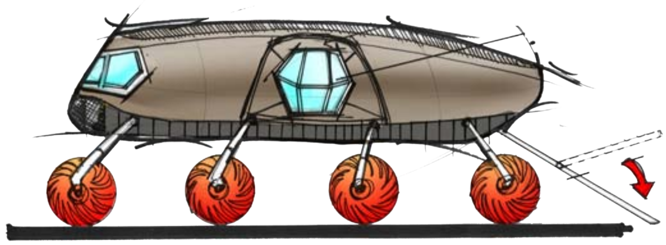


Figure 17. Alpha Rover, one of the first concepts produced during the mission conceptualization.

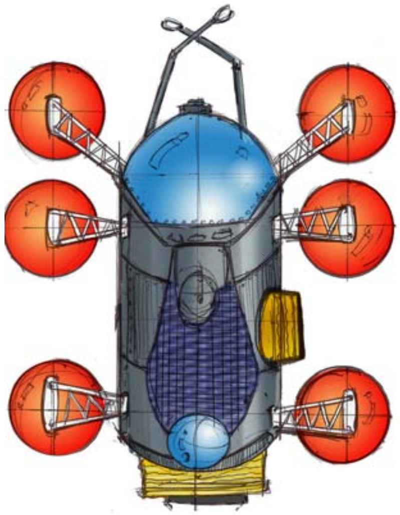


Figure 18. Gamma Rover, top view showing a solar cell skin, 6 wheel configuration, and 2 manipulator arms.

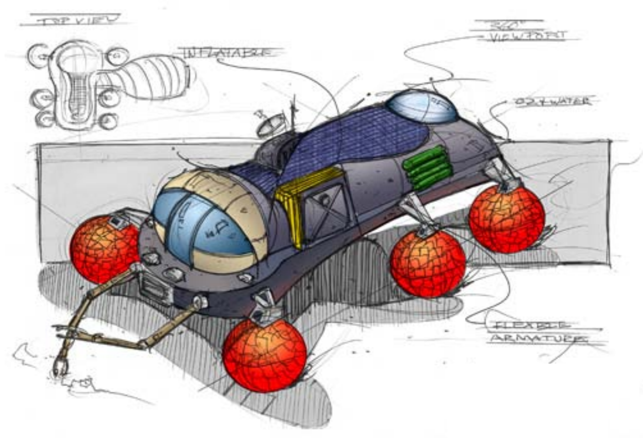


Figure 19. Beta Rover, a more define rover starting to show the placement of some of the subsystems

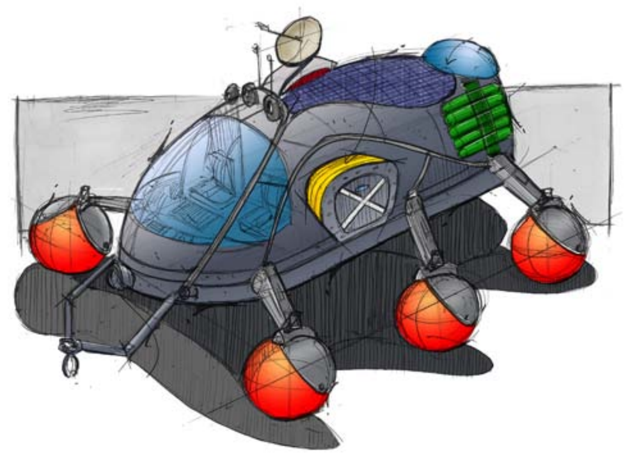


Figure 20. Gamma Rover, perspective view indicating major features and more detailed subsystems placement

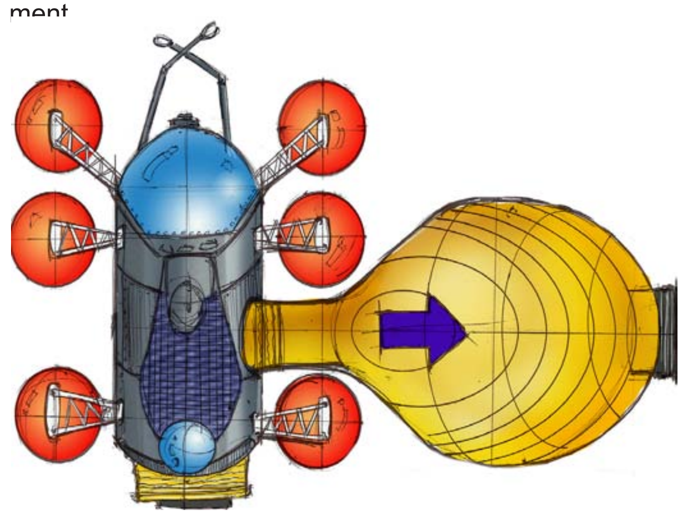


Figure 21. Gamma Rover, top view with inflatable environment deployed.

Conceptual Design (continued)

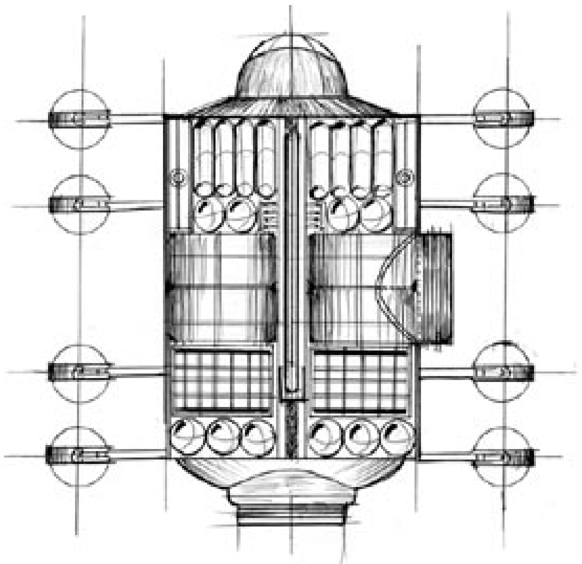


Figure 22. Delta MSR, drawing defining structural geometry, final wheel configuration and inflatable placement.

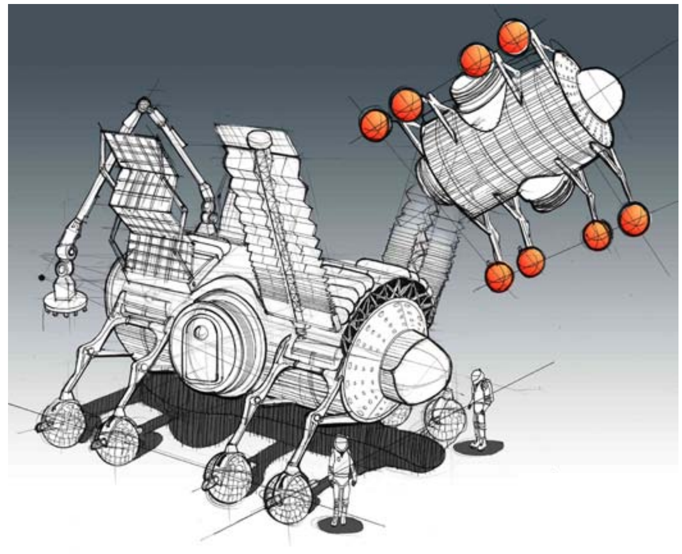


Figure 23. Delta MSR axonometric, indicating placement of solar arrays, radiators and manipulator arm.

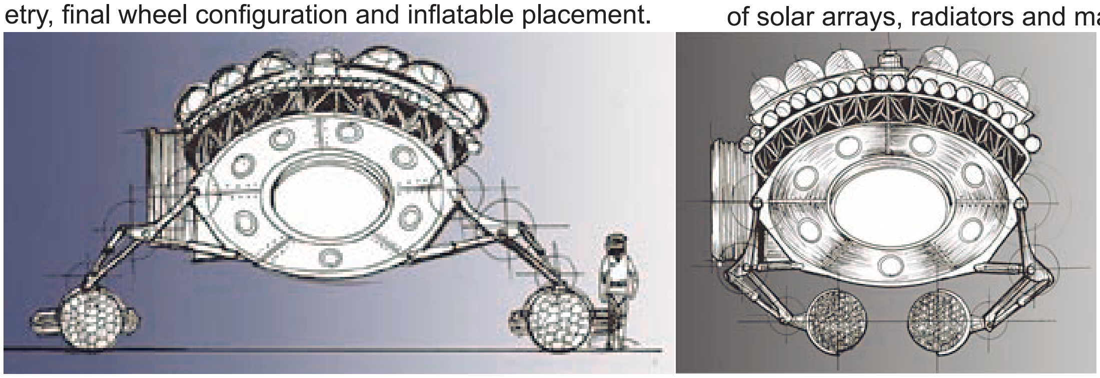


Figure 24. Delta MSR, Front view with unfolded legs for maximum extension to reach over the perimeter of a small crater during a solar flare event, and to fold the legs for maximum compactness during launch. The ability to adjust the span between wheels and the height of the vehicle helps to keep the center of gravity as low and possible and maintain stability over all kinds of terrain. A micrometeorite shield is mounted over the pressurized hull.

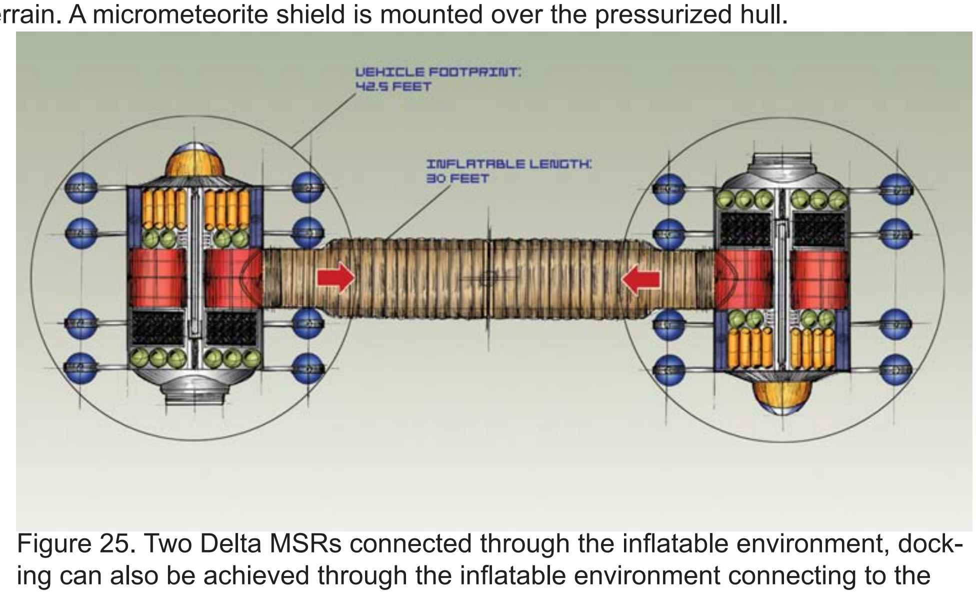


Figure 25. Two Delta MSRs connected through the inflatable environment, docking can also be achieved through the inflatable environment connecting to the inflatable airlock at the rear of the vehicle.

Mother Ship Rovers (MSR) Final Design

The MSR “Scorpion GT” is a highly mobile, smart, autonomous computational system. The computational requirements for the MSR are enormous and operating all the required subsystems will be complex, however, with the new developments in hardware and software systems we feel that the appropriate computational system can be designed for this class of rover.

Pressurized Structure Dimentions: 11.2 m long, 5.8 m wide, 3.4 m high
Maximum Wheel Base Width: 10 m
Estimated Wight: 12 mT
Deployed Pressurized Inflatable Environment: 9.15 m long, 3.04 m diameter
Deployed Pressurized Inflatable Airlock: 2.44 m long, 3.04 m diameter
Two docking rings with hatches

MSR Scorpion GT Exterior Design Features

Meteorite Shield: The MSR is protected for high angle impact micrometeorites by a shield 25 cm away from the pressurized hull. This shield could me aluminum, however, further studies need to consider making the shield out of composite, ceramics, and new nanotechnology materials. The top of the shield is equipped with a plug-in connector grid system for quick exchange of different size tanks of consumables like hydrogen, oxygen, water, etc. The ‘backbone’ of the MSR is a track where the manipulator arm is mounted on a sliding car that can travel from the front to the back of the vehicle to assist with EVA operations, payloads, samples, and tools handling. All the antennas necessary for communication and navigation are located on the shield (roof) of the MSR Scorpion GT.

Solar Arrays and Radiators: Two 9 m long telescopic arms mounted on a three degree-of-freedom joint supports the solar arrays on the starboard and port sides of the vehicle allowing them to track the sun to maximize the output of the arrays. The two foldable radiators are also mounted on the same type of joint to minimize solar exposure.

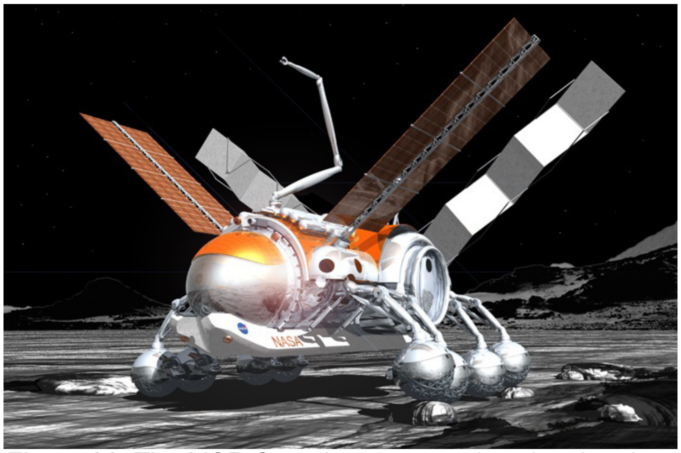


Figure 26. The MSR Scorpion, perspective showing the manipulator arm on a track over the radiation shield, two large skids to rest on when sitting on the surface, and independent arm and wheel articulation.

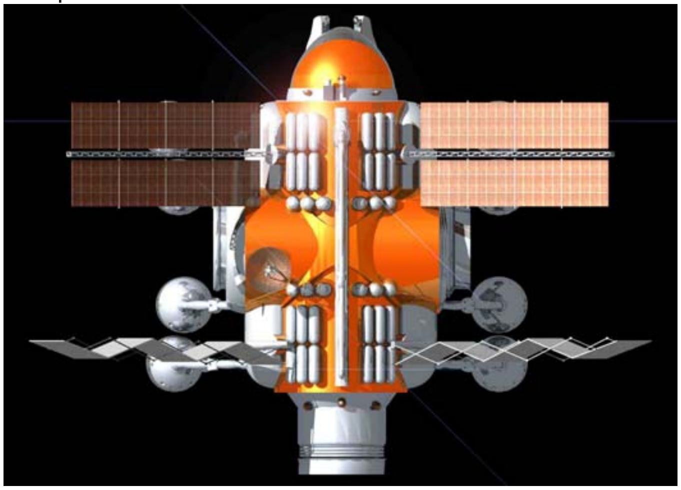


Figure 27. The MSR Scorpion, top view showing the micrometeorite shield, solar panels, radiators, folded manipulator arm, antennas, and consumables tanks.

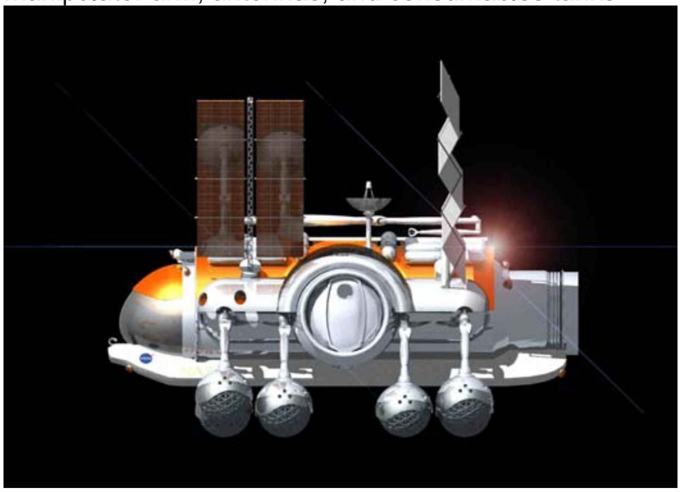


Figure 28. The MSR Scorpion, side view showing the hatch and folded inflatable environment and airlock, lateral viewing ports, and legged configuration.

MSR Scorpion GT Exterior Design Features (continued):

The Drive Train System: The Scorpion is composed of 8 articulated legs with 4 degrees-of-freedom capable of elevating the pressurized hull up to 2 m above the lunar surface as well as to let it rest on its skids on the surface. The legs are able to fold under the body to minimize the overall vehicle size during launch. The novel EXP-Arch wheel concept includes wheels that are 1 m diameter spheres made of an elastic mesh grid that aids in the suspension system, maximizes the contact patch on various terrain angles, and minimizes dust dispersion. The wheels are also provided with a large fender to minimize the amount of dust pick up. The MSR is equipped with 2 electric winches one on the front and one on the rear of the vehicle.

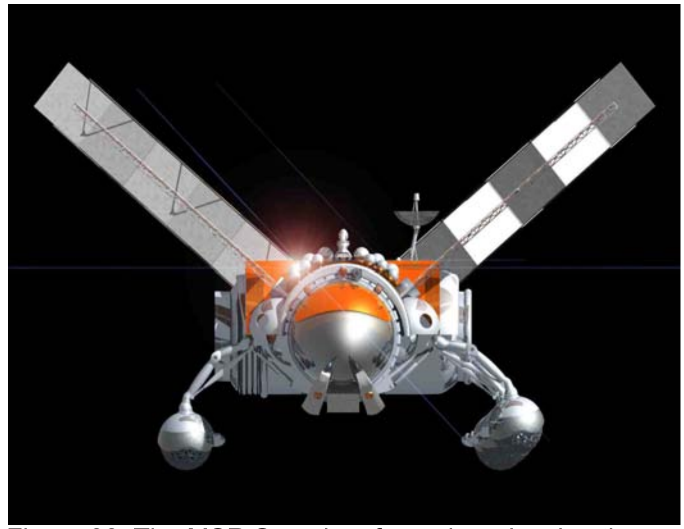


Figure 30. The MSR Scorpion, front view showing the large domed cockpit, wheel span, winch between the skids, and tracking angles of solar arrays and radiators.

Underside: There are 2 massive skids under the MSR for the purpose of protecting the pressurized hull when sitting on the surface, and in case the MSR gets stuck on sandy regolith it can be pulled out by the winches and dragged out on the skids without damaging the arms and wheels. The winches and pull hooks are mounted between and on the skids, respectively. The other main feature is a hatch equipped with an inflatable emergency shelter that can be deployed downward under the vehicle into a custom made crater (Detailed in the Radiation Protection Section).

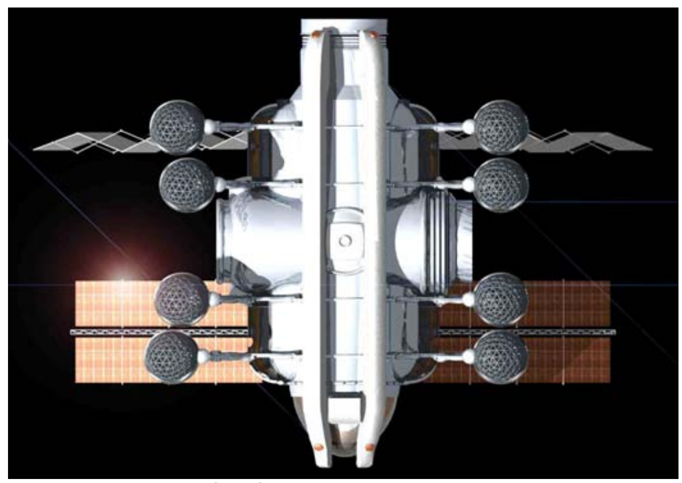


Figure 31. The MSR Scorpion, underside view showing the two massive skids, protector panel of the deployable 'solar storm' shelter, spherical gridded wheels.

Miscellaneous External Features: The MSR is equipped with lights and video cameras that allow 360^0 visibility around the vehicle. It will also have plug-ins for power and life support umbilicals. Small tool storage compartments will be accessible by astronauts during EVAs.

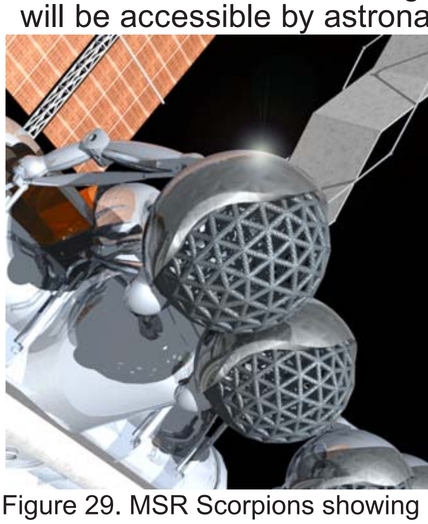


Figure 29. MSR Scorpions showing arm articulation, dust control fender, and one of the several designs for the wheel grid pattern.

Figure 32. Two MSR Scorpions, top view showing them connected through the inflatable environments, three different docking configurations can be achieved.

MSR Scorpion GT Interior Design Features

Limited time was devoted to the interior design/configuration during this effort. However, it was determined that the internal volume (>65 m^3) was sufficient for a crew of 4 to have a productive working and living environment. Each MSR is able to house a crew of 4. This volume doubles when the inflatable environment is deployed when in ‘camping’ mode. Coming in from the airlock located at the rear of the vehicle the astronauts enter the EVA suit storage and repair area where the 4 EVA suits hang from the walls, on the starboard and port sides of this area there will be parts storage and a working bench to perform maintenance and repairs on the suits.

Hygiene Area: Moving through a bulkhead the astronaut enters the main cabin; and on the port side he/she passes the hygiene area furnished with a toilet, a hand washer, mirrors, and storage for all hygiene related activities. The area is separated from the main cabin by a foldable partition that can be closed for privacy and for showering. We estimate that showering capability in the lunar environment is significantly more critical to crew health than in the International Space Station (ISS) given the dusty conditions and allergic reactions that some astronauts experienced during the short Apollo missions.

Racks: A rack system lines both sidewalls of the vehicle, the racks are modular (like on the ISS) and can be moved. The racks are exchangeable and can be loaded and unloaded through the main hatch and airlock. The racks contain the myriad of equipment needed during the missions (i.e., personal belongings, tools, food, equipment, etc.).

Figure 33. MSR Scorpion, interior forward view from the wardroom table, showing workstations and seats.

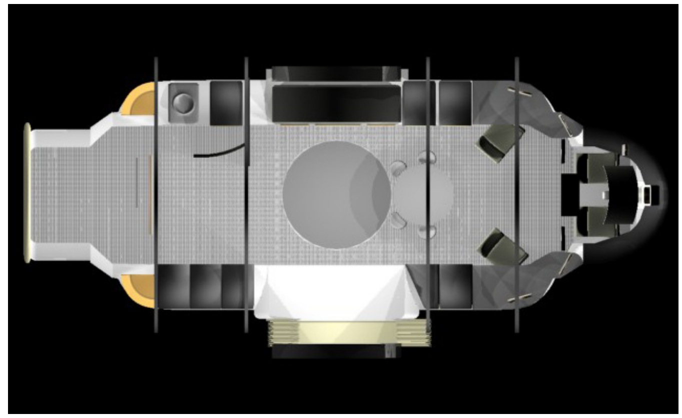


Figure 34. MSR Scorpion, interior floor plan

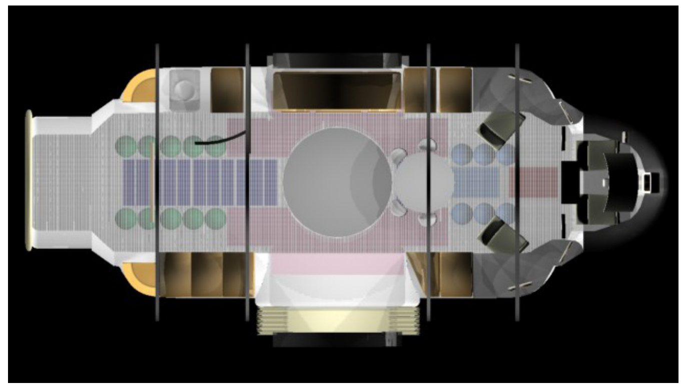


Figure 35. MSR Scorpion, interior floor plan showing the equipment configuration under the floor.

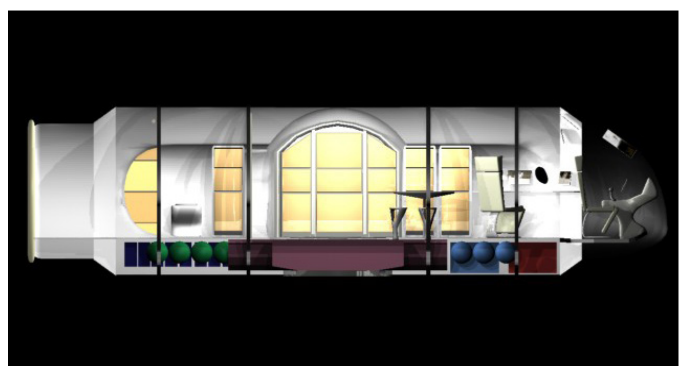


Figure 36. MSR Scorpion, interior port side view.

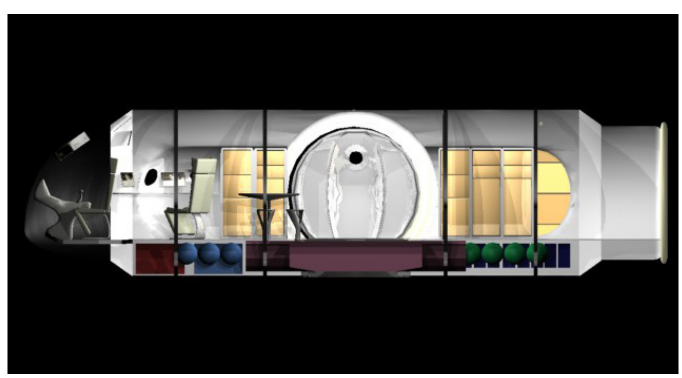


Figure 37. MSR Scorpion, interior starboard side view.

MSR Interior Layout

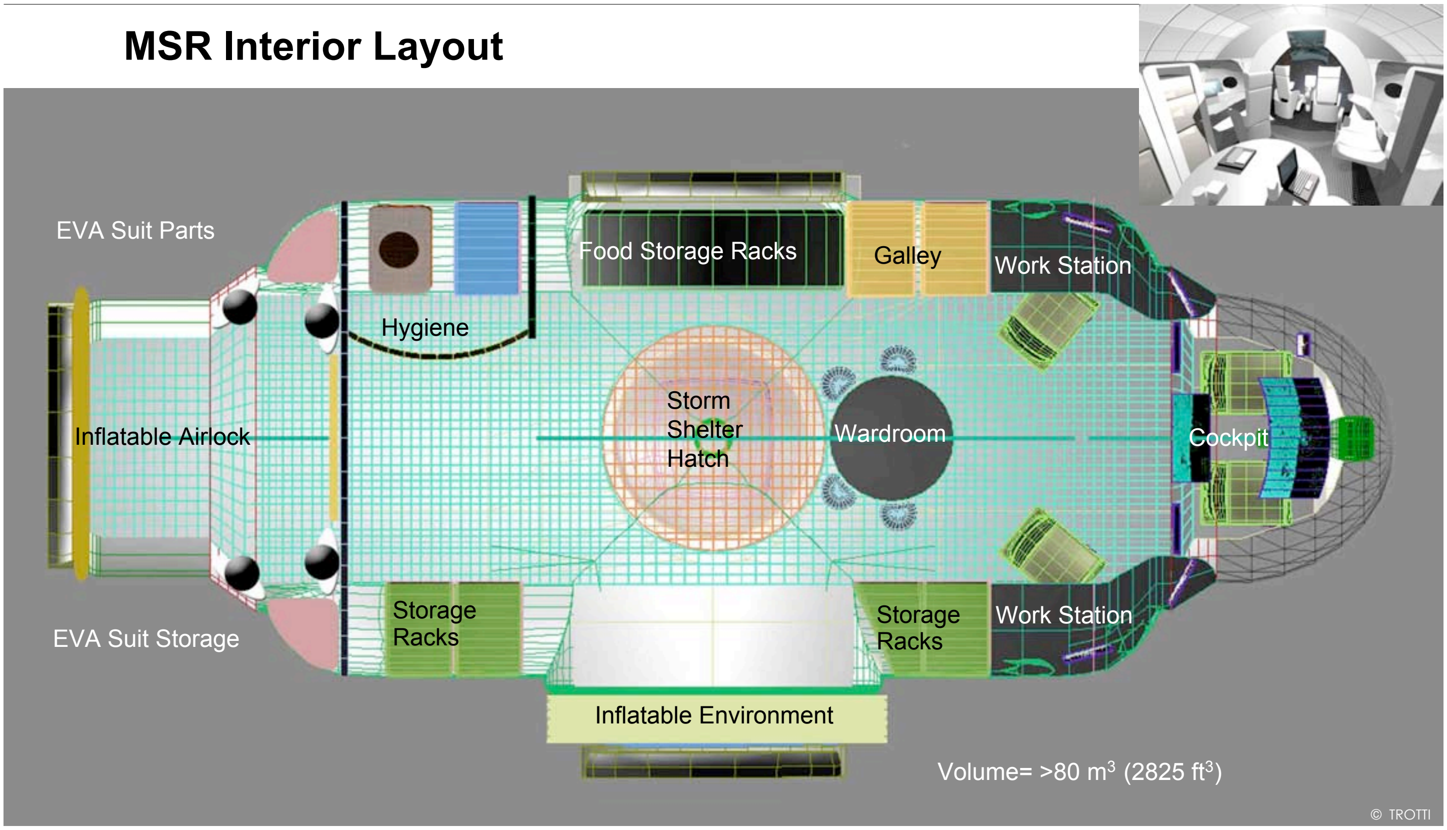


Figure 38. MSR Scorpion, floor plan layout. All racks are modular and interchangeable, the food storage racks are movable in case of using the port side for docking. The wardroom table, chairs, and grid floor panels are movable.

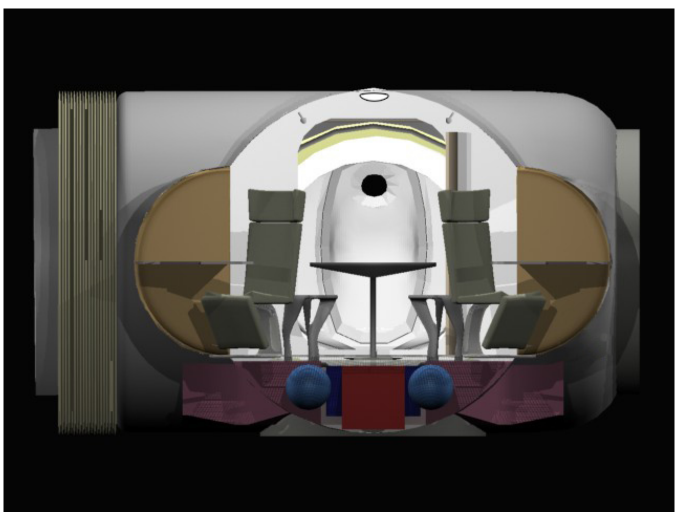


Figure 39. MSR Scorpion, rear cabin view through dust control bulkhead.

Figure 40. MSR Scorpion, front cabin view.

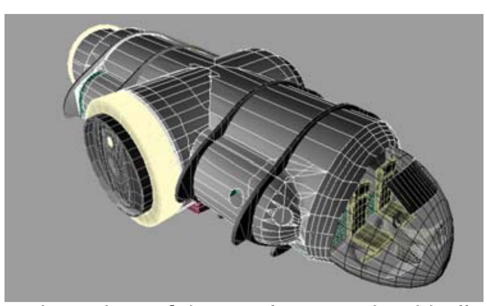


Figure 41. MSR Scorpion, view of the total pressurized hull with the attached folded inflatable airlock at the rear and the inflatable folded environment on the starboard side.

MSR Scorpion GT Interior Design Features (continued)

As the astronauts continue moving forward in the vehicle they will step over the hatch that opens to the emergency inflatable shelter discussed in the Radiation Protection Section of this report.

Wardroom and Galley: In the middle of the cabin the crew will encounter a stowable table with chairs in the wardroom that acts as the dinning and conference table during the 'camp' mode operations. This area is provided with video conferencing capabilities with screens mounted over the bulkhead before entering the cockpit. On the port side of the wardroom there are two racks containing the galley equipment such as a mini-oven, food warmer, water dispenser, and a small refrigerator.

Workstations: Forward of the Galley and wardroom area on the port and starboard sides there are two workstations equipped with nonskid working surfaces, computer hookups, storage, power access for hand tools, and a comfortable seat attached to the floor. Both workstations are provided with small windows that allow vision to both sides of the vehicle. One of the workstations has access to a glove box/experiment airlock to retrieve and handle samples coming in from the exterior. The seats, although much lighter in structure and padding than airplane seats, resemble first class seats. They are fully reclineable with headrest, footrest, and seat belts. Two additional fully reclinable seats/beds are provided in the cockpit at the front of the rover. The cockpit is mounted on a platform in a high tempered glass dome; sunlight is controlled though adjustable sectored glass opacity capabilities and controls. All the vehicle controls are accessible from the cockpit resembling best practices in aircraft human factors engineering.

Handholds and Restraints: Given the rough terrain that the MSR will travel over, strategically located handholds are provided throughout the vehicle to support crew mobility during roving activities. In addition, all the equipment is firmly attached, stowed, and latched to prevent everything from coming loose.

Dust control: The fine dust of the moon the vacuum environment and low humidity makes the fine Moon dust highly adhesive to all surfaces. This will be one of the biggest challenges in designing the interior of any Lunar surface habitat. We are designing a laminar airflow on the vehicle from front to rear to keep as much of the dust in the EVA suit storage area. In addition, the floor will be a have soft grate panels which allow the dust particles to go below floor level where they can vacuumed from.

Lighting: The interior lighting of the vehicle is critical to human performance. General lighting will be provided by LEDs reflecting light to the vaulted ceiling of the cabin. Adjustable task lighting is provided over working stations and cockpit. Low level or red lighting is provided in the main cabin to avoid glare or blinding during roving.

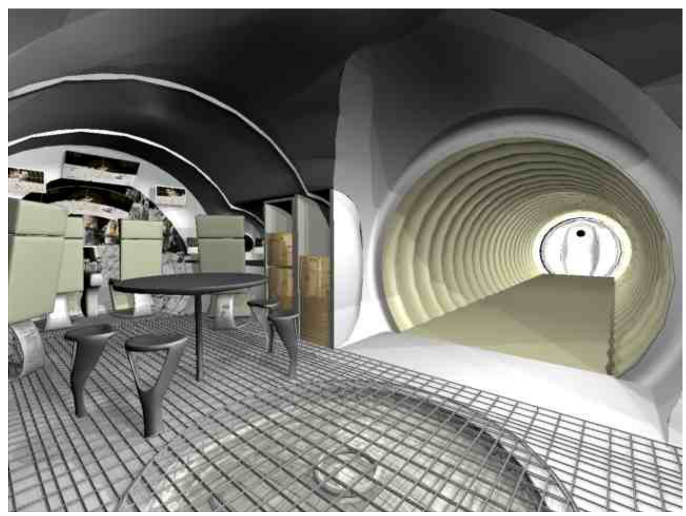


Figure 42. MSR Scorpion, interior view of the deployed inflatable environment doubling the volume of the MSR.

Figure 43. Astronaut Gene Cernan after an EVA during the Apollo 17 Lunar mission.

Power will be generated by solar arrays during the daytime and by Hydrogen / Oxygen fuel cells during the night.

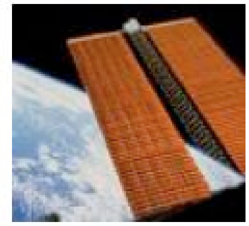
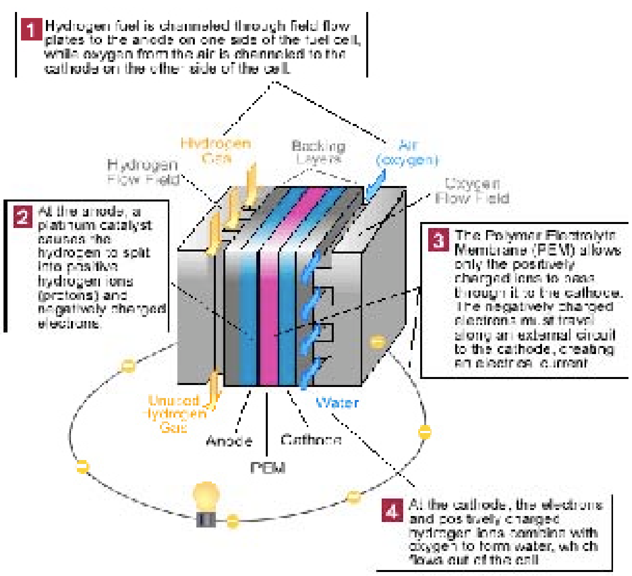


Figure 44. International Space Station Solar Array.

- Solar Array (50 kW each)
- Size: Two Arrays, each 3.75m x 10m long with tracking capability.
- Area: 75 m² @ 1345 W/m² insolation
- 50% Efficiency
- Gross Power Out: 50.4 kW
- Angularity Factor: 71% for an average of 45° off-axis
- Conductor Losses: 90%
- Power Conditioner: 75%
- Net Power output during daylight hours: 24 kW to batteries or for instant use.

Fuel Cell technology is maturing rapidly and should be highly efficient and reliable by the time we return to the moon.



The Shuttle fuel cell are 14" X 15" X40" and weighs 225 pounds
Three fuel cells provide the Shuttle a continuous output of 21kW

Figure 45. Fuel Cell basics.

- 25 kW Hydrogen Fuel Cells based upon electrolyzer / compressor efficiency and vehicle power needs other than locomotion.
- An estimated 9.6 kW available while in motion during daylight.
- Batteries Li-ion,NiCd,NiMH
- Carbon-Carbon (K1100) Radiators (50% lighter than aluminum, 3 times more conductive than copper)

Figure 46. Existing Fuel Cell samples.

Novel MSR Scorpion Wheel Design Concept

Throughout the design process the team researched the current innovative developments in the automotive industry. We also investigated designs and technologies used in industrial, recreation and military vehicles. One major development is focused on new, safer, and durable wheel designs that we adapted to for the MSR Scorpion suspension system while also accounting for the extreme temperature variables of the lunar environment.

The rovers will be equipped with 'proprioceptive' sensors to determine the position of each joint, amount of current drawn by each motor, 3 dimensional tilt (pitch, roll, yaw), and load on each wheel.

Figure 47. Wheel design samples.

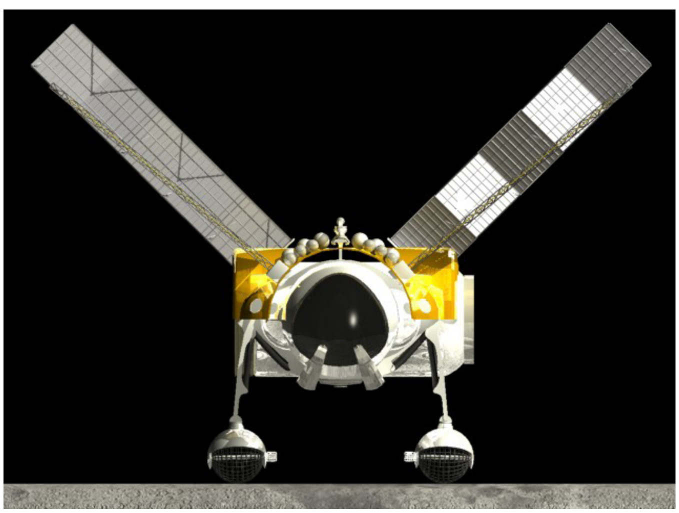


Figure 48. MSR Scorpion, showing maximum vertical extension of legs, 2 m above the surface allowing it to clear major obstacles.

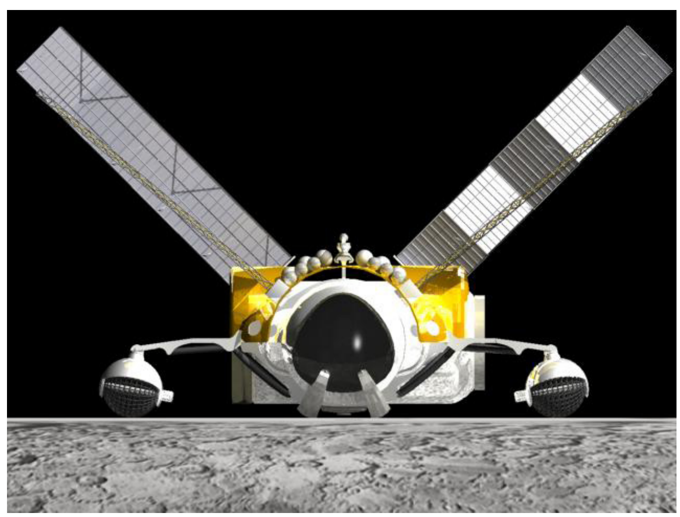


Figure 49. MSR Scorpion, sitting on the surface during 'camp' mode with a maximum lateral extension of 10 m.

Mini Rovers

Mini Lunar Rover Final Design

Similar to the MSRs, the Mini Lunar Rover, or Mini, design is a highly mobile, quick, smart, autonomous computational system that is capable of operating in 3 modes, namely, fully autonomous, teleoperated, or with a human pilot. The Minis are agile and quick assistants to the MSRs, each MSR is supported by two Minis. The principal roles of the Minis are to transport the crew to and from the landers and to exploration sites that the MSRs can not access. In their standard configuration each Mini can carry a crew of 4, in addition.

Other roles for the Minis include: cargo and tools transport, sample return, regolith moving, and support for the MSRs in creating shelters during solar flare events. Given the higher speed of the Minis they will be able to travel in advance of the MSRs and scout the exploration path for the MSRs to follow. In most cases two of the Minis will be equipped with a cockpit for crew transport and the other two will be mostly used for cargo and tool transport as well as hazardous operations.

The Minis are designed to be extremely flexible to handle various mission requirements (Saleh and Newman, 2003). The design is based on a 'skateboard' concept that serves as the support platform for the drive train, fuel cells, control and communications system, propulsion motors and winches. The top of the skateboard is designed to receive modular racks that contain the cockpit pod, cargo, tools, etc. The skateboard concept is presently being developed in the automotive industry at General Motors and other companies.

The Minis are equipped with several tools such as a highly dextrous manipulator arm capable of loading and unloading the cargo racks, picking up lunar samples, and aiding the crew during EVAs. All systems, including the manipulator arm, can be operated from the cockpit, remotely from a lunar site, remotely from the MSR, or from the Earth. On the front of the Minis there is a tool connector where the different regolith moving and drilling tools attach. The Minis are powered by solar arrays during the daytime and by fuel cells during the night for 28-day operational capability during the mission, particularly during emergencies and solar flare activity.

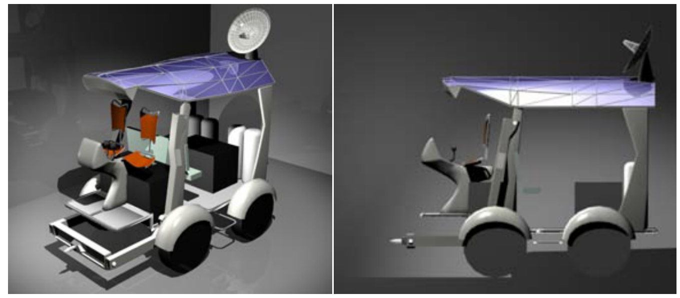


Figure 50. Early concept of a crew transport Mini Rover showing a solar panel and micrometeorite roof.

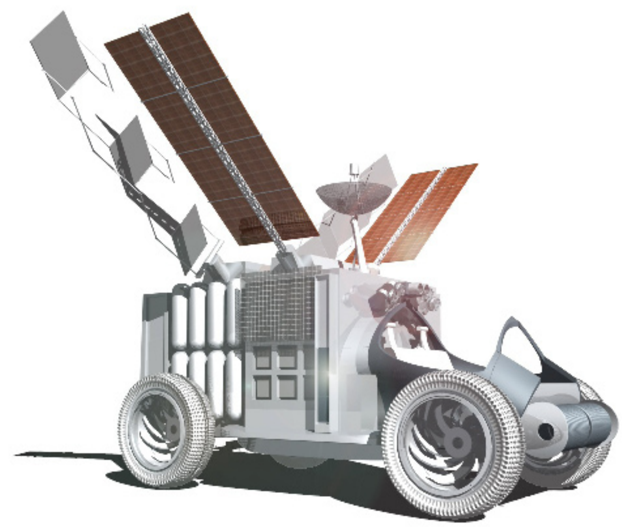


Figure 51. Mini Rover concept configured for a cockpit of two plus cargo racks over a skateboard.

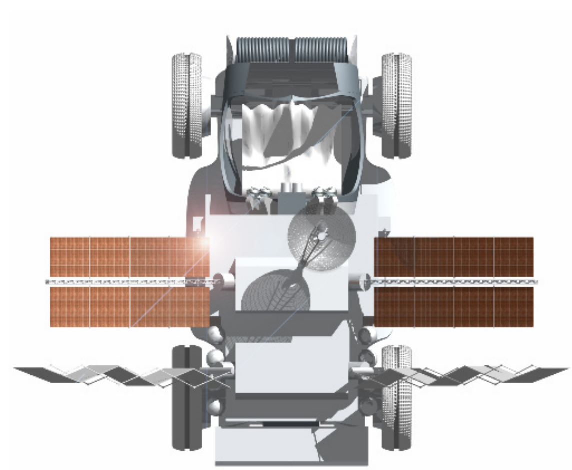


Figure 52. Mini Rover concept top view showing massive winch, cockpit, solar arrays, radiators and antennas attached to top of racks.

Mini Rovers (continued)

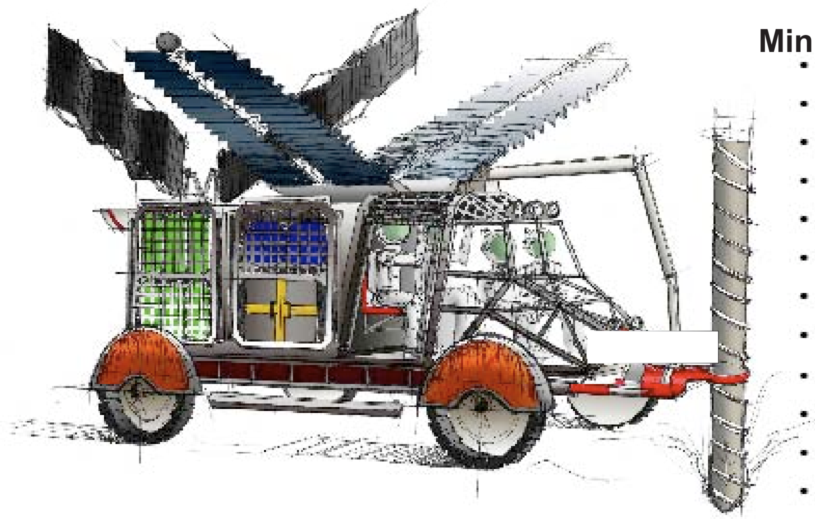
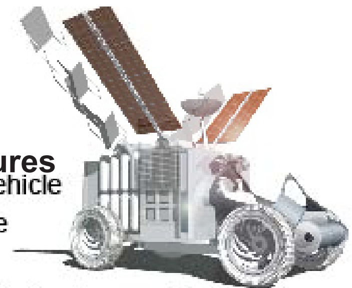
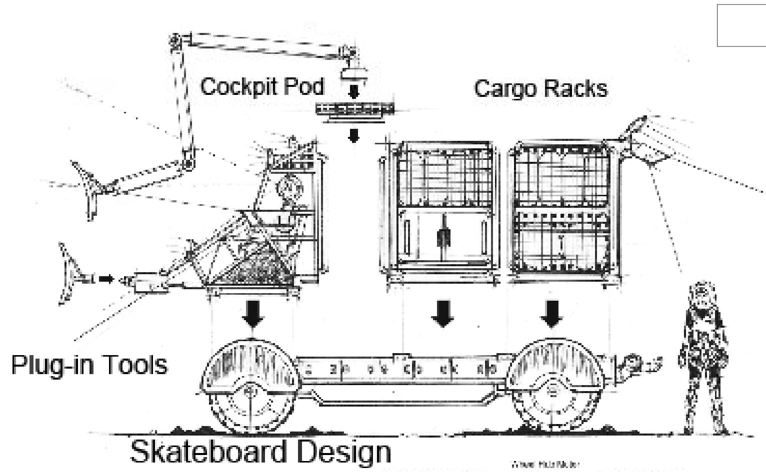


Figure 53. Mini Rover perspective.



Mini Rover Features

- All Terrain Vehicle
- 4 Wheel drive
- High traction
- Operational during day and night cycles
- Crew Transport (4 Astronauts)
- Cargo Transport
- Regolith mover
- MSR Assistant
- Tele-operation (from Moon and Earth)
- Stereoscopic vision
- Wireless controls
- Adaptable to mission requirements
- Mass - 2mT



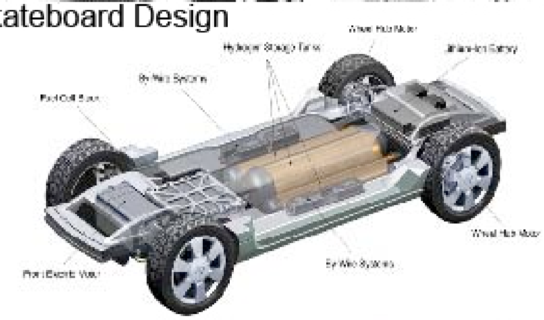
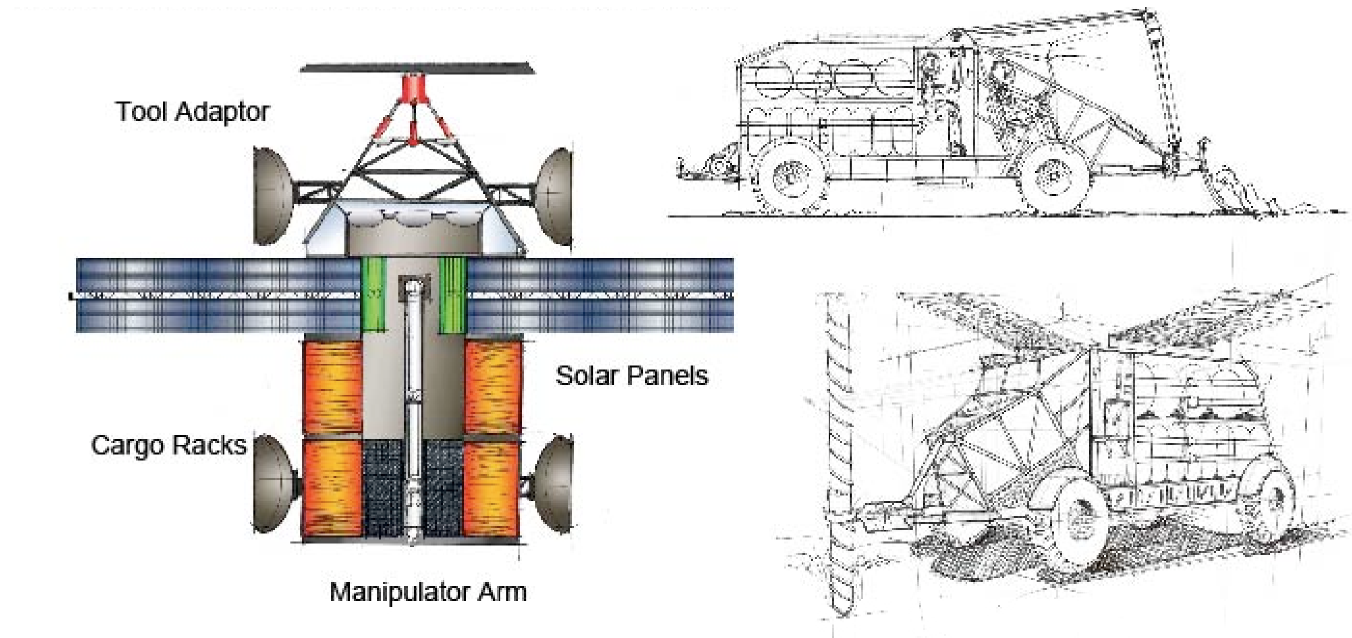


Figure 54. GM Skateboard concept.

- Skateboard containing batteries, fuel cell, and control systems.
- Dimensions: 3.65 m X 1.82 m X 2.13 m (12' long X 6' wide X 7' high)
- Launch Configuration: Roof and wheels are foldable to minimize volume during launch.
- Energy: Solar cells, fuel cells, batteries
- Propulsion: 4 independent electric motors.
- Mobility: Four wheels 90º rotation.
- Materials: Composites and aluminum.
- Tools: Winch, plow, drills, manipulator arm, trench digger, auger gun.
- Micrometeorite shielding: Mini's incorporate a structural canopy to provide some shielding and solar cell mounting.

Figure 55. Ellica 8 wheel drive train with independant electric motors.

Mini Rovers (continued)



Mini Rover Plan View

Figure 56. Mini rovers outfited with different regolith moving tools. A significant effort needs to be dedicated to defining the requirements and the design of all the equipment and tools necesary to support MSR operations, radiation shelters creation, and scientific research missions.

State-of-the-Art Electric Cars

Powerful, light weight, efficient electric cars are entering the consumer market quickly. The technology integration in these new vehicles is revolutionary. These new developments are adaptable to the space environment, and we propose partnerships with companies in these fields to develop cost effective and reliable solutions for mobile planetary exploration systems. Most of the subsystems in electric cars are completely electronic and under direct software control. In most cases these systems are not a collection of independent systems, rather they are designed as an integrated system. Designs incorporate computer systems architecture and complex network theories. These cars can accelerate from 0 to 100 mph in 7 seconds with motors that weigh about 70 pounds. The in-wheel drive units eliminate the transmission. The motor, reduction gear, wheel bearing, and braking system are integrated in a single unit, and the suspension arm adapter is attached to the outer motor casing.

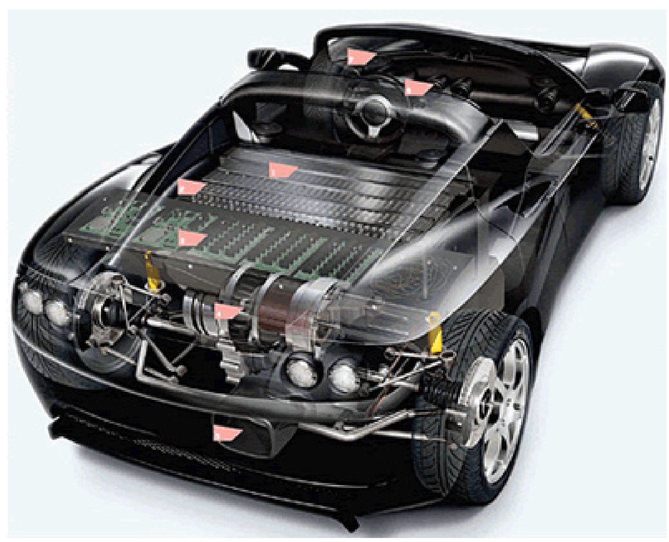


Figure 57. Tesla Roadster Electric car, an integrated computing system.

Figure 58. Ellica Electric car 230 mph, 185 miles range at lower speeds before recharging batteries.

NASA and industry have previously developed and built several full scale proof-of-concept prototypes (i.e., Spacehab, Honeywell-FTL AIA airlock, ILC Dover, Bigelow Enterprises).

The EXP-Arch inflatable structures studies contribute innovative new designs. We conducted several studies and constructed several models of re-deployable structures using origami principles and fabric folding techniques. We opted for the folding methods to reduce the number and complexity of folds. The EXP-Arch structures are built of multi-layer para-aramid materials with layers of mylar for thermal and UV radiation protection. There are 10 strap-winches that control the deployment and folding of the inflatables. The manipulator arm on the MSR assists in the deployment of the inflatables.

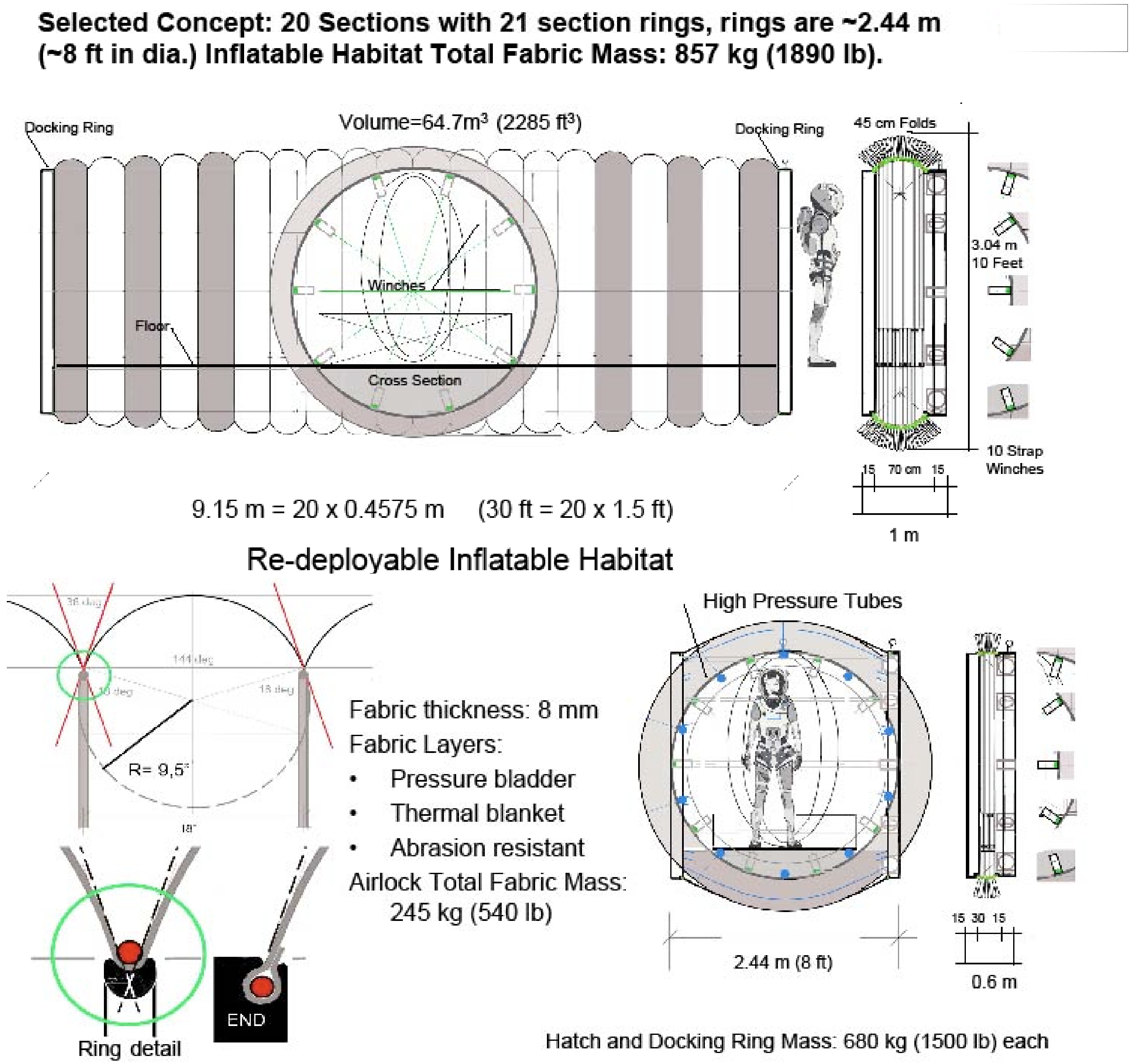


Figure 59. The geometry selected avoids 'creasing', a major problem identified with redeployable laminated fabrics. To avoid delamination we propose a semi-rigid 1" diameter rope ring slightly increasing in diameter as it reaches the center of the structure. The laminated fabric is reinforced and pre-bent around the rope to minimize creasing and chafing.

Radiation Protection Strategy

Protecting the crew from radiation is critical to the success of the mission. Given the difficulty to protect the crew from Galactic Cosmic Rays and Solar Flare radiation, we propose that astronauts should participate in missions with a pre-determined radiation exposure limit. Maximum exposure levels for lunar surface radiation exposure have not been determined. This issue needs to be studied further not only for lunar missions but for the longer exposure missions, such as missions to Mars.

Galactic Radiation Protection Strategy:
We have designed the pressurized rovers to carry all the high density equipment on the roof and sides of the vehicle to maximized the shielding with batteries, water tanks, and other high mass equipment and tools. This may prove to be enough to stop the detrimental radiation effects on the crew. However, if 100% of the radiation particles are not stopped by the structure then it might be better to lighten up the structure by means of using composites and removing some of the high density equipment from the upper areas of the vehicle to reduce secondary radiation effects.

Solar Flare Radiation Protection Strategy:
After considering several ways to provide short-term full radiation protection during solar flare activity we have concluded that a “deep well” solution is the fastest, safest, and lightest way to provide protection. During this period we looked at several ways that animals bury themselves under sand and soil to glean from Nature fast and effective ways to accomplish this. Water creatures, such as clams, eels and crabs, perform tasks by using a water jet. When water is not available, in the case of land animals, two main strategies are used: 1) skin undulating motion or 2) direct excavation. Given the size of the MSR and the short time the crew will have to protect themselves we opted for creating a “deep well” shelter with customized designed explosives. Even though the lunar surface is scarred by millions of craters, it is difficult to find deep and narrow craters suitable for shelter. By means of explosives we can create a crater over 6 m deep and a diameter of 10 m with the walls slightly bonded, or melted, by the heat of the explosion.

Figure 60. Bio-inspired radiation protection strategies, showing snakes, clams, and crabs’ survival methods.

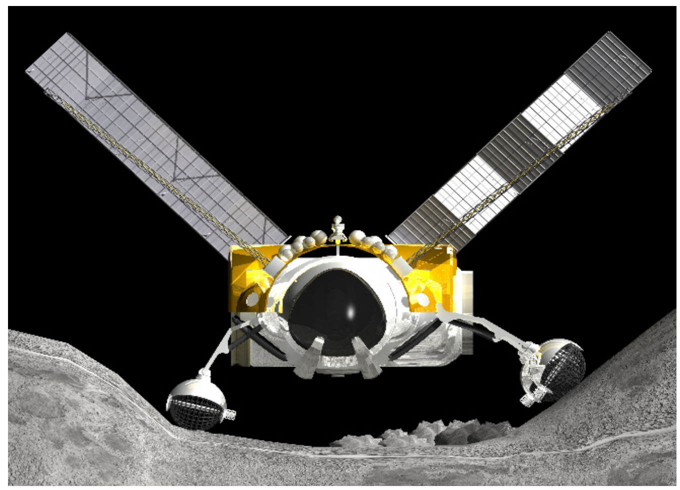


Figure 61. The MSR Scorpion traversing over uneven and obstructed terrain using the independent mobility legs.

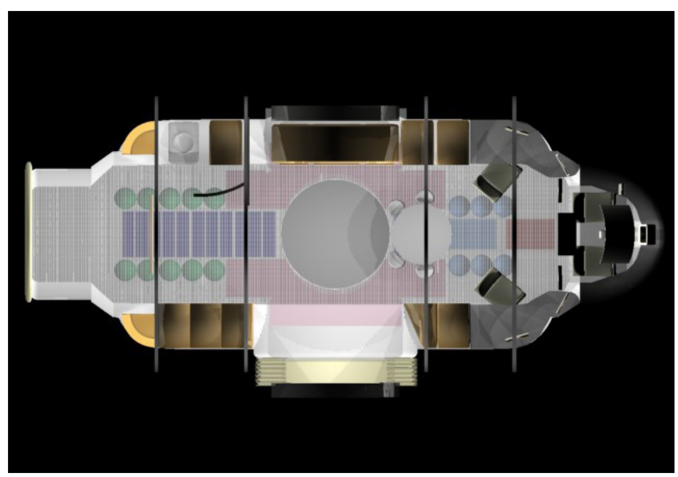


Figure 62. The MSR Scorpion passive shielding design under the floor locating water tanks and batteries around the solar storm shelter hatch.

Partial radiation shielding can make matters worse!

Shelter Deployment Process

We are estimating that the crew has a maximum of 3–5 hours to deploy and get in the shelter after they receive an alarm. This process is critical for the crew to master since it might be necessary during roving, sleeping, or exploring during EVA. This procedure resembles a fire or explosion drill on an offshore oil platform.

The general process is as follows:
1. The alarm is received, the crew immediately search's for the best site to create the shelter.
2. An unmanned Mini rover is sent to drill and set an explosive devise.
3. Once the specially designed charge is located at the right depth (~ 3 m) the Mini rapidly leaves the site.
4. The charge is detonated to create the deep customized crater.
5. The convoy approaches the crater, the MSR is driven over the crater. At the same time the Minis are installing tools to cover the shelter.
6. The inflatable shelter is deployed from the bottom of the MSR.
7. Once the inflatable shelter is deployed, a ladder is deployed to lower a portable toilet, water, food, and emergency equipment to survive for 5–7 days in the shelter. At the same time, other crewmembers are operating the Minis to cover the shelter from the sides of the MSR with shovels and auger guns. The shelter is now ready for the crew to inhabit.
8. During the solar flare the crew will remain in the shelter and will be able to monitor radiation levels in the shelter as well as in the MSR interior. Since radiation levels fluctuate significantly during a solar flare, there might be short periods of time when the crew can go up to the MSR for supplies.
9. Once the event is over and the crew has evacuated and emptied the shelter, the MSR floor hatch is closed and the shelter is depressurized.
10. The actual shelter inflatable structure might be retrieved, folded and remounted on the bottom of the MSR. However, the most likely scenario is that the shelter is disconnected from the MSR and disposed of. A new shelter will be delivered to the Moon and mounted on the underside of the MSR, very much like a life raft on an oil platform or tanker.

This is only one method to provide a radiation shelter for the crew. However, this is a critical issue not only for the Exp-Arch mission but to all Lunar surface missions particularly for the sortie short duration missions planned before a fully outfitted base is built. We believe that a significant research and design effort needs to be devoted to this issue.

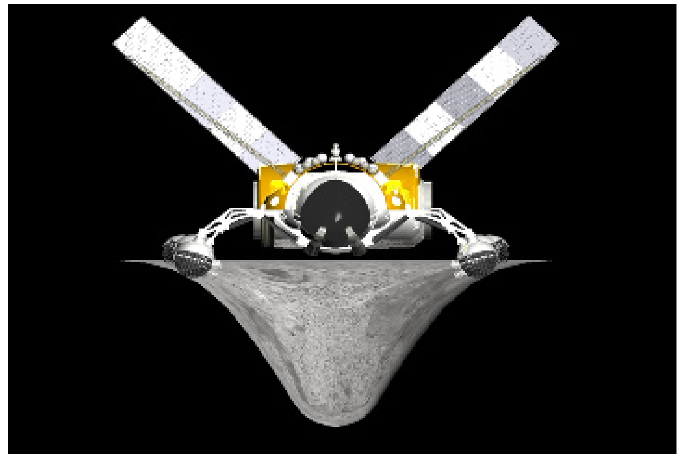


Figure 63. The MSR Scorpion driving over the customized crater with legs in the full lateral extension position.

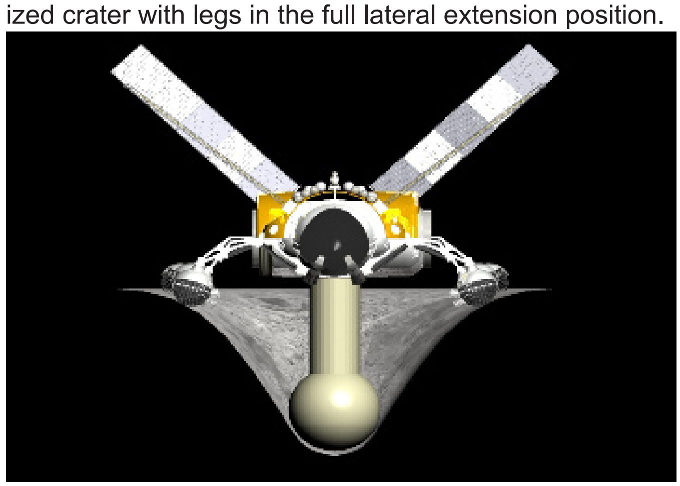


Figure 64. The MSR Scorpion over the customized crater deploying the inflatable crew shelter.

Figure 65. The MSR Scorpion over the crew shelter covered with 3 m of regolith.

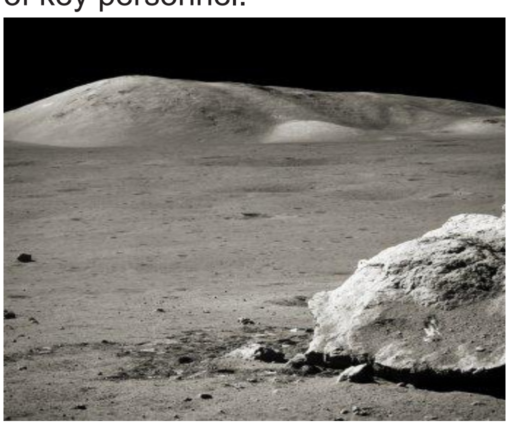
Conclusions

Definition: ex.plo.ra.tion 1. Traveling to discover what a place is like or where it is.

The EXP-Arch is a very different approach to human planetary surface exploration from what is presently envisioned. EXP-Arch is based on a complex system-of-systems design that incorporates small, agile, habitable, re-deployable, transformable, and autonomous capabilities. This mission architecture design allows NASA, the international space community, commercial enterprises, and the general global public to explore first-hand many diverse sites at all latitudes of the near side of the Moon. This 'active' architecture will promote participation by engaging the public in the daily experiences of the expedition crew, and be part of the 'live' and up-close discovery of new lunar surface features and composition. The Exp-Arch rovers are small highly flexible systems that can be customized for many different types of missions and requirements determined by the science, industries, and governments during the exploration of the Moon. We envision several convoys able to operate at the same time on different sites for very distinct purposes, operated by NASA and/or private enterprises.

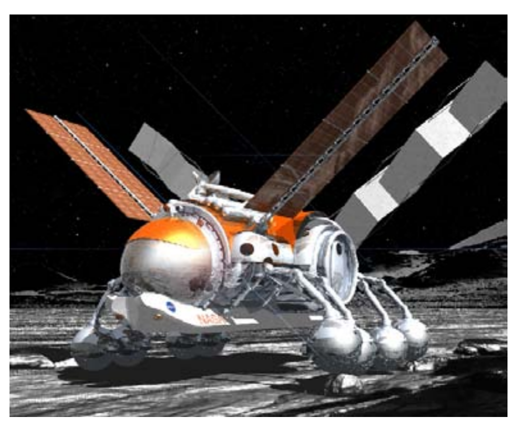
After this brief study of the Extreme Expeditionary Architecture Mission (Exp-Arch) we believe that there are no major technical or human show stoppers to the design concepts. However, this design challenges the state-of-the-art of existing technologies and requires the enlisting of the best engineering and scientific minds of our time. This concept pushes the envelope of planetary exploration and by no means is a repetition of the Apollo program. This will be the second step of humankind towards learning how to live and work on the surface of another planet. This type of mission will need the energy and passion that was required when president John F. Kennedy asked the congress and nation to commit to the goal of "landing a (hu)man on the moon and returning him safely to earth" in less than ten years. At the time scientists did not know what the composition of the moon was nor did they know whether they could land there at all!

It is with this brave spirit of discovery and vision of freedom that the Exp-Arch system approaches planetary surface exploration. Only when we learn how to develop, build, and maintain these type of mobile systems, we will be able to truly succeed in the wide range of expeditions that are required to really explore, understand and utilize the surface of the Moon, Mars and other planetary bodies in the solar system. This means that we are not going back to the moon to repeat ourselves. Rather future lunar exploration realized by the EXP-Arch embraces discovery, provides for human and robotic exploration, and finally adds another accessible 'continent' that might be inhabited by humankind. Given our present budgetary constraints we quote president JFK again "It means we cannot afford undue work stoppages, inflated costs of material and talent, wasteful interagency rivalries, or a high turnover of key personnel."



"As soon as somebody demonstrates the art of flying, settlers from our species of man will not be lacking [on the moon and Jupiter]... Given ships or sails adapted to the breezes of heaven, there will be those who will not shrink from even that vast expanse."

Johannes Kepler, letter to Galileo, 1610



Future Directions

The EXP-Arch work presented in this report was conceived and produced in a period of six months by a very small team of designers, engineers, and scientists. Therefore, many aspects of this mission architecture and systems design have not been developed in-depth. The high priority areas for future work, assuming additional funding, focus on the following aspects of the project:

1. To further develop the Exp-Arch mission architecture.
2. To further develop the novel designs for the MSR Scorpion GT and Mini convey of vehicles.
3. To conceptualize the design of all subsystems, including size, mass, and power requirements.
4. To design launching, landing and unloading systems.
5. To design, build, and test models of re-deployable inflatable structures.
6. To develop new strategies to protect the crew from radiation.
7. To design, build, and test models of radiation shelters.
8. To expand the existing partnerships with private industry to develop the required rover technologies, inflatable structures, energy, and computational architecture by leveraging the design, architecture, and engineering experience of the Exp-Arch team.
9. Expand the educational collaboration and research with universities in the areas of aerospace engineering, design, mining operations, materials sciences, and robotics.
10. Analyze the human and robotic interface requirements of the EXP-Arch mission architecture.
11. Develop a technology roadmap to accomplish the mission.
12. Actively promote discussion (through seminars, studios, and meetings) between the general public, commercial space ventures, and NASA on how to best realize ‘active’ exploration activities.

Acknowledgements

Trotti & Associates, Inc. Team
Santiago Alfaro
Hubert Davis
Mitchell Joachim, Ph.D.
Shaun Modi

Massachusetts Institute of Technology
Prof. Dava Newman
Prof. Jeff Hoffman

Rhode Island School of Design
Prof. Mickey Ackerman
Prof. Michael Lye
ID Space Studio Students

Nemo Equipment, Inc.
Cam Brensinger,
Suzzane Turrell,
Connie Yang,
Ahern Laurinat

Brown University
Professor Peter Schultz PhD.

EXP–Arch Advisory Board Members
Ted Bakewell, Bakewell Enterprises
Todd Dalland, Future Tents Ltd.
Einar Thorsteinn, Kingdomes

References

Aggarwal, A., Ramakrishna, S., Ganesh, V. K., (2001), "Predicting the In-plane Elastic Constants of Diamond Braided Composites", Journal of Composite Materials, 35: 8, 665-688.

Bakis, C.E., Bank, L.C., ASCE, F., Brown, V.L., ASCE, M., Cosenza, E., Davalos, J.F., ASCE, A.M., Lesko, J.J., Machida, A., Rizkalla, S.H., ASCE, F., and Triantafillou, T.C., M.ASCE, (2002) "Fiber-Reinforced Polymer Composites for Construction—State of the Art Review", Journal of Composites for Construction, 6(2): 73-87.

Bannister, M.K., (2004) "Development and application of advanced textile composites", IMechE, 218.

David W. Beaty (Mars Program Office-JPL/Caltech), et al. "An Analysis of the Precursor Measurements of Mars Needed to Reduce the Risk of the First Human Mission to Mars." 2005.

Bowen, C.R., Stevens, R., Nelson, L.J., Dent, A. C., Dolman, G., Su, B., Button, T. W., Cain, M. G., and Stewart, M., (2006) Manufacture and characterization of high activity piezoelectric fibres, Smart Materials and Structures, 15: 295-301.

Bunsell, A.R., and Renard, L., (2005), Fundamentals of Fibre Reinforced Composite Materials, Institute of Physics.

Caron, Ryan. "Radiation Shielding for manned missions to Mars." Worcester Polytechnic Institute. 2004. NASA-STD-3000. http://msis.jsc.nasa.gov/sections/section05.htm.

Chen, L. and Lee, C., (2006) "Interaction between Atomic Oxygen and Polymer Surfaces in Low Earth Orbit", Journal of Spacecraft and Rockets, 43: 3, 487-496.

Charles Dalton, and Edward Hohman, 1972 NASA/ASEE Systems Design Institute, Conceptual Design of a Lunar Colony, NASA Grant NGT 44-005-114.

Costes NC et al. 1972. Mobility performance of the lunar roving vehicle. NASA
TR R-401. http://www.hq.nasa.gov/office/pao/History/alsj/lunar_mobility_bible.pdf PDS geosciences node. 2006. http://pdsgeosciences.wustl.edu/missions/clementine/gravtopo.html.

Cook, AC. 2006. http://www.cs.nott.ac.uk/~acc/dems.html. NASA. 1971. Lunar Roving Vehicle operations handbook, Appendix A. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa-gov/19750069562_1975069562.pdf.

Conner HF et al. 1971. LRV lunar traverse obstacle avoidance study. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19790073848_1979073848.pdf.

Demaine, E., Laboratory for Computer Science, MIT, personal communication, http://theory.csail.mit.edu/~edemaine/linkage/animations/#ttree.

Dick, Steven J. and Keith Cowing, eds. Risk and Exploration: Earth, Sea and the Stars (NASA SP-2005-4701), available via NASA History Division or online at http://history.nasa.gov/SP-4701/riskandexploration.pdf

Eckart, 1999. Spaceflight Life Support and Biospherics. [NASA-STD-3000] http://msis.jsc.nasa.gov/sections/section05.htm.

Ferguson, P., Coleman, C. and Newman, D.J., "Characterization of human locomotor control strategies and adaptation across a spectrum of gravitational environments," in Proceedings of the 55th International Astronautical Congress, Vancouver, BC Canada, October 2004, IAF.

Harris, C. E., Starnes J.H., and Shuart, M. J., (2001), "An Assessment of the State-of-the-Art in the Design and Manufacturing of Large Composite Structures for Aerospace Vehicles", NASA.

Human Space Flight Mission Analysis and Design, Edited by Wiley J. Lardson and Linda K. Pranke, with John Connolly and Robert Giffen.

JPL. 1966. Surveyor I Mission Report Part II: Scientific Data and Results. JPL TR, 32-1023.

Jones CS, Nola FJ. Mobility systems activity for lunar rovers at MSFC. NASA TMX-64623. http://ntrs.nasa.gov/archive/nasa/casi.ntrs.nasa.gov/19720004516_1972004516.pdf.

Kieza, M.E., Readdy, W.F., Williams, R., Fogleman, G. and Davis, J.R., "Bioastronautics Critical Path Roadmap (BCPR)," Tech. Rep. JSC-62577, NASA, Johnson Space Center, Houston, Texas, 2004.

Mansur, L.K., Frame, B.J., Gallego, N.C., Guetersloh, S.B., Johnson, J.O., Klett, J.W., and Townsend, L.W., (2005) "Assessment of Shielding Material Performance for Deep Space Missions", Materials research Society Symposium Procrement, 851.

Melosh HJ. 1989. Impact cratering: a geological process. Oxford monographs on geology and geophysics, No. 11. Oxford University Press.

Mobility Performance of the Lunar Roving Vehicle: Terrestrial Studies, aka the LRV Bible (Costas, 1972) http://www.spacetoday.net/Summary/1262.

References (Continued)

Rising Above the Gathering Storm: Energizing and Employing America for a Brighter Economic Future, ISBN: 0-309-65463-7, Augustine, N. et al., The National Academies of Science, Engineering and Medicine. http://www.nap.edu/catalog/11463.html, 2005.

NASA, Apollo Experiments Catalog: Catalog of Apollo Experiment Operations. http://www.myspacemuseum.com/apollo.htm, web pages.

NASA. 2005. *NASA's Exploration Systems Architecture Study (ESAS)*, from <http://www.nasa.gov/mission_pages/exploration/news/ESAS_report.html>

NASA, Surface Journal: Apollo Lunar Surface Journal, http://www.hq.nasa.gov/office/pao/History/alsj/frame.html, web pages.

NASA, "The Vision for Space Exploration", February, 2004. Rising Above The Gathering Storm: Energizing and Employing America for a Brighter Economic Future.

NASA, CE&R: Draper/MIT CE&R Study, 2005.

Parnell, Thomas and John Watts. "Radiation Effects and Protection for Moon and Mars Missions" Marshall Space Flight Center. 1997.

Poe, C.C., Jr., Dexter, H.B., and Raju, I.S., (1997) "A Review Of The NASA Textile Composites Research", AIAA, 1126-1138.

Wang, Y., and Zhao, D. (2006). "Effect of Fabric Structures on the Mechanical Properties of 3-D Textile Composites", Journal of Industrial Textiles, 35(3): 239-256.

Saleh, J.H., Hastings, D.E., and D.J. Newman, "Flexibility in System Design and Implications for Aerospace Systems," Acta Astronautica, vol. 53, pp 927-944, 2003.

Sheridan, T.B., "Humans and automation: system design and research issues," New York: J. Wiley & Sons, Published in cooperation with the Human Factors and Ergonomics Society, 2002.

Smith BC. 1967. Journal of Geophysical Research 72(4):1398-1399.

Wilson, 1997. Wilson, J.W., F. A. Cucinotta, M. H. Kim, and W. Schimmerling. "Optimized Shielding for Space Radiation Protection." 1st international workshop on Space Radiation Research and 11th Annual NASA Space Radiation Health Investigators' Workshop., 1997.

Wilson, J.W., F. A. Cucinotta, M. H. Kim, and W. Schimmerling. "Optimized Shielding for Space Radiation Prtoection." 1st international workshop on Space Radiation Research and 11th Annual NASA Space Radiation Health Investigators' Workshop., 1997.

Dennis Ray Winco, Gordon Woodcock, Mark Maxwell, "Lunar Outpost Development and the Role of Mechanical Systems for Payload Handling". Skycorp Incorporated, 2007.

Yu, G., De-zhuang, Y., Jing-dong, X., Shi-yu, H., and Zhi-jun, L., (2006) "Effect of proton Radiation on Mechanical Properties of Carbon/Epoxy Composites", Journal of Spacecraft and Rockets, 43: 3, 505.

Appendices

Appendix A. Extreme EXPeditionary Architecture Bi-Monthly Report, November, 2006.

Appendix B. Extreme EXPeditionary Architecture Bi-Monthly Report, January, 2007.

Appendix C. Extreme EXPeditionary Architecture, Rhode Island School of Design (RISD), Industrial Design Department, Design for Extreme Environments, February, 2007.

Extreme EXPeditionary Architecture

PI: Guillermo Trotti, A.I.A.

Bimonthly Report, Phase I

November 2006

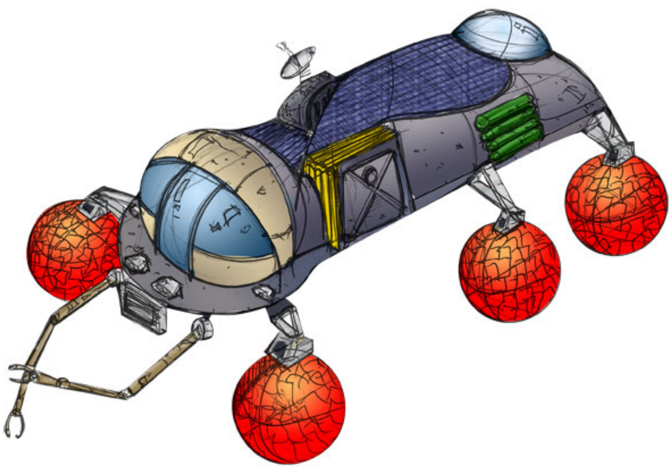


Figure 1. An *EXP-Arch* transforming vehicle concept.

Project Objectives

The Extreme EXPeditionary Architecture (*EXP–Arch*) project aims to develop an adaptable and mobile architecture capable of meeting a variety of space and earth missions.

The creative *EXP-Arch* self-mobilizing, transformable systems combine robotics, deployable lightweight structures, intelligent materials, combinatorial geometry (mathematical origami), and self-erecting systems for human and machine exploration of extreme environments (See Figure 1).

Expected Significance

This revolutionary idea of
'Extreme EXPeditionary architecture'(*EXP–Arch*)
for the solar system is in stark contrast to existing stationary base designs for lunar and Mars missions.

A paradigm shift is proposed to revolutionize exploration by creating an architecture, or a suite of systems, which are highly mobile, quickly deployable and transformable to enable autonomous robotic and human exploration for short and long-term investigations at many diverse sites.

Mission Architecture and Goals

The initial *EXP–Arch* architecture concept consists of two (2) pressurized rovers and one (1) un-pressurized rover. The pressurized rovers: 1 for habitation and 1 for laboratory/exploration incorporate deployable and retractable inflatable structures to provide significant expanding volume (See Figure 2). All rovers are capable of transporting a crew of 3 and cargo.

- Crew size: 3–6
- Design Life: 10–12 years
- Missions duration: weeks–months (moon), 2–3 yrs (Mars)
- Landing Systems: Balloons, Conventional Retrorockets
- Delivery Systems: Rovers (<3 mt) by available launch
- Science: Geology, Search for water/ice, Minerals, Masscons, Lava tubes.
- Search for Life in the Solar System.
- Human Experience: Surface operations, Planetary Exploration, Mars Mission Training, Self-Sufficiency.
- Technology Testbeds, Construction and Systems Testing.

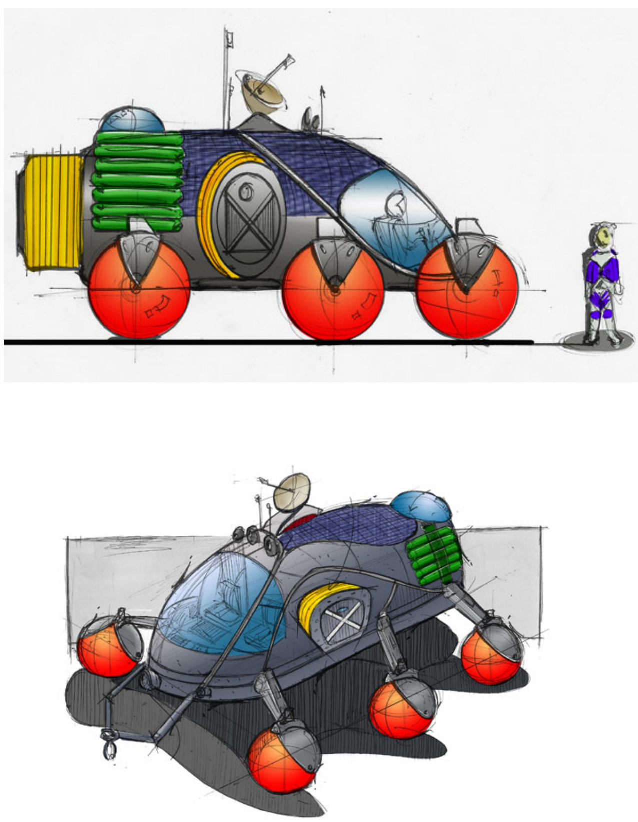


Figure 2. *EXP–Arch* pressurized rover concept that incorporates a drive train with 4-6 elastic wheels with independent electrical motors.

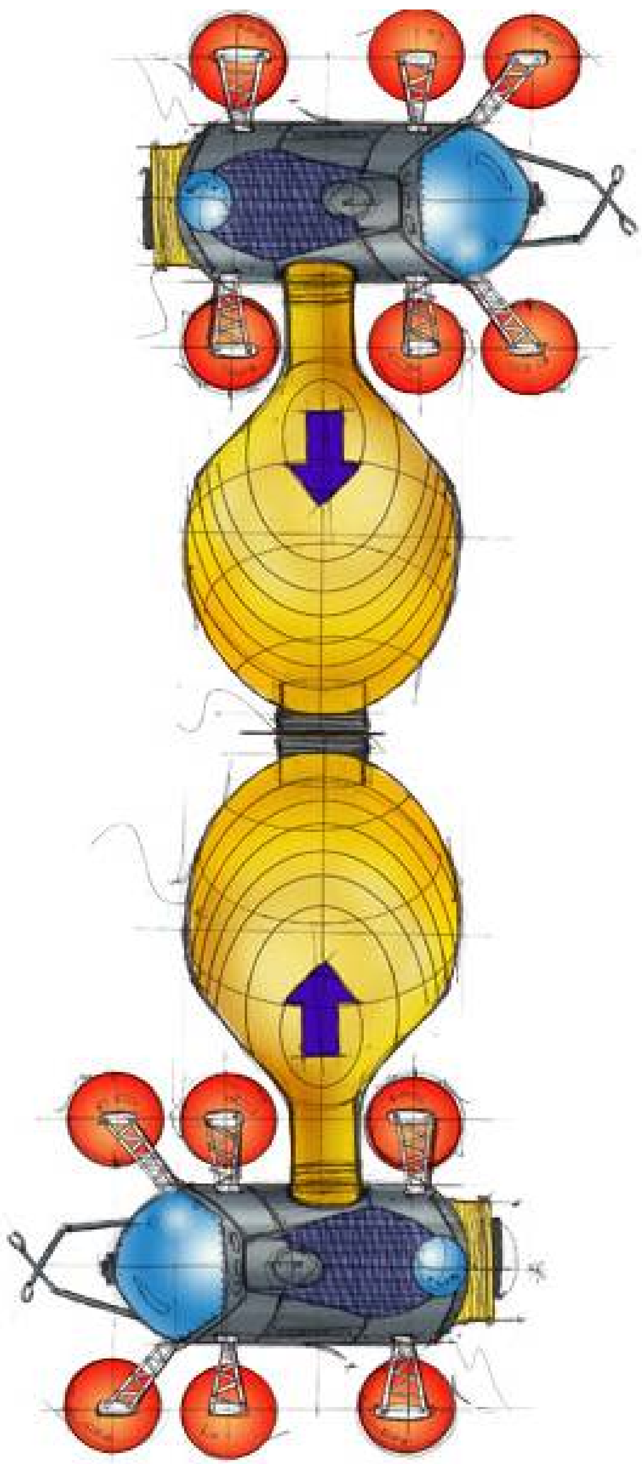


Figure 3. The *EXP-Arch* pressurized rover demonstrating extended legs and rotated wheels, which allow the rover to sit on the regolith and deploy the inflatable environment and dock to a second rover.

Strategic Design Approach

The *EXP–Arch* design approach is to define a mission architecture based on previous human exploration experience in the Antarctic, deserts, oceans, and other extreme environments. We will involve industry experts from the Automotive, Photovoltaics, Materials, and Marine / Diving sectors to contribute lessons learned. Our design approach recommends international cooperation for future exploration. Our initial concepts for pressurized and un-pressurized rovers are self-mobilizing, transformable systems with deployable lightweight structures (Figure 3).

Pressurized Lunar Rover Specifications

Pressurized Environment: 3 m dia. x 6 m length, composite structure.
Drive train: 4–6 wheels with independent electrical motors, composite structure.
Propulsion: Harmonic drive electrical motors, 1 per wheel.
Suspension System: Non-active elastic structure and wheels.
Thermal Control: Radiators on rover body
Speed: 20 km/hr maximum
Radiation Shield: Partial shield in shell structure. Ability to bury 1pressurized rover in 30 min.
Power supply and storage: Solar, fuel cells, batteries.
Cockpit: Control, navigation, and communication systems, seating for 2 crew.
EVA Suit Storage: 3 suits/vehicle
ECLSS: O2-N2 Tanks and H2O Tanks.
Airlock: Inflatable and directable.
Habitat and Workshop: Attached inflatable/tent structure.
Habitability: Food storage and heating; water dispensing and storage,cooling and heating; one toilet, personal storage for a crew of 6, medical supplies and storage.

Un-Pressurized Scout Lunar Rover

Specifications

Chassis: 2 m width x 3.5 m length
Drive train: 4 wheels with independent electrical motors, composite structure.
Propulsion: Electrical motors, 1/wheel.
Suspension System: Non active elastic structure and wheels.
Max Speed: 30 km/ hour
Payload Capacity: 0.5 m^3
Power: Solar, fuel cells.

Seating for 3 astronauts in EVA BioSuits.

Composite Materials Research

The *EXP–Arch* concepts rely heavily on lightweight structures, hence an initial advance materials review was performed and is highlighted herein. Advanced composite materials generally consist of a high performance resin systems with fiber reinforcement. These fiber reinforced materials have high strength and stiffness properties. Resins are divided into two major categories, thermo-sets and thermo-plastics. Thermo-sets are polymers that are made from a preset mixture that is cured at an allotted temperature and time. Once the polymer solidifies, the process is irreversible. Thermo-plastics are ideal for many different processing methods such as injection molding and extrusion. The structure of thermoplastics can be either completely amorphous or semi-crystalline. The concept of having an amorphous or semi-crystalline structure involves the degree of disorganization of the structure. The more amorphous the structure, the more structural disorganization (See Figure 4).

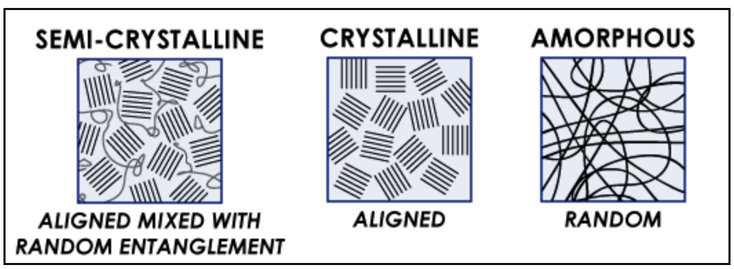


Figure 4. Three conceptual images of different polymer structures. Taken from www.atperpg.com/materialselection.html

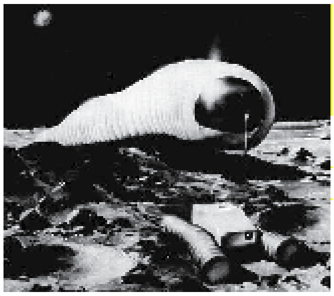
Semi-crystalline polymers exhibit a glass transition temperature from the amorphous portion while the crystalline portion also contributes to the material having a melting point. One issue with this property comes with processing the material. When heating the semi-crystalline material for shape forming, the likelihood of decreasing the percentage of crystallinity within the structure is high due to the increase of entropy to the system through heat [Wang and Zhao, 2006]. In the case of many thermoplastics, the added heat energy causes the structure to expand. This expansion increases the amount of free volume space within the polymer structure. Extra free volume space within the structure allows more chain mobility due to the tightly wound structure of the polymer chains, the motion of the polymer chains can only slide past one another (reptation). The added heat is responsible for melting of secondary bonds within the polymer structure, ultimately allowing reptation to occur.

Amorphous polymers have a highly disordered structure. The scientific community terms this as having no long range order. This means that the basic molecules that define the composition of the material are not aligned with neighboring molecules in any sort of repeatable pattern.

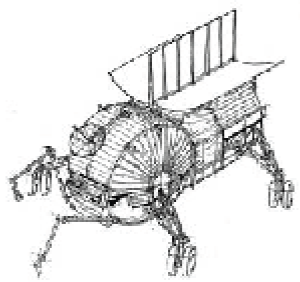
Reinforcement fiber materials can be arranged in seemingly infinite combinations with a resin to achieve the desired performance level. Some of the possible categories of fiber reinforcement are: Organic fibers, Glass fibers, Boron CVD fibers, silicon carbide CVD fibers, Carbon fibers, Alumuna-based fibers, SiC-based fibers, continuous mono-crystalline filaments, and whiskers [Bunsell and Renard, 2005].

References. Wang, Y., and Zhao, D. (2006). Effect of Fabric Structures on the Mechanical Properties of 3-D Textile Composites, Journal of Industrial Textiles, 35(3): 239-256.

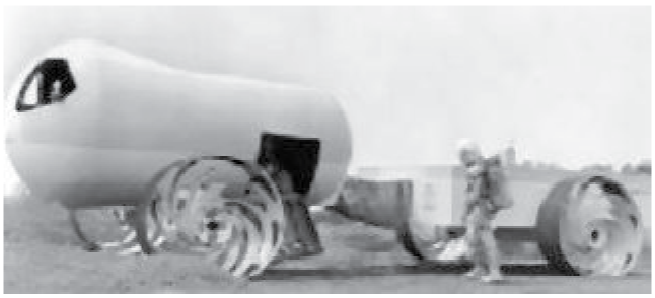
Bunsell, A.R., and Renard, L., (2005), Fundementals of Fiber Reinforced Composite Materials, Institute of Physics.



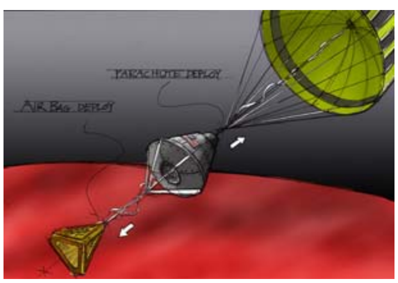
Lunar worm with bellows concept. Philco Corp.

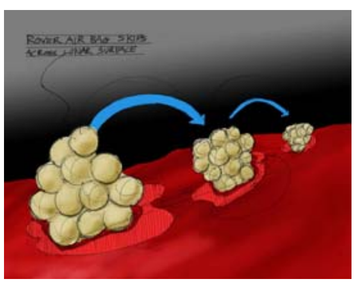


Daylight rover by Boeing, 1990.



The Grumman Lunar Logistics System Project 344 Mockup. 1963.





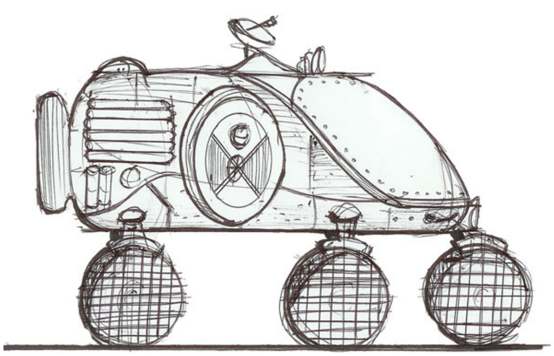


Figure 5. Top three images: Previous creative rover designs briefed to RISD students. **Bottom three images:** Sketches and illustrations of the *EXP-Arch* planetary landing system concepts and pressurized rover from RISD industrial design internship students.

EXP–Arch Education Initiative with the Rhode Island School of Design

Trotti & Associates, Inc. (TAI) is contributing to a Design Studio at the Rohde Island School of Design (RISD), Industrial Design department. The Studio is headed by Prof. Michel Lye and is funded by the Rhode Island Space Grant and RISD. Ten (10) undergraduate students are taking the studio to design various aspects of the rovers proposed on the Extreme EXPeditionary Architecture (EXP-Arch) project.

Architect G. Trotti (TAI), former astronaut Dr. J. Hoffman, and Designer C. Brensinger (NEMO Equipment) are all supporting the RISD Studio giving lectures in Space Human factors, Extra-Vehicular Activity, Inflatable Structures, the Space Environment, and Design for Extreme Environments related to the EXP-Arch project.

TAI has hired two additional RISD students as interns, both receiving course credit for their participation in the *EXP–Arch* project.

EXP–Arch Team and Advisors

We have assembled a world class team of architects, designers, and engineers to accomplish our goals.
Trotti and Associates, Inc. - Guillermo Trotti - Hubert Davis - Dava Newman - Cam Brensinger - Mitchell Joachim - Shawn Modi - Santiago Alfaro
Board of Advisors - Jeff Hoffman - Mike Massimino - Todd Dalland - Einar Thornstein - Edward Bakewell
Rhode Island School of Design Industrial Design Department - Mickey Ackerman - Michel Lye - 10 Studio Students.

EXP–Arch Future Work

In the next two months we have targeted further research in to advanced materials, power systems, instrumentation and controls, radiation protection, launch system capability, and enhanced mission architecture. The TAI team will also complete the preliminary design of the entire *EXP–Arch* rover layout, investigate various deployable structure concepts, and design the geometry of the wheel and suspension system. Deliverables also include design studio concepts including: origami foldable structures, design inspired by nature, and vehicle systems.

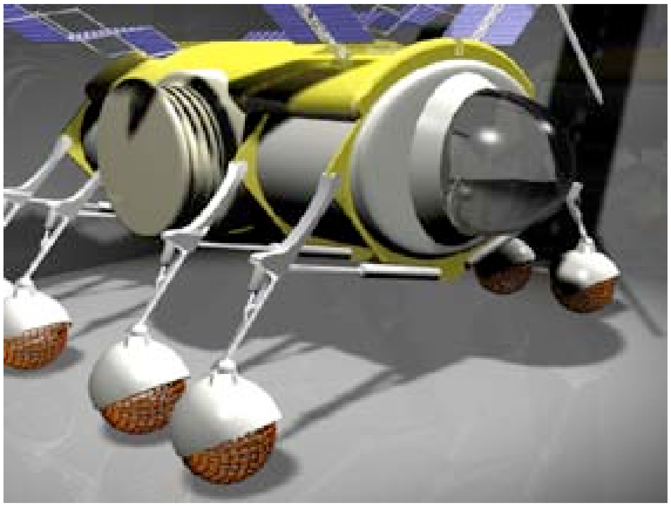


Figure 1. *EXP-Arch* transforming vehicle concept.

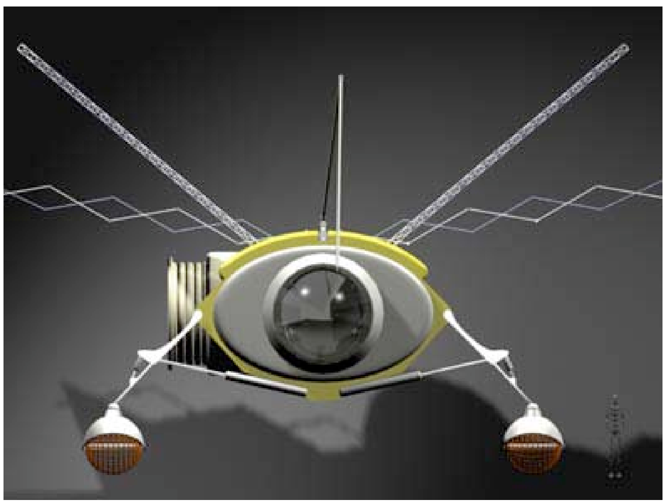


Figure 2. *EXP-Arch* transforming vehicle concept (front view).

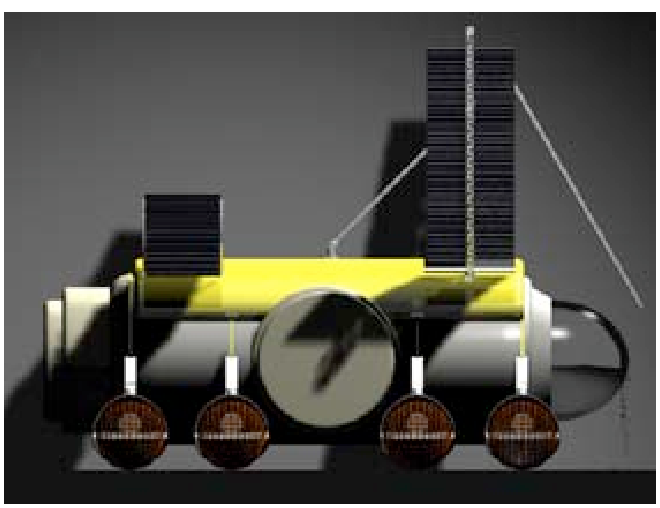


Figure 3. *EXP–Arch* pressurized rover concept (side view).

Table of Contents

Introduction

The Extreme EXPeditionary Architecture (*EXP–Arch*) project aims to develop an adaptable and mobile architecture capable of meeting a variety of space and earth missions. Lunar exploration under the *EXP-Arch* concept is a stepping stone for Martian exploration with the goal of learning how to explore in a truly mobile way. Earth exploration has demonstrated that mobility is fundamental to great discoveries. The architecture proposes self-mobilizing, transformable systems combining robotics, deployable lightweight structures, intelligent materials, combinatorial geometry (mathematical origami), and self-erecting systems for human and machine exploration.

This revolutionary idea of 'Extreme EXPeditionary architecture'(*EXP–Arch*) for the planetary surfaces is in stark contrast to existing stationary base designs for lunar and Mars and most Earth Polar missions. A paradigm shift is proposed to revolutionize exploration by creating an architecture, or a suite of systems, which are highly mobile, quickly deployable, self shielding, and transformable to enable autonomous robotic and human exploration for short and long-term investigations at many diverse sites.

Mission Architecture Update

The *EXP–Arch* architecture concept proposes a Lunar surface exploration mission from Pole to Pole searching for the best possible site to establish a future Lunar Base and accomplish many other scientific objectives. The mission will be performed by a "convoy" of rovers, two (2) pressurized rovers and four (4) un-pressurized rovers. The pressurized rovers: 1 for habitation and 1 for laboratory/exploration incorporate deployable and retractable inflatable structures to more than double the initial volume.

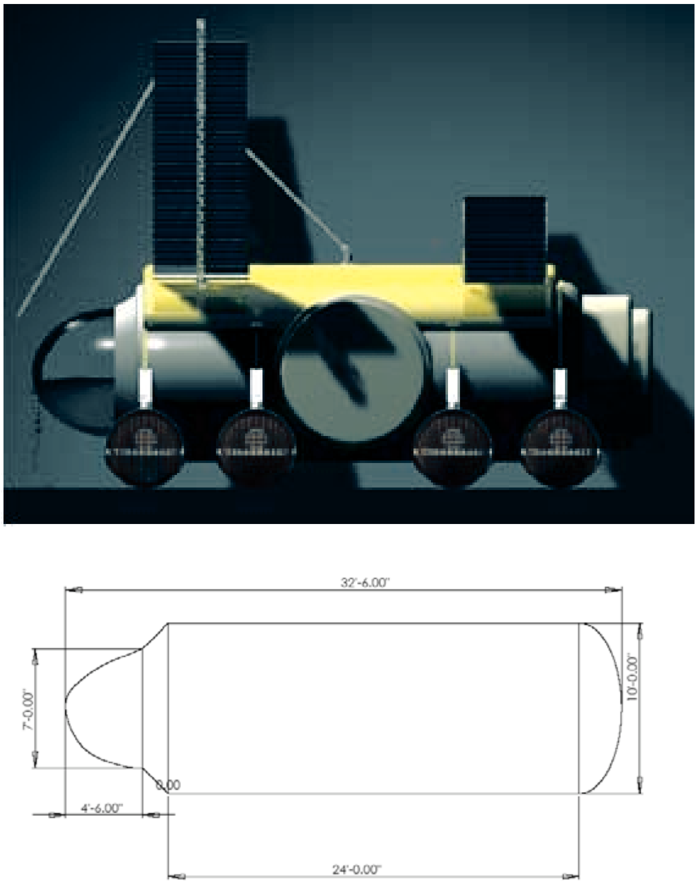


Figure 4. Top. *EXP–Arch* pressurized rover concept (side view). Bottom. Dimensioned pressurized volume.

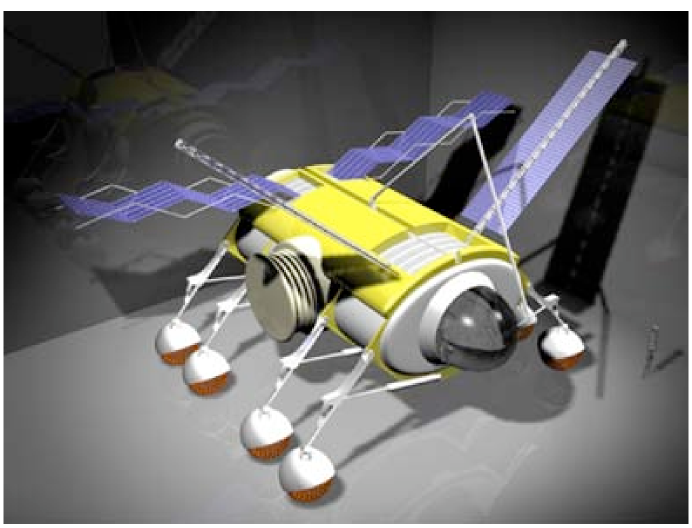


Figure 5. *EXP–Arch* pressurized rover concept that incorporates a drive train with 8 spherical elastic wheels and elastic composite legs with independent electrical motors.

Mission Architecture Update (cont.)

Each pressurized rovers is capable of transporting a crew of 4 and the necessary supplies and equipment for the mission.
- Crew size: 4–8
- Design Life: 10–12 years
- Missions duration: weeks–months (moon)
- Landing Systems: Conventional Lunar Landers Architecture.
- Delivery Systems: 2 Pressurized Rovers (8 mT each) on the Ares V System proposed by NASA. Capable of delivering more than 20 mT to the Lunar surface.
- Mission Purpose: Geology, Search for water/ice, Minerals, Masscons, advanced robotic operations.
- Human Experience: Surface operations, Planetary Exploration, Mars Mission Training, Self-Sufficiency.
-Technology Testbeds: Mining, Construction, Rapid Excavation and Regolith Movement (for solar flare radiation protection), and other Systems Testing.

Lunar Traverse Mission:
Although detailed analysis for the mission needs to be further developed, the initial mission concept is to land the convoy of rovers (2 pressurized rovers and 4 mini rovers) at an initial site where they will self-deploy solar arrays, radiators, and inflatable environments. The two *EXP-Arch* rovers will test docking and undocking mechanisms autonomously. The crew will arrive on a separate human rated lunar lander with the necessary supplies for their planned mission. After all the *EXP-Arch* systems have been verified the crew will retract the inflatable environments and start a “day light” traverse with the entire convoy. During the lunar night the convoy will stop and go into “camping” mode to reduce energy consumption. During the camping mode astronauts could perform EVA’s, collect and analyze samples, and conduct scientific experiments and observations. After the initial mission is completed the astronauts have two pre-established alternatives to return to Earth 1) Return to the lander they came in, or 2) Fly back on another lander that is waiting for them on another site. The alternate alternate is equipped with additional supplies cashes (i.e., oxygen, water, spare parts, tools, etc.). After the crew leaves for Earth the convoy of rovers either 1) stays in place until the next crew arrives or 2) traverses autonomously to another location where the next crew will meet them. The cycle repeats itself for many years until all the mission goals are accomplished. Given the short duration of Phase I we will not propose a route for the traverse mission. However, we hope to perform detailed mission traverse analysis during Phase II including sites to be visited (poles, Apollo sites, etc.), cashes needed, crew composition, and to prototype operational rovers.

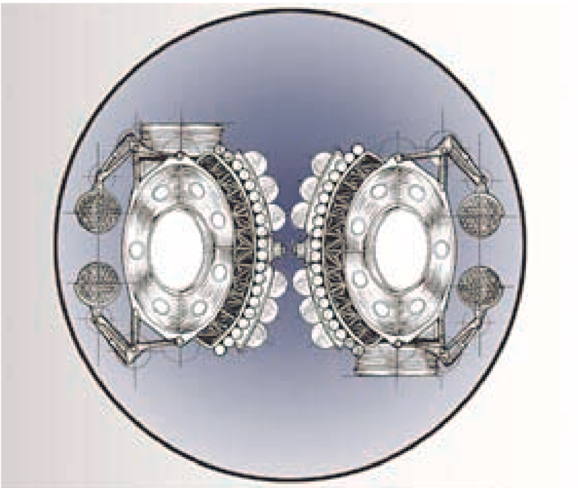


Figure 6. Two Mother Ship Rovers configured for launch on the Ares V (top view of Ares V).

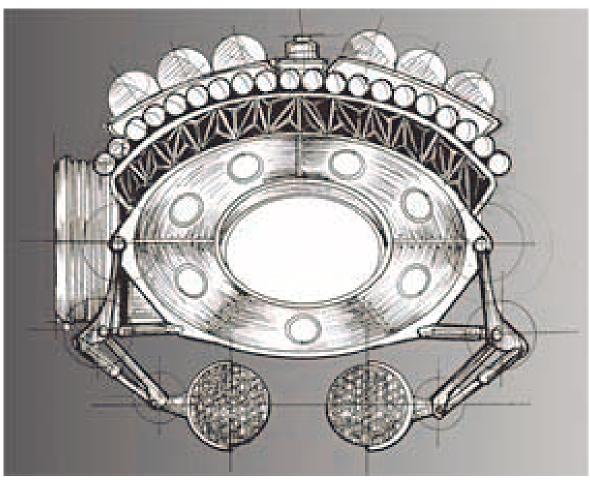


Figure 7. Mother Ship Rover folder for launch configuration (front view).

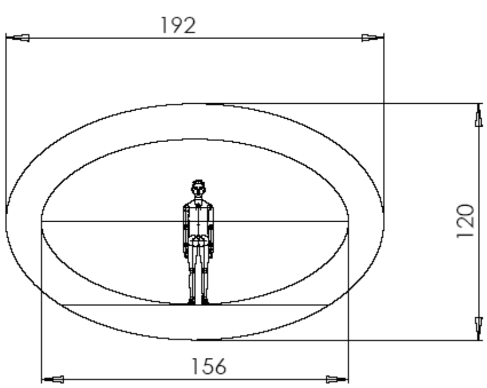


Figure 8. Pressurized environment of the Mother Rover (cross-section, dimensions in inches).

Rover Concepts (See Figs. 1-10)

Launch Configuration:
Two Mother Ship Rovers will be launched in on a Ares V rocket (See Figs. 6-7).
Propulsion: All the rovers will be equipped with independent electric motors at each wheel.

Mobility and Docking capabilities: All the rovers will be highly mobile, all the wheels will be able to turn 360 degrees independently from each other. In addition, the Mother Rovers will be able to elevate themselves up to 2 m, and also 'sit' on the surface of the Moon.

Micrometeorite Protection: The Mother Ship Rovers are designed with a rack for mounting equipment (like the ISS) as well as an aluminum shield to protect the pressurized module.

Materials: The rovers will be a hybrid of metal and composite materials. We propose to maximize the use of custom designed composites for the various parts of the rover to reduce the over all mass of the rovers (See Composite Material section).

Power Generation: The rovers will be equipped with two deployable and adjustable large solar arrays. The masts will be more robust to counteract the effects of the low gravity of the moon.

Radiators: The radiators will also be foldable and adjustable to minimize sunlight exposure.

Special Features: The Mother Rover is designed with a manipulator arm mounted on a track on the roof rack from front to back as the 'back bone' for servicing the rover (See Fig. 5). The arm will be used to exchange tanks, batteries, tools, and other equipment mounted to the roof rack. Winches will be mounted in the front and rear of the rovers to support them in case of getting stuck in the regolith.

Deployable Environment
Airlock and Dust Control: An inflatable airlock is mounted on the rear of the rovers; and is similar in design to one tested, developed and fabricated by Honeywell and FTL. From the airlock in the rear of the rover the astronauts will step into a suit storage and repair area where they will don and doff their extravehicular suits. This area will be isolated from the rest of the vehicle by a hatch and will also be provided with a negative flow of air to prevent regolith particles to flow into the habitable environment.

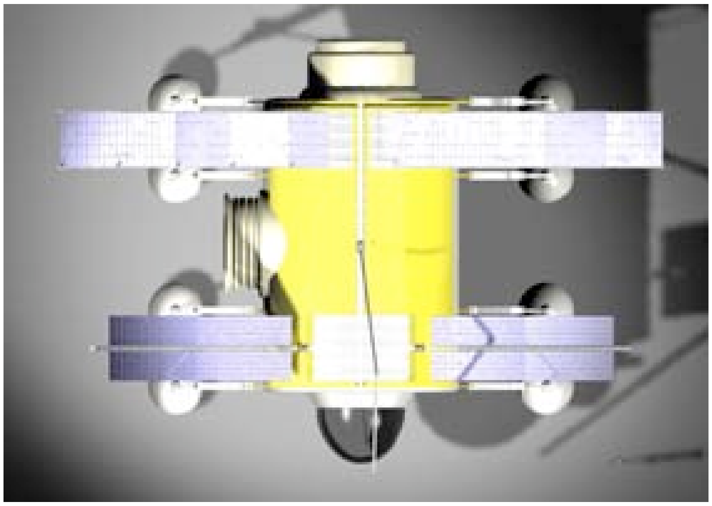


Figure 9. Mother Ship Rover with micrometeorite and radiation shielding (top view).

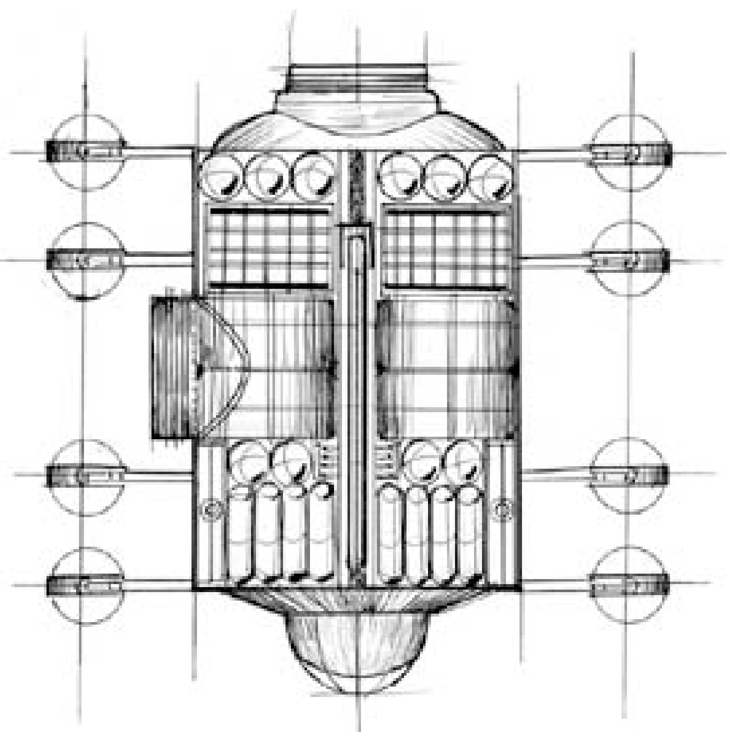


Figure 10. Mother Ship Rover line drawing showing water and oxygen tanks, batteries, radiators, and solar arrays optimizing design layout for radiation protection (top view).

Rover Concepts (continued)

Habitable Environment: The pressurized areas of the rovers will accommodate a maximum crew of 4 (See Fig. 8). Both rovers will be provided with a waste management facility and a cockpit for the crew members. One of the rovers will act as the 'habitation' rover and will have a full galley and most of the food storage, the other one act as the 'laboratory' rover and will have minimal galley and food storage. However, the laboratory rover will carry most of the research and scientific equipment, field tools, sample storage, etc.

Radiation Protection

Protecting the crew from radiation is critical to the success of the mission. Given the difficulty to protect the crew from radiation (Galactic Cosmic Rays, Solar Flares) we propose that astronauts should participate in missions with a pre-determined radiation exposure limit. Since maximum exposure levels for lunar surface radiation exposure have not been determined we estimate that astronauts could be minimally exposed for a maximum of 90 earth days. However, this issue needs to be studied in detail not only for lunar missions but for the longer exposure missions such as the missions to Mars.

Galactic Radiation protection Strategy:
We have designed the pressurized rovers to carry all the high density equipment on the roof and sides of the vehicle to maximized the shielding with batteries, water tanks, and other high mass equipment and tools (see Figs. 9-10).

Solar Fare Radiation Protection Strategy:
We are considering two ways to provide short term full radiation protection during solar flare activity.

1) Bury one of the pressurized rovers with all the crew inside in a customized crater, which has been created via an explosion. The unpressurized mini rovers and the other pressurized rover will remain outside during the flare and then will uncover and pull out the safe rover carrying the crew by using winch, bulldozer, auger, and plow attachments.

2) Create a "well" or"safe haven" with specially designed explosives where the crew can hide for the period of the solar event in a pressurized bladder connected to the underside of a pressurized rover. These methods will be studied further and updated on the final report.

Rover Concepts (continued)

Mini Rovers

We have developed a preliminary design concept of the Mini-rovers, most of the design effort has gone into the design of the Mother Ships given that most of the technology and systems needed to operate the Mini rovers already exists. The Mini rovers are the support vehicles to the mother ships. The general concept for these Minis is that they will be highly mobile equipped with many different tools for regolith moving and highly independent to be able to pick up and deliver crews to and from landing vehicles. The Minis are designed to carry 4 crew in EVA suits plus some cargo (i.e., oxygen and water tanks, scientific equipment, tools, etc.) In the next two months we will conceptually design the tools and outfit the Minis to be able to support the Mother Ships. The mission architecture calls for a total of 4 Mini rovers.

General Dimensions: 12' long X 6' wide X 7' high 9 (unfolded)
Launch Configuration: Roof and wheels are foldable to minimize volume during launch.
Energy: Solar cells on roof, batteries
Propulsion: 4 independent electric motors.
Mobility: Four wheels 90 degrees rotation.
Materials: Composites and aluminum.
Tools: Winch, plow, drills, manipulator arm, trench digger, auger.
Micrometeorite shielding: The Mini's will have an aluminum canopy to provide some shielding and mounting of the solar cells.

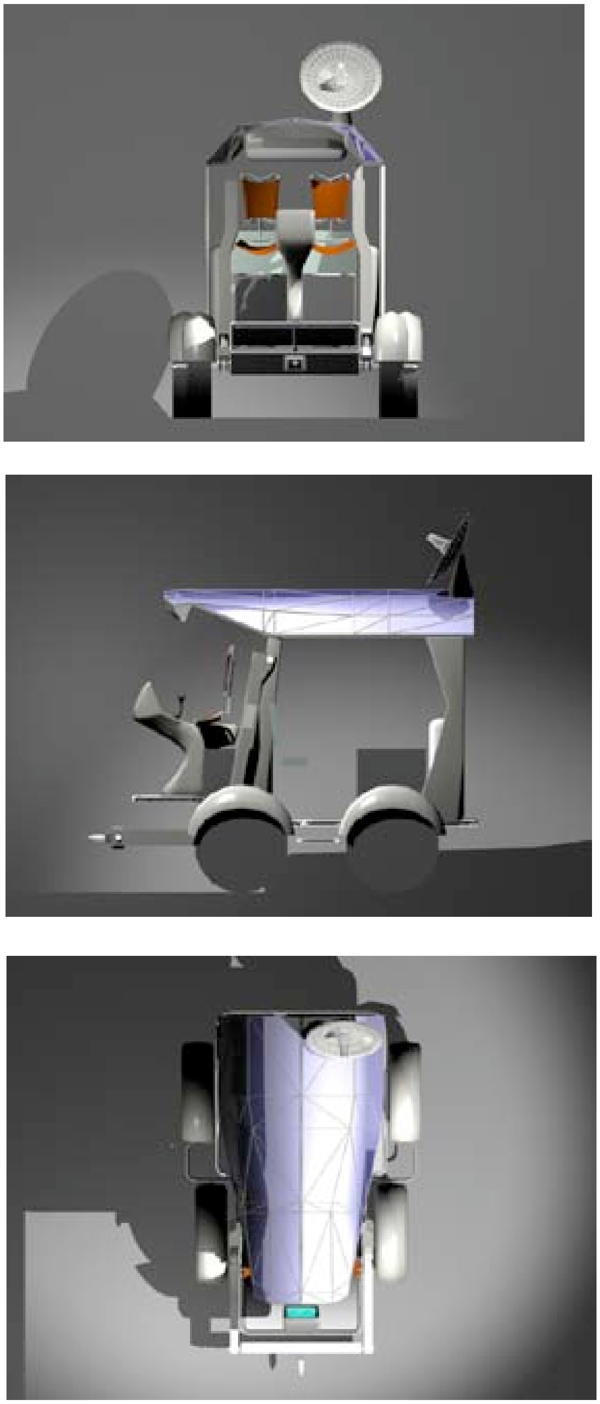


Figure 11. Mini Rover initial concept (front, side and top views).

Figure 12. Deployed Mini Rover (perspective view).

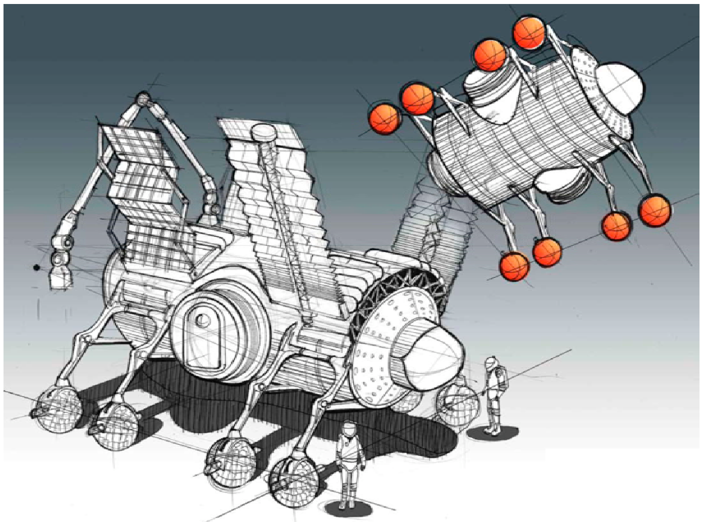


Figure 13. Mother Ship Rover with solar arrays, radiators, and robotic arm. Top right. Mother Ship Rover underbody structure.

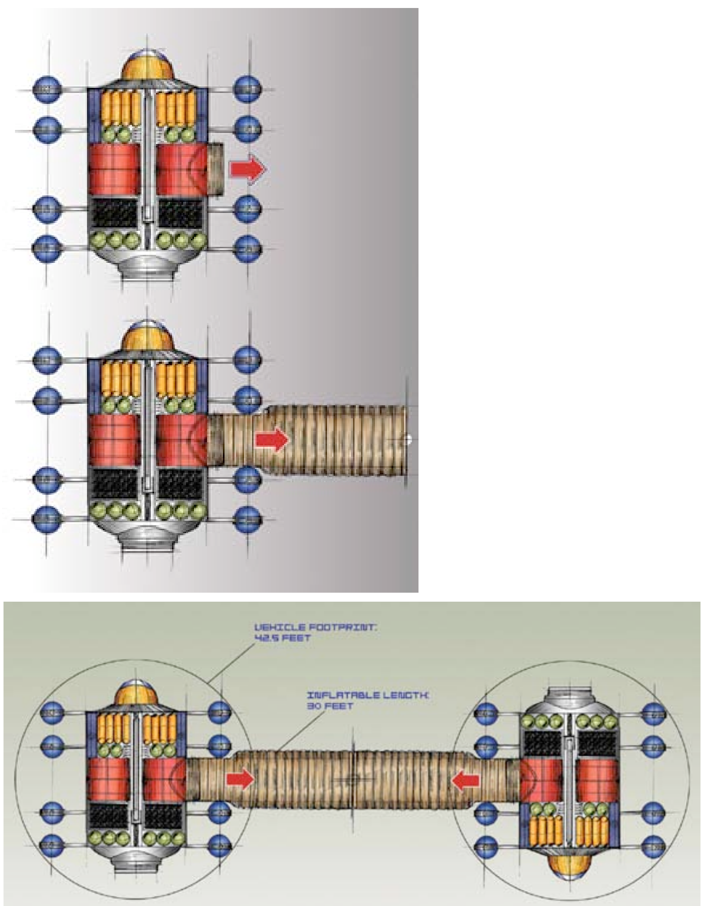


Figure 14. Top. Mother Ship Rover (top view) with inflatable environment (folded, top) and inflated (extended, bottom). Bottom. Two Mother Rovers connected through their inflatable environments (extended).

Rover Concepts

As described earlier, we propose 2 large pressurized agile, but slow moving rovers for habitation and long traverses in relatively smooth terrain, and 4 small very agile, fast moving rovers for the exploration of steep and rugged terrain. We call the large rovers the Mother Ship Rovers and the small rovers the Mini Rovers (or Minis). All rovers are highly automated with the ability to fully operate without humans on the Lunar surface and also have the capability to be teleoperated from Earth, LEO, or the lunar surface. Each Mother Rover rover will be supported by 2 Minis.

Mother Ship Rovers

General Dimensions
Mass: 8 mT
Overall length:32’-6”
Width:16’
Height: 14’
Atmospheric Pressure: 10.2 psi
Pressurized Module:
The pressurized module of the rover will be fabricated of a composite structure rigidized by a rib grid to minimize torsion and bending during the lunar traverses in rough terrain. In the front of the vehicle is located the cockpit which is designed to allow for maximum visibility. An inflatable airlock is located at the rear of the vehicle.

Inflatable Environment: General dimensions are 10 ft in diameter by 30 ft long. The inflatable environments will be used for habitability and work, their structures will be made of multi-layer aramid materials such as Kevlar and Vectran insulated with layers of Mylar for thermal and UV radiation protection. NASA has developed a couple of concepts for pressurized environments (i.e, Spacehab) and private companies such as Bigelow Enterprises have designed and built several inflatable environments. The main difference in the requirements of the inflatable structures suggested in *EXP-Arch* is that these environments will have to be deployed and contracted/folded many times during the life span of the structures. We have been researching / modeling some solutions to avoid uncontrolled folding and sharp creasing of the fabric.

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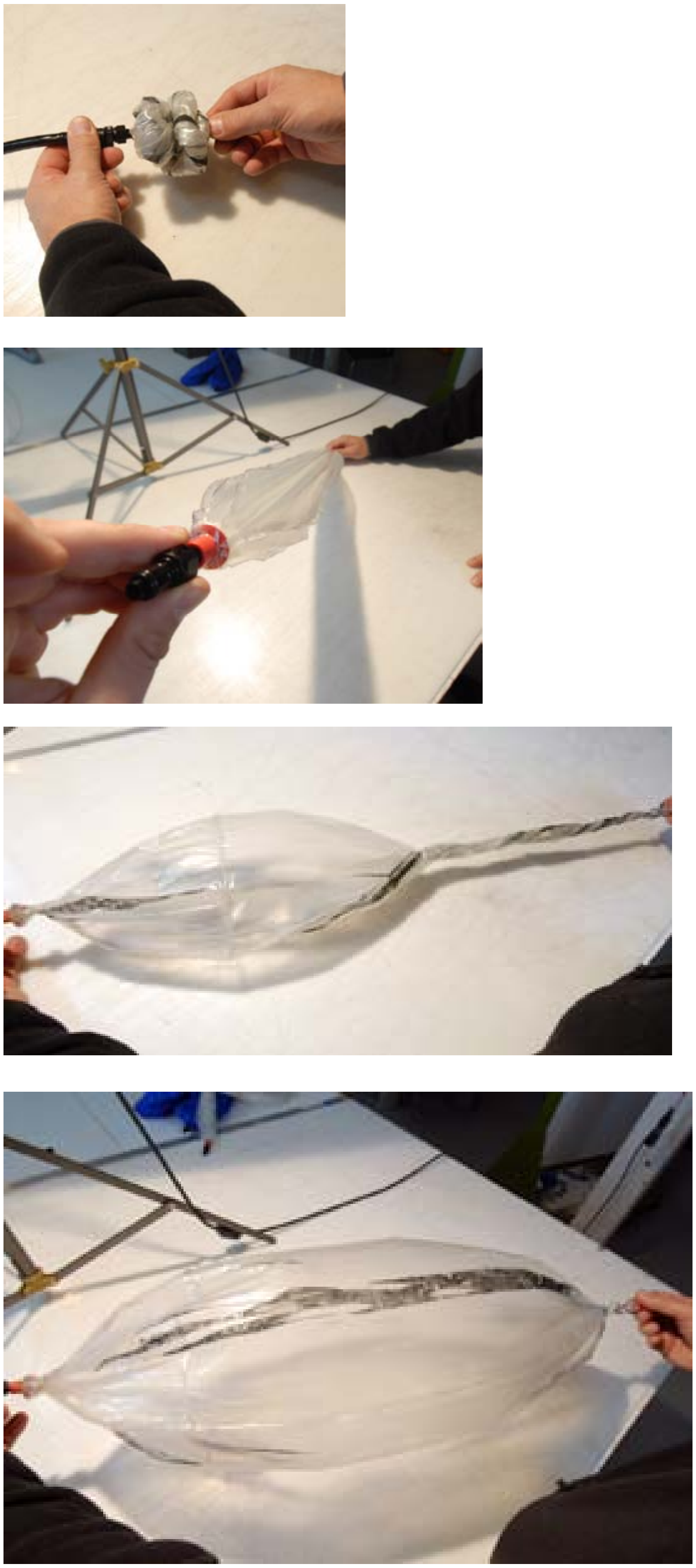


Figure 15. Lightweight structures demonstrating controlled twisting/rolling with soft folds. Top. Fully contracted. Top middle. Extended. Bottom middle. Initial inflation. Bottom. Inflation process and controlled deployment.

Inflatable Structures

Two main concepts have been developed:

1) Controlled twisting/rolling with soft folds (See Figs. 15-16).
   In this case we are researching the natural folds produced by controlled rolling and a pre-designed seam geometry. We have an optimized design that folds and unfolds always along the same geometric pattern for repeatable inflation and deflation without the necessity of a secondary structure.
2) Origami geometric controlled tight folding.
   In this case we have chosen a 12 sided polygon folding geometry that provides the best fabric thickness to number of folds ratio (see following section).

Figure 16. Fully inflated lightweight structures (side view and end view) indicating seam pattern.

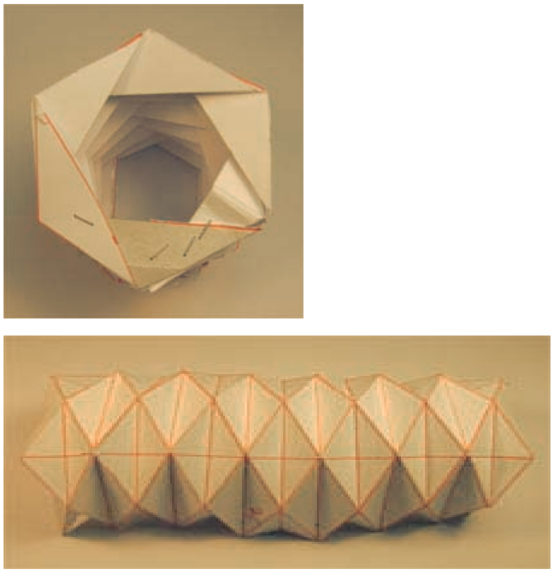


Figure 17. Origami hexagon (6-sided) folded structure model.

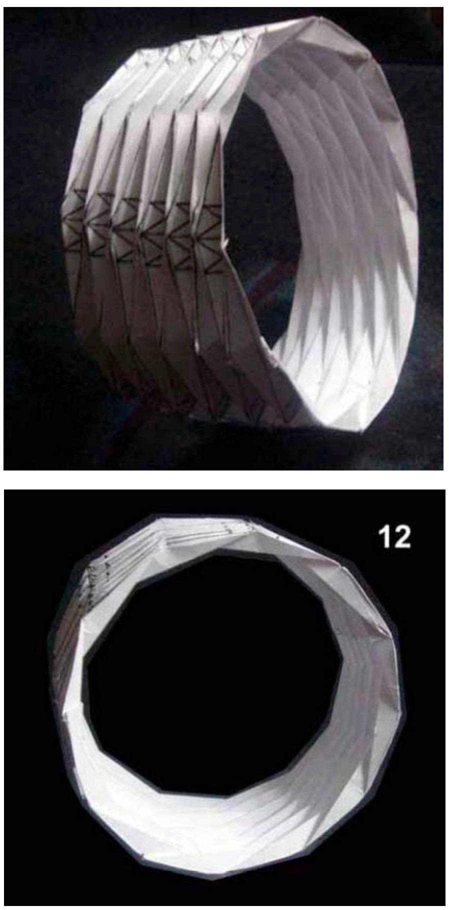


Figure 18. Origami 12-sided dodecagon folded structure.

Origami / Foldable Structures

Origami studies for the inflatable environment attached to the sides of the Mother Ship Rovers

After close examination of various folding geometries for the inflatable high pressure habitat we focused on a trade study between polygons with 6 to 20 sides. We also studied the best ratios of fabric thicknesses versus the overall diameter of the environment. We have concluded that the ratio between the fabric thickness and the pure (non-material) geometry is critical.

Our models show that a 0.4 mm skin thickness with a diameter of 140 mm (ratio 350:1) seems to be the limit. Thus a cylinder of 243.48 cm (8 feet) allows for a 7 mm foldable wall fabric.

The dodecagon or 12-sided polygon folded structure resulted in the best geometric option from the trade study. The original hypothesis was that more sides (i.e., 20) would be better given the closer approximation to a circle, however, we found that the folding of such complex structures is not practical, especially when designing for complete autonomy. The origami folds were not achieved with the 20-sided polygon with the 0.4 mm thick material. We concluded that the maximum origami folds should not be more than 15. Given that the inflatable environment has to be self-deployable and self-retractable, we chose the 12 sided polygon a the safest and most efficient geometry.

Next, we needed to know the difference between an outside diameter and inside diameter (opening) of such a structure at any point in the cross section. To do this we calculated the outer edge and the inner edge of the polygon folded structures according to equations below:

$360°/ (2x(\# \text{ corners})) = q°$;
For a desired diameter of 8 ft (243.48 cm) then the outer edge, E, is:
$\tan q° \times 243.48 \text{ cm} = E$; and finally the thickness, T, is:
$\sin q° \times E = T$;

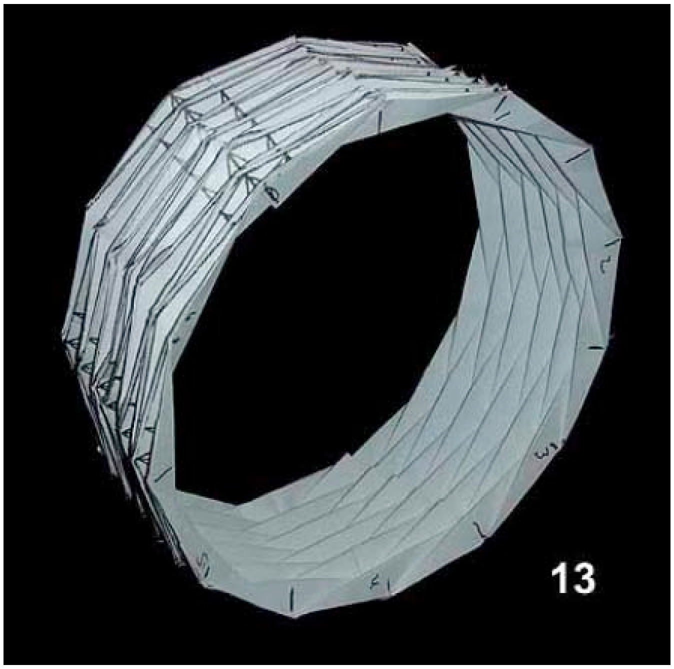


Figure 19. Origami thirteen-sided (13) folded structure model.

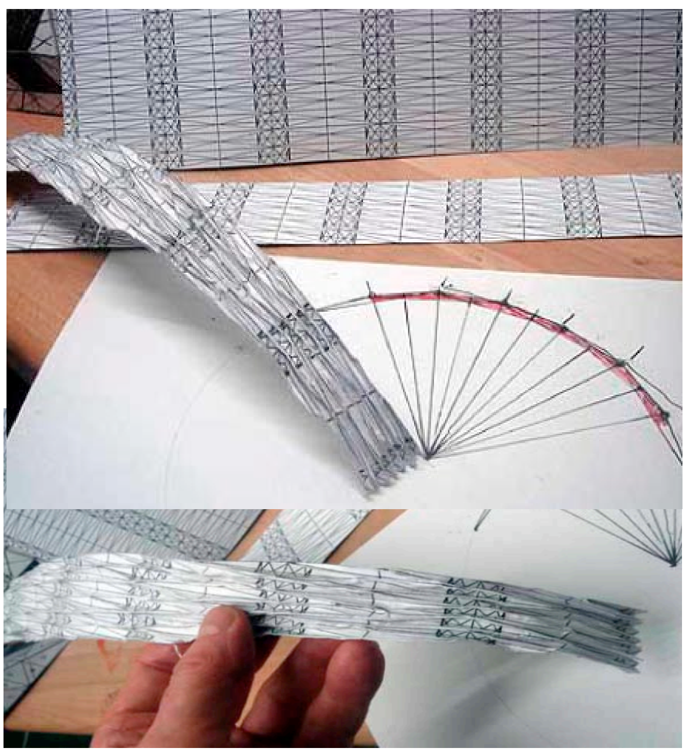


Figure 20. Origami twenty-sided (20) folded structure model, which indicates the complexity and difficulty of folds.

Origami / Foldable Structures (continued)

Origami Folded Structures Calculations:

The following show results for 12, 20, and 8 edge structures.

12 edges:
360°/24 = 15°; tan 15° x 243.48 cm = 65.24 cm; sin q°x 65.24 cm = 16.88 cm. The inner diameter of the folded structure is then **209.7 cm** (243.48 – 2 x16.88 = 209.7 cm).

20 edges:
360°/ 40 = 9°; tan 9° x 243.48 cm = 38.56 cm; sin 9° x 38.56 cm = 6.0 cm**.** The inner diameter of the folded structure is then **231.48 cm** (243.48 – 2 x 6.0 = 231.48).

8 edges:
360°/ 16 = 22°.5; tan 22°.5 x 243.48 cm = 100.85 cm; sin 22°.5 x 100.85 cm = 38.59 cm. The inner diameter of the folded structure is then **166.29 cm** (243.48 – 2 x 38.59 = 166.29 cm).

The trade study and calculations show that 12-sided dodecagon is optimal compared to the 20-sided and 8-sided geometry due to the relation between outer and inner diameters, which depends on T, thickness of the fold. For the 20-sided geometric structure, a thickness of 6 cm is not practical because of the number of folds required and the limited thickness. For the 8-sided geometric structure, a thickness of 38.59 cm reduces the inner diameter by more than 30% in relation to the outer diameter, therefore, too much interior volume of the folded structure is lost for storage purposes.

In the process of building the models, more detailed geometrical analysis reveals that a 12-sided folded structure aligns with a 13-sided geometry when folded due to the fabric thickness. The material thickness and properties folds naturally to align in this manner. This analysis points to the possibility of slightly changing the geometry in order to account for specific materiel thickness. In this example, instead of using 360°/24 = 15°; we would use a geometric design of 13°- 14° and to be able to fold it more easily into a stiff frame or enclosure.

Composite Materials Research

Materials: Textile Composites

Composite materials have been used to greatly enhance the properties and behavior of products, and are desirable for space applications. Advanced composite materials are ideal for use in products that are necessarily lightweight and require high strength performance. The Extreme EXPeditionary Architecture (*EXP-Arch*) project proposes to develop an adaptable, mobile architecture that will utilize composite textile materials, therefore, an extensive literature review was performed on textiles and advanced materials.

Bunsell and Renard (2005) outline the overall process of composite manufacturing in the following steps: starting materials, impregnation of fibers by the matrix material, preparation of the quantity and dimension of composite material to be used, processing of the composite, cross-linking of thermosetting resin matrix systems, removal of finished composite, and quality control of composites.

3D Braided Fabrics. Braiding of fibers is a relatively simple and cost effective approach to manufacturing composites. 3D braided fabric is constructed by intertwining two sets of yarn to form an integral structure. The orientation of the braider yarns is at approximately 45 degrees. NASA Langley Research Center scientists computationally analyzed the stress-strain behavior of braided fibers (Poe *et al*., 1997). Some of the applications of 3D braiding have been in the area of rocket engine nozzles and nose cones for commercial use. Other applications for this textile patterning are: lightweight bridge decks, propeller blades for the navy, propulsion shafts, and an array of medical devices. Even though braiding is a very versatile textile pattern, the current commercial use is still limited. There is also limited understanding regarding the effect of braiding structure and material choice on the mechanical behavior of the composite. Another braided structure is identified as the diamond braid. Diamond braid testing revealed significant tensile tests differences in mechanical behavior between continuous and discontinuous braided specimens (Aggarwal *et al*., 2001). Overall, the braiding process offers optimum combination of conformability, drapability, torsional stability and structural integrity (Wang and Zhao, 2006). 3D braiding techniques are capable of producing highly intricate designs and are easily adapted to changes in patterning style during the fabrication process. The proposed *EXP-Arch* requires strong, flexible, and lightweight materials to allow mobility, compactability, and protection from the space environment, which might be partially realized through braided fabrics.

Stitched composites are another means of textile fabrication. Stitching is the simplest procedure for producing fabric layers with a high-strength yarn developed to produce three dimensional composite components, and can be performed with the smallest investment in specialized machinery (Wang and Zhao, 2006; Poe *et al*., 1997). Even though there is a plethora of possible yarns to implement in to textile patterns, Aramid yarns are the most preferred due to the resilience exhibited during the rough handling that occurs while stitching. The main limitations to Aramid (nylon) materials involve their propensity towards softening through moisture absorption, as well as their lack of versatility for bonding to various polymer resins (Bakis *et al*., 2002; Poe *et al*., 1997; Bunsell and Renard (2005). Stitched components can be fabricated with the simple use of standard industrial stitching machines. For aerospace applications NASA and Boeing have developed a method to stitch reinforced composite materials in advanced aircraft wings. Stitched composite patterning has also been utilized in the fabrication of a Euro-fighter fuselage (Bannister, 2004). The benefit of stitching materials has spread into the realm of reinforcing foam core materials. Webcore technologies, has used a product line of stitched foam core materials. This fiber reinforced foam core product line is called Tycor™. Table 1 compares Tycor to other composites, and the Tycor composite material exhibits the highest strength to weight ratios. The Aztex Corporation uses stitched composites and a special process to fabricate foam structures, called z-spinning. The technique for combining in-plane reinforcement and thickness reinforcement is termed Technical Embroidery. This technique is unique because the embroidery head can be controlled by a computer, and fine-tuned to meet different manufacturing needs. The machines available are capable of stitching along the directions of greatest stress to increase the strength in a particular direction. Relative to other textile fabrication techniques, the use of stitching is by far the most cost effective and simplest process.

Table 1. Comparison of Stitched Composites.

Comparative Performance of Various Sandwich Core Materials						
Product	Density lb/ft³ (kg/m³)	Shear Strength psi (Mpa)		Shear Modulus ksi (Mpa)		Compressive Strength psi (Mpa)
		L (Along Web)	W (Across Web)	L (Along Web)	W (Across Web)	
TYCOR® G6‡ Resin Infused Density	5.5 (88)	261 (1.8)	26 (0.18)	19 (130)	0.8 (5.5)	410 (2.8)
Polypropylene Honeycomb* Dry Core Density	4.8 (77)	72.5 (0.5)	-	1.16 (8.0)	-	188 (1.3)
PVC Foam* Dry Core Density	5.0 (80)	145 (1.0)	-	4.5 (31)	-	175 (1.2)
TYCOR® G18‡ Resin Infused Density	6.5 (104)	448 (3.1)	34 (0.23)	37 (255)	0.9 (6.2)	1095 (7.6)
PVC Foam* Dry Core Density	8.1 (130)	290 (2.0)	-	7.5 (52)	-	360 (2.5)
End-grain Balsa* Dry Core Density	9.4 (150)	427 (2.9)	-	22.8 (157)	-	1837 (12.7)

Composite Materials Research

Materials: Textile Composites (cont.)

3D Woven Preforms. Weavings were originally developed for the replacement of high-cost metal alloys for airplane wings. Three-dimensional weavings offer a wide selection of materials. The amount of woven material can be tailored to fit specific mechanical demands such as combinations of in-plane and thickness stresses. These woven fibers are currently restricted to applications requiring minimal shear or torsional performance due to lack of efficient 45 degree fibers (Bannister, 2004). Advantages of weaved material include thickness in the weave, which enhances impact performance, and ease of handling. Woven fabrics can fold out into complex shapes, and could be useful for the *EXP-Arch* project. Examples include the Beech starship with its "H" woven configuration, and implementation in to Lockheed Martin's F-35 fighter plane. Three dimensional woven textile processes have the fastest production rates, but further research is needed in connections between structural and mechanical properties.

3D Knitted Composites. This process is relatively new in textile fabrication. There is a limited understanding of 3D knitted composites compared to the three previous techniques. In certain cases, glass fabric and knitted carbon are primarily used. 3D knitted composite fabrics are highly flexible and conformable. The disadvantage of this technique is the low performance in mechanical behavior. 3D knitted composites have yet to be established within the commercial sector, but have shown potential for major development. The most commonly understood knitted products are clothing, apparel, and other nonstructural items. This is due to the structural design of the knitted pattern, which consists of curved threading. There are advanced industrial knitting machines available with the ability to fabricate intricate knitted structures at high speed and efficiency. These machines are also able to incorporate segmented fibers in any chosen area of the fabric, and Bannister (2004) mentions the production of a car wheel well for an electric vehicle, which might be applicable for the *EXP-Arch* pressurized rover design concept. In sum, the advantages and limitations of various textile processes are reported in Table 2.

Table 2. Advantages & Limitations of Composite Textile Materials.

Textile Process	Advantages	Limitations
2D Woven Fabric (baseline)	Good in-plane properties Good drapability Highly automated perform fabrication Integrally woven shapes possible Suited for large area coverage Extensive database exists	Limited tailorability for off-axis properties Low out-of-plane properties
3D Braided Preform	Good balance in in-plane & out-of-plane properties Well suited for complex shapes	Slow perform fabrication process Size limitation due to machine availability
Stitching	Good in-plane properties Highly automated process provides excellent damage tolerance and out-of-plane strength Excellent assembly aid	Small reduction in in-plane properties Poor accessibility to complex curved shapes
3D Woven Fabric	Moderate in-plane & out-of-plane properties Automated perform fabrication process Limited woven shapes possible	Limited tailorability for off-axis properties Poor drapability
Multiaxial Knitting	Good tailorability for balanced in-plane properties Highly automated perform fabrication process Multi-layer high throughput material suited for large area coverage	Low out-of-plane properties

Space Environment Effects on Materials

The impact of the harsh environment of space on exposed materials was investigated due to the high relevancy to mission completion, vehicle and hardware/software reliability, and astronaut safety. An update on research on material utilization for air and space environments was completed and is included in this section. One recent study reviews results for 12 different materials tested for shielding for deep space missions, and then more detailed reviews are given for polymeric matrix composite materials, carbon/epoxy composites, atomic oxygen and polymer surface interaction, and piezoelectrics.

Mansur *et al.* (2005) recently assessed shielding material performance for deep space missions. Investigators evaluated 12 different materials for their deep space usefulness. The twelve materials included: high density polyethylene foam, low density polyethylene foam, low density polyethylene monolith, Kevlar fabric, spectra fabric, zylon fabric, spectra epoxy, spectra shield, zylon/PVB phenolic, IM 7/Epoxy, Epoxy, and low density polyethylene. Galactic cosmic rays (GCR) are common in the deep space environment, and can inflict serious material damage. Typical spacecraft materials, i.e., aluminum, are deemed inadequate for the shielding against galactic cosmic rays. Mansur *et al*. conclude that materials containing high proportions of hydrogen and other low atomic mass nuclei provide improved GCR shielding. Polyethylene is identified as having excellent shielding performance properties for deep space applications. Preliminary results show that of the materials analyzed to date, the low density carbon fiber monolith and low density carbon foam, each infiltrated with polyethylene, were the next most effective shielding compared to the polyethylene reference material.

Composite Materials Research
Space Environment Effects on Materials

Harris *et al.* (2001) assessed **polymeric matrix composite materials** for large airframe structural components, including surveying 56 people and 32 organizations that were directly involved in the design, fabrication and supportability of the composites. The results from their survey include:

1. Design and certification requirements for composite structures are generally more complex and conservative than for metallic structures.
2. Successful programs have used the building-block approach with a realistic schedule that allows for a systematic development effort.

    This approach simplifies complexities in manufacturing by relying on tests of elements and sub-components to establish the effects of details and internal load paths on structural behavior. Development tests address manufacturing scale-up issues, which is crucial in the manufacturing of composite structures. It is extremely challenging to accurately scale-up the curing kinetics to large-scale fabrication.
3. The use of basic laminates containing 0/90/+45/-45 plies with a minimum of 10% of the plies in each direction is well suited to most applications.
4. Mechanical joints should be restricted to attachment of metal fittings and situations where assembly or access is impractical using alternative approaches.
5. Large, co-cured assemblies reduce part count and assembly costs, but may require complex tooling.
6. Understanding and properly characterizing impact damage would eliminate confusion in the design process and permit direct comparison of test data.

Harris *et al.* identify limitations of the manufacturing process for advanced composites. For space applications, the establishment of standards for characterizing impact damage is highly recommend. The building block approach is useful in manufacturing the complex configuration of advanced composites desired in space applications.

Carbon/Epoxy composites were studied, specifically the effect of proton radiation on their mechanical properties. Hu *et al*., (2006) tested different mechanical properties after exposure to radiation for AG-80 epoxy resin and unidirectional M40J/AG-80 composites. Increased cross-linking density was found for the epoxy resin when subjected to 120-KeV protons. This in turn, increases the bend strength and the modulus of the composite. The 120-keV proton irradiation leads to random changes in mechanical properties of the M40J/AG-80 composite, including bend strength and modulus, as well as interlayer shear strength. Continuing to increase the energy density tends to decrease these properties. The interlayer shear strength shows a similar trend. As for the cross-linking density of the polymer, added heat energy will affect the amount of bond stiffness. The cross-linked bonds of the polymers are known to be the strongest bond next to the carbon-carbon bonds in the main chain structure. This change in crosslink density will change the crystalline percentage within the polymer structure. The percentage in simple terms is the amount of organization and stability in the polymer chain. Crystalline versus amorphous polymer chains are analogous to rope ladders versus bundles of single rope.

Chen *et al.* recently investigated the interaction between **atomic oxygen and polymer surfaces** in Low Earth Orbit (2006). Their **interaction potential model** for an incoming particle impacting a polymeric material surface was developed and applied to estimate the reactive probability and energy accommodation coefficient for Kapton, a very versatile polyimide film. Kapton has a useful temperature range of –296 to +400 ^{o}C. The reactive probability combusted by Chen *et al.'s* model was 16.8% less than experimental flight data from Space Shuttle STS-46, whereas the value of the EAC computed with Chen's model lies in the range between the value using the hard-sphere model and experimental data. Numerical experiments confirm the law of dependency of the reactive probability upon the incident angle deduced from the flight experiments. Different cosine power laws for the dependency of EAC upon the incident angle characterized by different powers between incoming particles impacting the polymer surface and the metal surface were also been found. This research is useful in revealing the probability density of interaction potential for space materials. Data obtained from simulation can be used in planning various material use and frequency of maintenance during missions.

Piezoelectrics show promise for space applications, especially for actuation, valves, and low profile health and status monitoring. Bowen *et al.* (2006) recently described the process of manufacturing and characterization of piezoelectric fibers. Comparisons were made between piezoelectric fibers that were in high and low electric fields as well as those commercially available at present. The research concluded that piezoelectric fibers manufactured via polymer processing techniques had superior properties to fibers from other fabrication processes.

Composite Materials Research

Space Environment Effects on Materials (cont.)

Piezoelectrics (cont.) Highly sensitive piezoelectric materials are important for the application of health monitoring for vehicles, spacecraft, and humans. High piezoelectric values allow for greater efficiency in detecting mechanical strains. Current areas requiring further study include: effect of radiation, extreme hot and cold temperature cycles, miscellaneous space debris impact, and atomic oxygen exposure. Celina *et al.* (2005) investigated piezoelectric materials performance and operational limits for the space environment. The different simulated space conditions tested were temperature, strong ultraviolet (UV) exposure, and atomic oxygen. Results focus on the change in hysteresis, and the change in d_{33}, which is the piezoelectric charge constant. The piezoelectric constant is the relationship that links the mechanical strain values with electrical energy values. When this constant changes, the effective mechanical-electrical energy conversion changes as well. The term hysteresis is the lag between an applied condition to a resulting condition. In the context of this study, hysteresis is the delay between the applied mechanical energy and the converted electric energy. Effects of UV exposure appeared to be minimal, in spite of damage to the polymer chain structure, the piezoelectric properties were maintained. Thermal exposure has been noted as the single most important factor in changing piezoelectric properties. Results also implied that radiation exposure created defects within the polymer structure. This was observed through changing melting points. Atomic Oxygen exposure is linked to the severe erosion of the polymer structure without changing the piezoelectric properties.

In general, limited information on vacuum UV polymer material absorptivities, degradation mechanisms and failure doses is available. It appears that one of the key issues in assessing LEO ultraviolet exposure and damage is the correlation of total sun hours with material radiation sensitivities and degraded changes. These relationships need further investigation to improve LEO lifetime predictions.

References

Bunsell, A.R., and Renard, L., (2005), Fundamentals of Fibre Reinforced Composite Materials, Institute of Physics.

Poe, C.C., Jr., Dexter, H.B., and Raju, I.S., (1997) "A Review Of The NASA Textile Composites Research", AIAA, 1126-1138.

Aggarwal, A., Ramakrishna, S., Ganesh, V. K., (2001), "Predicting the In-plane Elastic Constants of Diamond Braided Composites", *Journal of Composite Materials*, 35: 8, 665-688.

Wang, Y., and Zhao, D. (2006). "Effect of Fabric Structures on the Mechanical Properties of 3-D Textile Composites", *Journal of Industrial Textiles*, 35(3): 239-256.

Bakis, C.E., Bank, L.C., ASCE, F., Brown, V.L., ASCE, M., Cosenza, E., Davalos, J.F., ASCE, A.M., Lesko, J.J., Machida, A., Rizkalla, S.H., ASCE, F., and Triantafillou, T.C., M.ASCE, (2002) "Fiber-Reinforced Polymer Composites for Construction—State of the Art Review", *Journal of Composites for Construction*, 6(2): 73-87.

Bannister, M.K., (2004) "Development and application of advanced textile composites", IMechE, 218.

Mansur, L.K., Frame, B.J., Gallego, N.C., Guetersloh, S.B., Johnson, J.O., Klett, J.W., and Townsend, L.W., (2005) "Assessment of Shielding Material Performance for Deep Space Missions", *Materials research Society Symposium Procrement,* 851.

Harris, C. E., Starnes J.H., and Shuart, M. J., (2001), "An Assessment of the State-of-the-Art in the Design and Manufacturing of Large Composite Structures for Aerospace Vehicles", NASA.

Yu, G., De-zhuang, Y., Jing-dong, X., Shi-yu, H., and Zhi-jun, L., (2006) "Effect of proton Radiation on Mechanical Properties of Carbon/Epoxy Composites", *Journal of Spacecraft and Rockets*, 43: 3, 505.

Chen, L. and Lee, C., (2006) "Interaction between Atomic Oxygen and Polymer Surfaces in Low Earth Orbit", *Journal of Spacecraft and Rockets*, 43: 3, 487-496.

Bowen, C.R., Stevens, R., Nelson, L.J., Dent, A. C., Dolman, G., Su, B., Button, T. W., Cain, M. G., and Stewart, M., (2006) Manufacture and characterization of high activity piezoelectric fibres, *Smart Materials and Structures*, 15: 295-301.

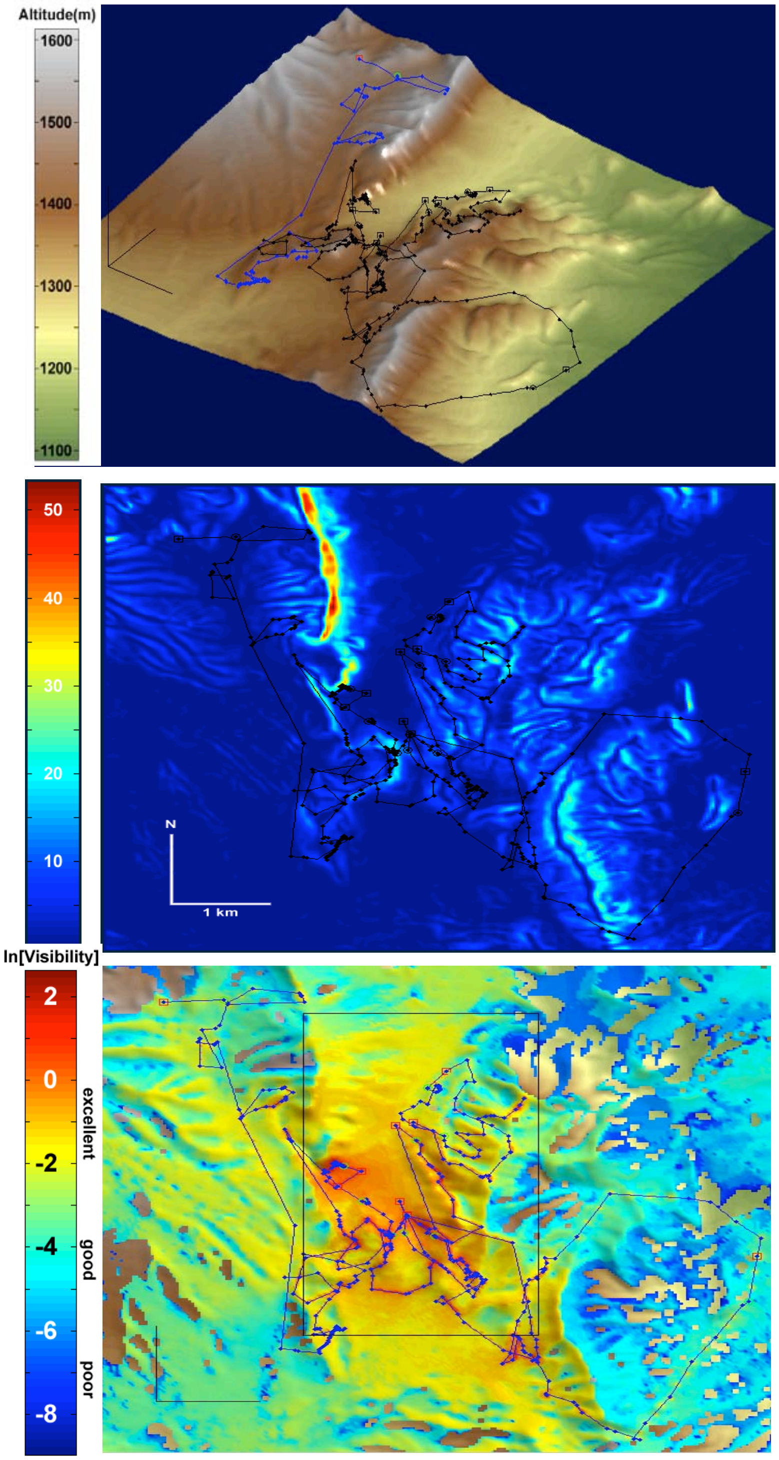


Figure 21. Example *EXP-Arch* mission traverse planning strategy. Top. Illustrative topographic map showing elevations and multiple traverses. Middle. Exploration slope analysis (in degrees) for various traverses. Bottom. Visibility map for multiple exploration traverses showing the best visibility.

EXP–Arch Educational Outreach Rhode Island School of Design Studio

Trotti & Associates, Inc. (TAI) contributed to a Design Studio at the Rhode Island School of Design (RISD), Industrial Design department. The Studio is headed by Prof. Michel Lye and is funded by the Rhode Island Space Grant and RISD. The students completed their Fall studio work and a final presentation was given during an all day design review on December 14, 2006. Many exciting concepts were presented. A final report is being prepared showing the results of the studio and will be included in the final report of the Extreme EXPeditionary Architecture (*EXP-Arch*) Phase I project.

Gui Trotti (TAI), former astronaut Dr. Jeff Hoffman, Prof. Dava Newman from MIT, Designer Cam Brensinger (NEMO Equipment), and Dr. Mitch Joaquim along with members of the *EXP-Arch* Advisory Board Ted Bakewell and Einar Thornstein participated in the the final studio review. Two TAI RISD student interns (Shaun Modi and Santiago Alfaro) who are receiving course credit for their participation in the *EXP–Arch* project were also present during the studio review, and have worked on the project for the past 4 months.

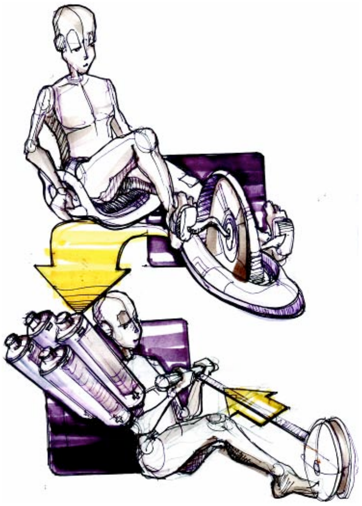
An emerging educational outreach idea is to have students design and operate rovers and participate in a lunar “Pole-to-Pole Challenge”. Imagine multiple lunar mini vehicles racing from Pole-to-Pole, visiting past Apollo sites, testing autonomous systems, and human teleoperation capabilities. The race can also serve as a testbed for real-time lunar path planning and navigation, and to be scaled up to the *EXP-Arch* human expedition concept.

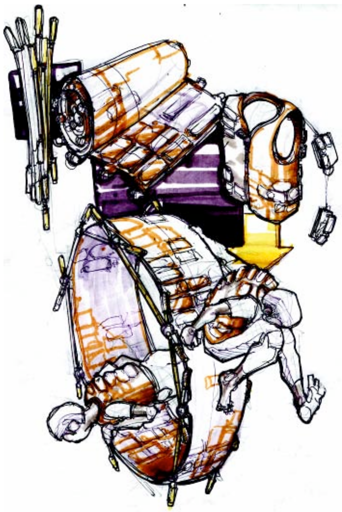
An Advisory Board design review and meeting was held on December 15, 2006 at the TAI studio. *EXP-Arch* project progress and updates were given followed by a design discussion to finalize overall mission architecture and the inflatable structures concepts. Mission traverse planning was discussed, topographic maps were illustrated (See Fig. 21), resulting in a collaboration with MIT.

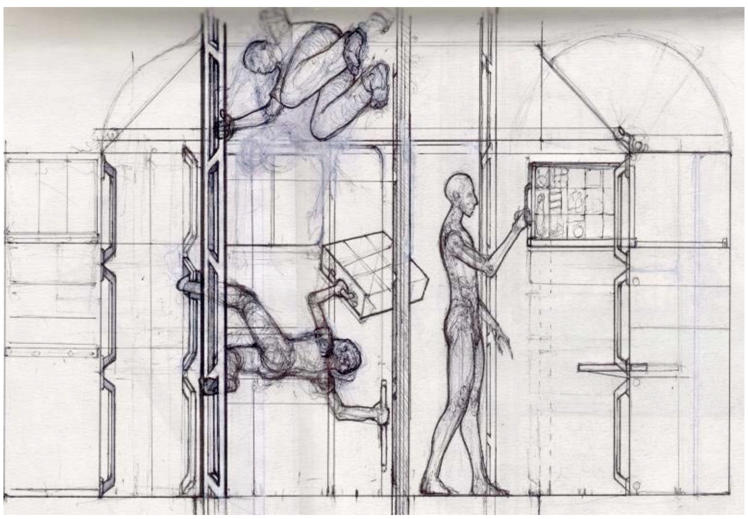
EXP–Arch Future Work

In the next two months we will continue further research in, deployable structures, power systems, radiation protection, and we will further detail the mission architecture. The TAI team will also complete the design of the entire *EXP–Arch* rover interior layout, further develop the deployable structure concepts, and further design the geometry of the wheel and suspension systems. Deliverables also include the final RISD design studio concepts.

Fall 2006







Rhode Island School of Design Studio "Design for Extreme Environments"

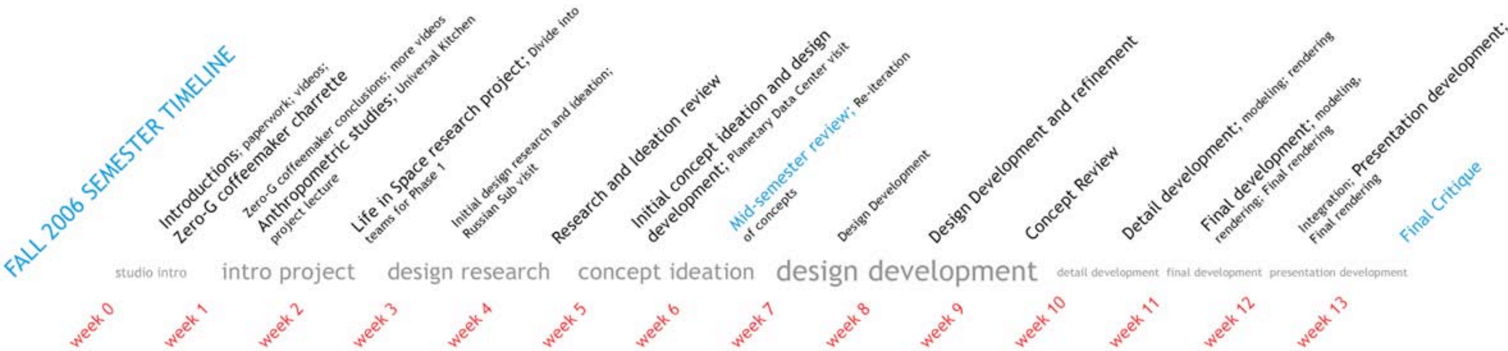
Introduction

Over the past 13 years, the Industrial Design department at the Rhode Island School of Design (RISD) has offered a series of interdisciplinary studio classes based on a general theme of "Design for Extreme Environments". These studios teach design through the constraints imposed by extreme environments, highlighting the design process with an unparalleled emphasis on the user.

The courses have been created to explore the application of innovative design for the physical, emotional and psychological needs of the astronauts, and hence allow students to use skills developed during these studios on future projects, whether non-terrestrial or terrestrial. The subjects for these studios have included micro-gravity exercise equipment and astronaut restraints to digital electronic medical assistants for use on long duration missions to lunar habitations and mobile exploration vehicles among many others.

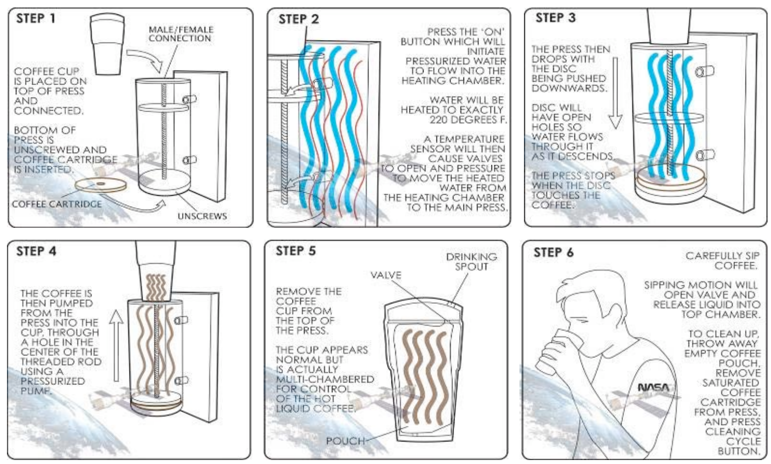
Studios like these fit into the long tradition at RISD of teaching universal and socially responsible design, as a means to emphasize a uniquely human perspective on design and design methodologies. The students' emphasis in the RISD/NASA studios is to design beyond survivability and to strive to incorporate a more human approach in their visions for space and other non-terrestrial design.

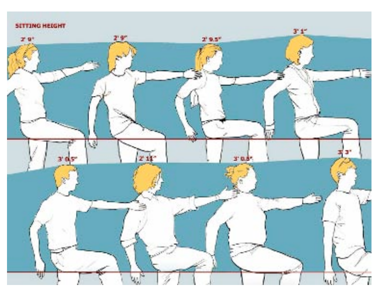
The over 150 students that have been part of this studio at RISD have come primarily from the Industrial Design (ID) department but have benefited greatly from the presence of students from other departments and with other backgrounds. Students from the Architecture and Interior Architecture programs have joined the ID students when working on many of these projects. This interdisciplinary environment offers a diversity of perspectives and problem-solving approaches, ultimately assisting the students to find more of the best solutions.

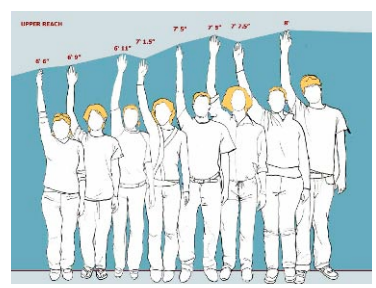


Studio outline

In the fall of 2006, fifteen students enrolled in the RISD Industrial Design department's advanced studio class, "Design for Extreme Environments." At the beginning of the 12 weeks the students were introduced to designing for non-terrestrial environments with a design charette for a Zero-G coffeemaker. Additional research projects emphasized anthropometrics and human-factors, as well as lunar and micro-gravity environments with presentations by Peter Neivert of the Planetary Data Center at Brown University and Peter Schultz, Professor of Geological Sciences and Director of the Rhode Island Space Grant.







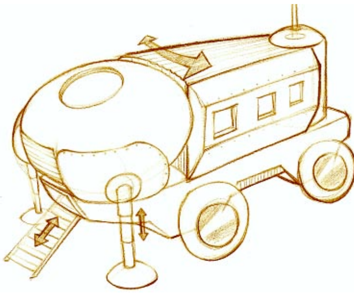
Although human factors and ergonomics are areas of expertise in their own rights, it is very useful for designers to have a basic fundamental understanding of these factors. A design cannot be completely successful if it does not take into account the fact that the people that will interact with design are not all the same. This project looks to quantify just a few aspects of the variability of humans, so that students may begin to understand the wide range that design must accommodate in space as well as here in our everyday lives.

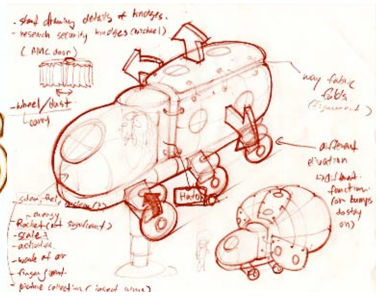
After the initial research and short projects were completed, the remaining eight weeks were dedicated to the main projects of the semester. This semester students had an opportunity to select between two main projects. One of the projects focused on the design for a proposed Lunar Surface Access Module (LSAM) Ascent Stage. The other was the Extreme EXPeditionary Architecture project. These two projects, though distinct, were closely related. Although both projects were based in the lunar environment, a more significant similarity was the design approach taken by both.

Students approached the design of habitats and spacecraft from the inside out, by beginning with the astronauts that would inhabit the craft rather than allowing the designs to be driven primarily by the technology and engineering requirements.

This human-centered design approach, a crucial element of the education at RISD, focused first on the needs of the people, the astronauts that would be using the vehicles, while meeting all the demanding technological and engineering demands required in the extreme environments of space and the lunar surface.

Project details





In the fall semester of 2006, ten students worked with Guillermo Trotti of Trotti & Associates, Inc. (TAI) on the Extreme EXPeditionary Architecture (EXP–Arch) project, to develop an "adaptable, mobile architecture capable of meeting a variety of space and earth missions." Working within the framework of EXP-Arch, the students were asked to design "self-mobilizing, transformable systems combining robotics, deployable lightweight structures, intelligent materials, combinatorial geometry (mathematical origami), and self-erecting systems for human and machine exploration."

The students in the studio focused on the design of mobile expeditionary habitats, as a primary element of the larger system. Beginning with research into the basic requirements for lunar habitats and the tasks and activities which astronauts would conduct on the lunar surface, the students began generating concepts for the habitats. The student projects, while conceptual in nature, needed to meet the basic "real world" engineering demands required by the EXP-Arch project.

In order to begin to better understand what life in a small, enclosed environment, such as a lunar habitat, might be like, students visited a Russian submarine berthed in the Providence harbor. This Cold War era sub, part of a naval museum, afforded the first-hand experience of an environment that is a close terrestrial analogue with similar structural and environmental concerns, to a lunar habitat. One difference from proposed lunar habitats was the size of the crew. Rather than the 60-80 sailors aboard the sub, the lunar habitats were designed to accommodate a nominal compliment of four astronauts.

To help students intuitively understand the volumes four astronauts might need, students built quick, full-scale study models (basic cylinders) out of corrugated cardboard based on their own estimates of volumes needed for four, eight, or twelve hour stays in a "habitat." Teams of four students then spent a minimum of four hours, though in some cases much longer, inside their structures. These rapid volumetric studies allow designers to quickly experience space in three-dimensions, helping them understand issues of scale, reach and space in ways a two-dimensional drawing or scale model could never allow. As the semester progressed, the benefits of cardboard, low-cost and easy workability, also allowed for the very rapid iteration of new ideas and solutions, each iteration providing additional feedback and inspiration.

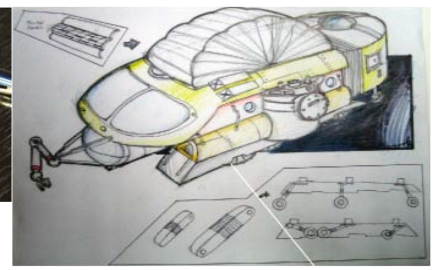
Student Projects

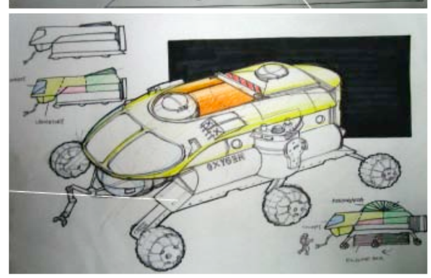
Myung Hwan Kim: Design for a self-mobilized, lightweight, quickly deployable lunar habitat - one element of a larger exploration architecture for extreme environments.

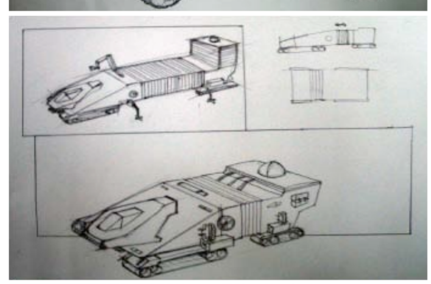
This habitat incorporates a top-mounted expandable sleeping loft, an axially expanding mid-section, as well an expandable airlock.

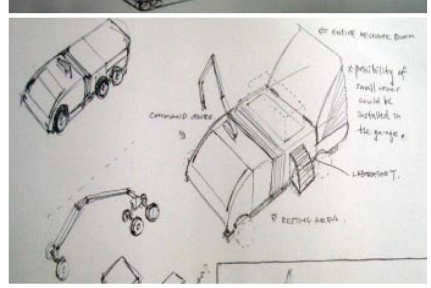
In it's normal configuration, the airlock is just large enough for EVA suit stowage and only expands to accommodate the astronauts during ingress, egress, or for EVA preparations.

This vehicle was inspired by collapsible structures such as accordions, folding fans and CD holders, as well as by insects such as the pill bug.

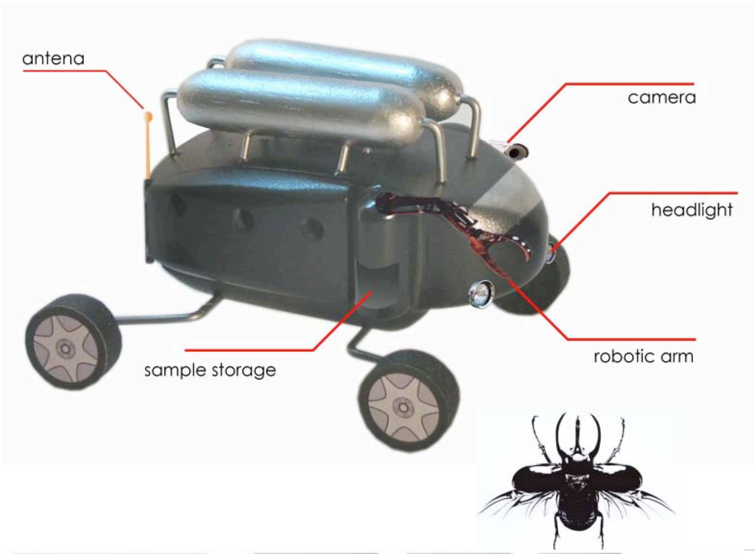








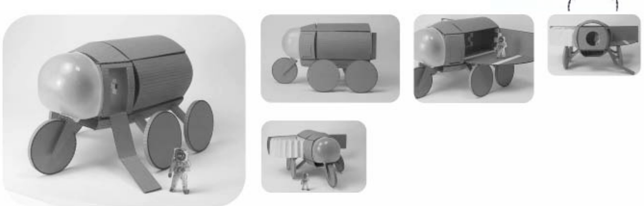
These early small-scale cardboard models explore configurations, suspension and expansion options for a mobile lunar exploration habitat.



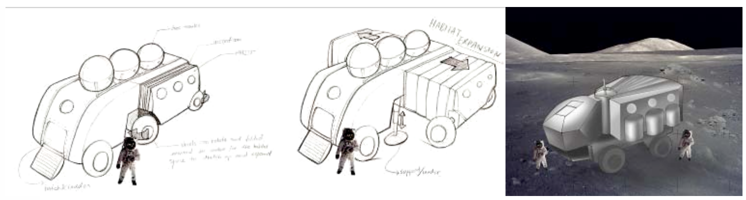
Student Projects

Eugene Suh: Mobile Habitat inspired by the wings of beetles.

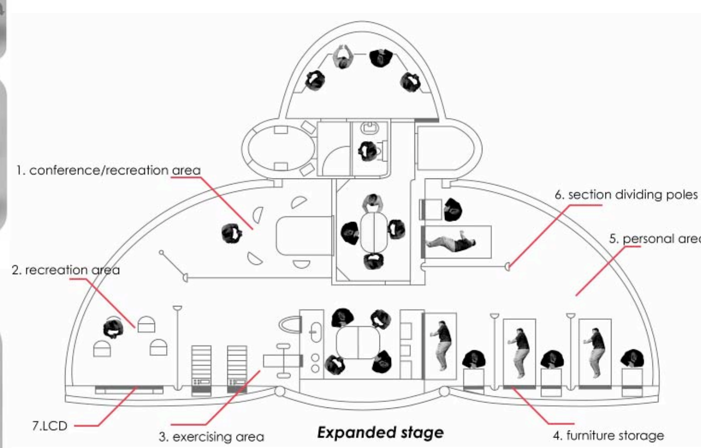
This mobile habitat features “wings” that unfold from the rear of the structure significantly expanding the usable living and working space. The habitat would be accompanied by a smaller independent rover that could carry one astronaut or be operated remotely or autonomously. A solid front portion would contain the cockpit, airlock and hygiene areas. The galley and some lab space would be contained in the mid-deck. The collapsible spaces would include the sleeping, recreation,additional working and conference areas.



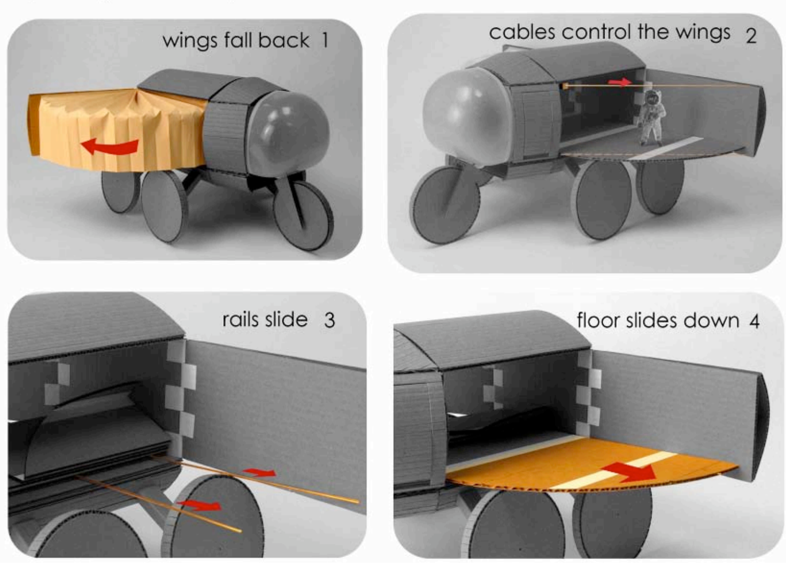
Main Rover with Habitat

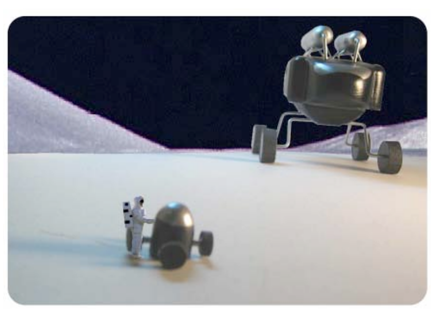


Expandable Independent Rover

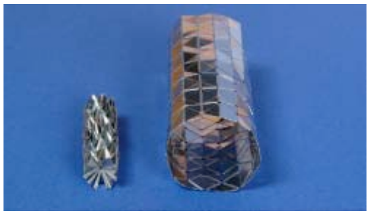


expanding for habitat process





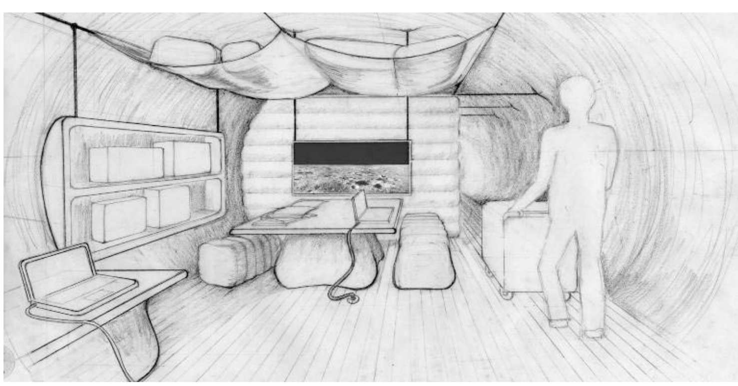
Design Inspiration: Origami Stent Graft



Geometrically simple, cylindrical structure
Predictable folding pattern
Good ratio of collapse to expansion

Origami techniques for compact folding of lightweight materials.

Transformation of two-dimensional surfaces into three-dimensional forms with structural integrity

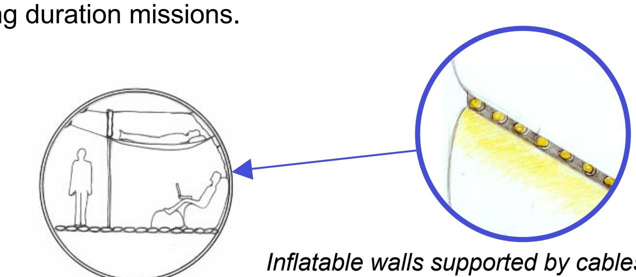


Student Projects

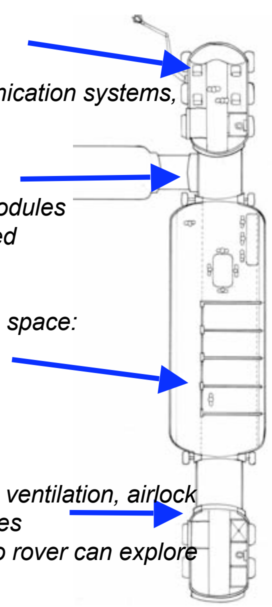
Elizabeth Thelan: Origami inspired Folding Structure studies.

These studies explored origami as inspiration for a folding structure. The design considerations and goals for the project were to create a simple, integrated collapsible structure, which allowed for deployment without the need for an EVA. The principles of origami would help to achieve a high structural efficiency – a good ratio of collapse to expanded volume – and a very lightweight, foldable form.

When used as an integral part of a habitat, the folded structure would give flexible space to accommodate various living scenarios. It would help to achieve a feeling of expansive space while providing for work, living and exercise space. The high ratio of expansion would also allow for extra personal space for astronauts, essential for long duration missions.



Inflatable walls supported by cables
Acoustical inserts increase privacy in personal spaces
Ambient light provided by LEDs integrated into fabric



Rover - contains core functions:
- *Cockpit and expandable airlock*
- *Power, plumbing, ventilation, communication systems, basic hygiene*

Expandable connectors:
- *Create circulation spaces between modules*
- *Enable additional modules to be added*

Inflatable Habitat - provides expandable space:
- *Work space for crew*
- *Private space for each crew member*
- *Exercise space*

Caboose - supports habitat:
- *Provides redundant power, plumbing, ventilation, airlock*
- *Expanded hygiene and kitchen facilities*
- *Enables habitat to be self-sufficient so rover can explore or escape during solar storm*

"The best way to have a good idea is to have lots of ideas" - Linus Pauling

Design is not a perfectly linear process. It can at times be messy, convoluted and yet still surprisingly effective. The design process may include brainstorming, library and web research, mind-mapping, ethnography, two- and three-dimensional sketching, among other techniques needed to find inspiration and ideas. As ideas are generated they may raise new questions or suggest new perspectives from which to examine or to define a problem.

Design is an iterative process. Each attempt at a solution may suggest new problems or new opportunities. Some of these may lead away from the final direction but be valuable in another context. Through reexamination and reiteration ideas evolve and become stronger. A more diverse set of ideas will ultimately allow for the best ideas to be developed.

This studio would not have been possible with out the support of Mickey Ackerman, Industrial Design Department, and Guillermo Trotti. It was funded in part by the Rhode Island Space Grant Consortium – Peter Schultz, Director, and by the Rhode Island School of Design.

"The students want to focus on how removed the astronauts are, and how they feel disconnected, and they are trying to find ways to reconnect them. And they sit down and really try to put themselves in that place."

-Mickey Ackerman, RISD - Industrial Design Department Head

Although only the work of a few of the students is featured here, this project would not have been possible without the efforts of all of the students that were involved with it: Keith Archer, Hyung Yun Choi, Amy Chuang, Rachael Gordon, Myung Hwan Kim, Kris Lee, Juan Martinez, Irene Noh, Eugene Suh, Elizabeth Thelen.

Michael Lye – Design for Extreme Environment Instructor

Special thanks to: Dr. Jeff Hoffman; Dr. Dava Newman; Cam Brensinger; Dr. Mitch Joaquim;Ted Bakewell; Einar Thornstein; Trish Mullen; Shaun Modi; Santiago Alfaro; Kevin Gallagher; Khipra Nichols; RI Space Grant consortium and Peter Schultz; Dorcas Metcalf; all the NASA personnel that have helped - particularly Janis and John Connolly; and all the students over the years who have committed their minds, hands and hearts to this studio.