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Expandable Habitat Technology Demonstration for Lunar and Antarctic Applications

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ABSTRACT

NASA's vision for Space Exploration includes a long term human presence on the surface of the moon and missions to Mars. In support of these missions, habitation structures will be developed to support operations in these challenging gravitational environments and maximize safety and comfort to the crew. One class of structures that is under study is expandable structures because of their mass and stowed volume efficiency. These structures follow the natural paradigm of exploration that has been observed for centuries. An expandable technology demonstration unit has been constructed and is being tested in the lunar analog environment of Antarctica, over several years. The habitat has yielded test data regarding transport and deployment, sensor integration, reconfigurability, habitability, performance in harsh environments, radiation shielding and dust mitigation. Data from these tests is being used by NASA to support lunar architecture studies. Performance data from this work is also being studied by the National Science Foundation (NSF) Office of Polar Programs (OPP) to determine if this class of structures can improve mission efficiency in polar exploration.

INTRODUCTION

Under the Vision for Space Exploration, NASA has outlined four tasks necessary to return to the moon in 2018, one of which is to develop a reference lunar exploration architecture concept to support sustained human and robotic lunar exploration operations[1]. To this end, NASA is considering the use of pre-fabricated expandable structures as part of the architecture to capitalize on their potential for volumetric efficiency for launch & landing (Figure 1). NASA is also studying pre-integrated (hard shell) structures and in-situ structures such as caves as probable structural options[2]. Requirements for habitation on the lunar surface include maximizing usable space while minimizing weight and packed/launch volume, and remote deployment. Maximizing the ratio of packed volume to deployed volume of the structure will optimize operability and affordability by reducing the number of launches required to deploy the same volume of living space. The use of expandable structures offers larger living volume per crew per launch, and system mass reduction through more efficient filling of launch vehicle fairings and structural reductions due to the greater amenability of expandable structures to rugged launch environment.

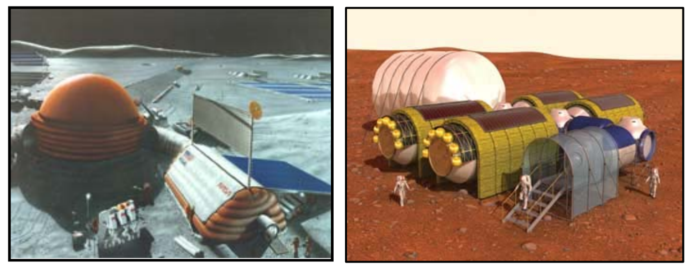

Figure 1 – Examples of expandable structures on the lunar and Mars surface NASA studied in the Space Exploration Initiative and Constellation Programs

The National Science Foundation (NSF) has objectives in their Antarctic Program which are similar to NASA's lunar exploration objectives. Scientific teams performing research in the Antarctic environment require protection from the harsh and unpredictable climate. They need shelters which are easily transportable and mass efficient. Currently, tents (Scott, dome, etc.) or rigid framed deployable shelters (Jamesway, Rac-Tent, etc.) consisting of plywood floors, wooden supports and fiberglass/wool insulation are typically employed at remote research sites. These structures represent the range of habitat options and balance transportability with internal volume in their approach.

ILC Dover, in conjunction with NASA and the NSF, has been studying inflatable deployable structures to expand the architectural options available for exploration in lunar and Antarctic environments, through a NASA Innovative Partnership Program (IPP). Within this program, our team has designed and fabricated a technology demonstration structure and tested it in a laboratory environment and in Antarctica to gather information in support of both NASA and NSF objectives (Figure 2).

The IPP was led by NASA JSC, who also developed the sensor and monitoring systems. The NSF provided the test facility, transportation to the site, and personnel to monitor the system in Antarctica (Raytheon Polar Services). ILC Dover designed and manufactured the structure, electrical and pressurization systems. The program duration was approximately one year with the bulk of the manufacturing occurring within 2 months. Program expenditures for the development of the system were shared between NASA and ILC, and NSF supported the deployment of the system through a Space Act Agreement.

Figure 2 – The Expandable Habitat deployed at McMurdo Station Antarctica and Packed Half Unit

Goals and objectives were developed for the program that centered on building our knowledge base of large expandable structures for use in lunar and earth polar environments.

NASA STUDY OBJECTIVES

- Packing efficiency & packing methods
- Shipping/handling (vibration / environmental) survival
- Deployment operability in a gravitational environment and in polar gear (representing space suits)
- Adaptability to uneven and rugged surfaces representing the lunar surface & guying practices
- Reusability and reconfigurability through joining of large components (habitats and airlocks)
- Performance in a harsh environment (cold, UV, flex, crew interface)
- Deployment with integrated electronics (power, lighting, sensors, etc.)
- Remote structural health monitoring over long periods of time
- Internal suspension/attachment of components (electrical, partitions, equipment, etc.)
- Use of in-situ materials for shielding from radiation
- Lunar dust mitigation practices
- Integration & function of windows

NSF STUDY OBJECTIVES

- High packing-efficiency deployable structures performance
- Transportability and set-up under harsh conditions (wind, cold) and in extreme cold weather gear
- Power consumption in the Antarctic environment
- Modularity and reconfigurability
- Long term survivability
- Multiple-use performance
- Damage tolerance and safety
- Simplicity of packing & deployment to reduce personnel required

The expandable structure technology demonstrator was deployed at McMurdo Station in Antarctica by members of the IPP team in January 2008 and will continually be studied in remote through an integrated sensor system, and monitoring by NSF personnel during the year following the deployment. Antarctica is a NASA recognized analog for study of systems for use on the lunar surface. Even though it isn't completely analogous to the lunar environment, it allows the study of several relevant factors to help understand and advance the technology. Among these are system packing, transport survivability, deployment in a gravitational environment while in harsh conditions, human interface while wearing protective equipment, and long-term survival in extreme environments. Having the system in McMurdo also facilitated web-based connection to the integrated sensor systems and on-site personnel to monitor the system over long periods while in harsh environments. Simply getting to the analog deployment site in Antarctica is reservedly comparable to getting to the moon. The advanced planning and preparation the team performed guided the system design and support equipment selection. The team learned a great deal about all aspects of developing, manufacturing, and fielding habitation systems in harsh environments, and found the experience to be comparable to how NASA intends to use the moon as a learning ground for going to Mars.

The expandable demonstration system is comprised of two inflatable habitat halves, an inflatable airlock, doors, windows, an insulation package, sensors & instrumentation, and an inflation system. The habitat halves and the airlock are comprised of thermally welded coated fabric in a series of intersected tubular sections that form faceted inflatable structural arches. Each component is an independent volume that can be connected to adjacent volumes with an inflation port and zippers, thus making the system footprint easily expandable in size. The internal footprint of the habitat is 4.87mx 7.31m. A flexible insulation package is attached to the exterior of the system, including under the floor. Guy lines and ground anchors are used to stabilize the structure in high wind conditions. The inflatable structure is pressurized to 6.9kPa in operation and can withstand a 44.7m/s wind load with the guy lines attached.

The 453kg system packs into two 1.21m x 2.43mx 0.76m packages (4.53 m^3), and provides a living space of 70.8 m^3, yielding a 15:1 packaging efficiency. The flexible nature of the materials allowed the shape of the package to be altered to fit the transport vehicle, such as a Twin-Otter aircraft, to facilitate simple transport. It was transported to McMurdo Station in January 2008 by the

NSF, where it was deployed by a 3 man crew in under 0.8 hours (50 min). The inflation event took 0.17 hr using a standard blower. A low-power compact pressure compensation system was used to maintain the pressure in the inflatable structure over long durations to compensate for pressure decay with permeation or atmospheric pressure changes. The system also has two 1.46kW quartz convection electric heaters, LED light strings, electrical outlets, and the interfaces to attach equipment to the walls.

A series of "regolith holders" were also tested for feasibility during the initial deployment activity. These pockets on the side of the habitat were filled with snow to simulate the addition of a prescribed thickness of regolith to act as a radiation shield on the lunar surface. The pockets performed well and also demonstrated utility in Antarctic applications as storage space, for guy line replacement features, and for water production facilities.

The system will remain inflated in McMurdo through 2008 where it will be studied with a suite of integrated sensors. The sensor system, developed by NASA, uses wireless and wired sensors along with a central data acquisition system which is connect to the internet thus allowing our team to monitor and track system performance during the harsh Antarctic winter. This mirrors the manner in which a lunar habitat would be monitored after its deployment. Many parameters including temperature, pressure, humidity, CO_2 concentration, power consumption, and light impingement will be monitored. The system is also equipped with internal and external web-based cameras to record use activity and allow remote inspection and performance monitoring (Figure 3).

Figure 3 – Internal and External Habitat Web Cameras (Left) and Pictures Taken From Them (Right)

RELATED WORK

There have been numerous projects over the past several decades for the development of expandable habitat structures for use in space and terrestrial applications. This work provided a starting point for the work conducted in this IPP. This paper is not intended to be an all-inclusive study of past work, but some of the efforts most familiar to the authors are presented here to show efforts which influenced the development of the Antarctic Habitat and support the validity of the approach. Numerous other resources are available for study in the areas of expandable space and terrestrial habitation.

SPACE HABITATION

The earliest credible work on expandable space habitats was done by Dr. Werner VanBraun and published in 1946 and enhanced throughout his career[3]. VonBraun recognized the advantage of the collapsible nature of expandable structures early. His work influenced many expandable habitat, tunnel and airlock developments at NASA LaRC and Goodyear Aerospace in the 1960s. The first demonstration of human-rated expandable / inflatable structures in space occurred in March of 1962 when Alexi Leonov performed the first spacewalk by exiting the Voskhod 2 spacecraft through an expandable airlock[4]. Since this event, many single person expandable habitats in the form of space suits have flown in space garnering lessons that have been applied to subsequent habitat efforts.

Modern day work in expandable space structures began with the development of deployable habitat structures lead by Lawrence Livermore in the late 1980s, and supported by ILC[5]. This work created a technology basis that was adopted by the team that developed the NASA lead Transhab project[6]. ILC supported this effort under a space act agreement and assisted NASA JSC in design and manufacturing activities. This work in turn became the basis of design for the work conducted by Bigelow Aerospace. This work was geared towards zero-g applications. It wasn't until the Exploration program was started by NASA, that a lunar habitation structure was manufactured and tested. This work, performed by ILC and NASA LaRC, lead to an expandable demonstrator habitat that began developing data for use in gravitational environments[7]. Perhaps the best known "habitats" are space suits. These single people articulated habitats have given us decades of experience in expandable structures and provide a technology basis for the development of larger structures. Some examples can be seen in Figure 4.

TERRESTRIAL HABITATION

It is important to note that much of the technology used in designing and fabricating expandable space habitats is derived from terrestrial applications. Historical expandable terrestrial structures have also had an impact on the development of structures the NSF uses for polar exploration. Many expandable military habitat structures have been fielded to provide battlefield protection from chemical and biological agents over the past 50 years. The M51 and the more recent M28 systems are a few examples of systems that were designed to operate in harsh environments per MIL-STD-810E. These structures were designed to be easily transportable in their packed state, and robust enough for military use. Numerous similar expandable military shelters have been developed over the past several decades by military sources.

Another recent example of a large expandable structure is the 30.48m diameter SBX Radome that is on a mobile platform in the pacific being used for missile defense. This inflatable structure can withstand category-5 hurricane winds and has a 20 year service life and is used in harsh environments. Examples of several deployable terrestrial structures can be seen in Figure 4.

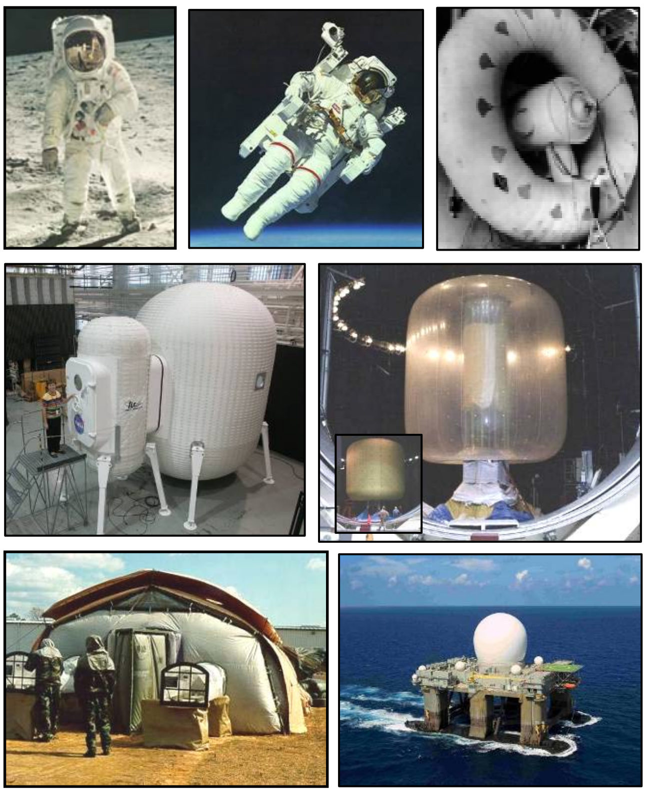

Figure 4 – Habitat Examples (Apollo & EMU Space Suits – single person space habitats, NASA LaRC Toroidal Habitat, ILC InFlex Habitat, NASA Transhab, ILC M28 & ILC SBX Radome)

SYSTEM REQUIREMENTS

The requirements for the Antarctic habitat demonstration structure stemmed from the combined objectives of NASA and NSF for a deployable and habitable structure. NASA'S broad study objectives included field demonstration offloading, positioning and set up of the structure; dual ingress and egress in the structure, feasibility of using local materials for radiation shielding; habitat element leveling, alignment and connection; dust mitigation and integration & function of windows in the structure[8]. A Comprehensive list of requirements was generated with input from NASA and NSF to address all the objectives of the demonstration[9]. The requirements of the system were categorized into requirements of the structure, requirements imposed by operational loads on the structure, environmental requirements and operational/logistical requirements. The critical needs and demonstration features for the system are summarized below in abbreviated fashion.

STRUCTURE

The requirements of the structure included a deployable habitat, airlock and a rear door that could be used as alternative ingress/egress, inclusion of structural feature to enable in-situ materials utilization for radiation protection demonstration or structural stabilization, viable design for incorporation of window(s) in the deployable structure, a consistent insulation included in the structure (walls and floor) that provides a minimum R value of 7 (consistent with the Jamesway habitat). The materials should be easily repairable.

LOAD

The structure will withstand the dynamic loading caused by a wind of 44.7m/s and loads imposed by snow and ice. The structure will withstand a kick load of 56.69kg over an area of $25.80cm^2$ and internal walls of the structure will be equipped with features to support localized loads of at least 1.36kg.

ENVIRONMENT

The habitat and its constituent materials should be able to survive a temperature range of $-50\,^{o}C$ to $8\,^{o}C$, for the duration of deployment (~ 1yr). The habitat's structural performance should not deteriorate during the period of operation. The materials selected for the habitat should be fire retardant, whenever the selection of such a material is applicable. The habitat should not be damaged due to vibrations during shipping and shock experienced due to reasonable handling.

OPERATIONS AND LOGISTICS

The habitat should be designed for easy assembly in the field, disassembly and reassembly to accommodate relocation. The habitat should be designed to survive up to three deactivations and redeployments in the field after the initial set-up. The time required for the deployment of the habitat system should be 4 hrs or less after it has been removed from the shipping containers. The system should be sectioned so as to require no more than four personnel trained in the deployment operations to move and deploy the system. The shelter system sections should have provision to be inflated via an inflation system; either through pneumatic connections between the sections (interconnects) or with separate lines from the inflation source. The habitat should include structural feature to enable electrical outfitting.

SYSTEM DESIGN

The system is comprised of the main habitat structure, and an airlock. The airlock was intended to be a reconfigurable entry airlock from either side of the habitat. However, the system design was altered late in the program to include a larger entry door to facilitate storage of a large submersible robot the size of a small car. The main habitat structure is designed as a bi-modular structure; the two modules are conjoined by means of a multiple-zipper integration system. The doors and larger elements are replaceable and reconfigurable to allow alteration of the system footprint. Figure 5 shows the different components of the habitat system. The entire habitable structure is normally surrounded by a snow skirt extending 1.21m-1.82m from the base of the structure (but was not used in McMurdo because of limited snow cover during deployment). The habitat structure provides a maximum head room of 2.43m and a floor space of 35.67m^2.

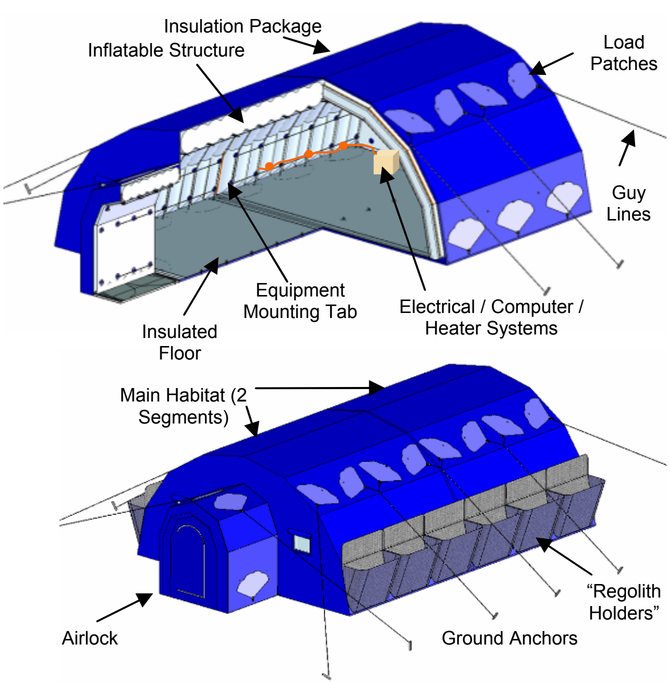

Figure 5 - Overview of the inflatable habitat system

The aspect ratio of the inflatable structure is 1:12. The air lock provides a maximum head room of 1.98m and a floor area of 2.23m^2. The main inflatable structure is covered by a flexible laminate of insulation on the outer side and a layer of liner material on the interior. The liner layer on the inside wall of the habitat is for protection of the inflatable from inadvertent contact and also acts as a fire retardant layer.

The floor of the habitat is the same material used in the inflatable section, but is surrounded by a full insulation layer under it and modular foam floor on top. The foam floor is an industrial flooring material and provides insulation. The outer insulation blanket and the interior liner are indexed to the inflatable wall to preclude the possibility of relative shifting between the three individual layers prior to and during deployment.

The cross-sectional view of structure in figure 5 shows the insulation laminate, inflatable cylindrical sections and the liner. The habitat design also includes inflatable columns for support in the back of the structure. The habitat structure also includes several fan patches to tether guy wires and anchors that serve to stabilize the structure under dynamic loading. The habitat is outfitted with windows that can be covered with zippered localized flaps made from flexible insulation laminate. Numerous mounting tabs are integrated into the interior surface to provide platform for equipment, electrical and sensor outfitting.

CONFIGURATION

Several different design configurations were considered for the habitat structure and a trade study was conducted to guide the selection. The design configuration under consideration included structures with inflatable walls, structures stabilized by air pressure, and structures with rigid but modular wall construction. The critical parameters of the trade study were system mass, packing efficiency, thermal regulation, power consumption and load stabilizing capacity. While the trade study provided an empirical method for ranking different configurations, the final selection was also influenced by contextual analysis of the different configurations.

Based on the trade analysis, the habitat structure with inflatable walls was selected because of its unique mass and volume related advantages absent in some of the rigid or pressurized configurations. A habitat structure deployed by means of inflating its wall warrants a unique floor and door design that further augments the advantages such as high packing efficiency, mass and ease of deployment. Several different configurations were considered for the floor including use of coated fabrics, rigidizable floor, and wood panels, inflatable floor made from drop-stitch fabric and a flexible laminate of coated fabric over insulation material. The lower mass and packing efficiency offered by the insulation laminate made it the obvious choice for floor configuration. A similar trade study was conducted to select the door design. The configurations that were evaluated included sprung overlap flaps, wooden door on hinges, inflatable frame fabric door, hook-to-close flap, zipper door and drop thread door on hinges. The zipper door configuration was selected due to the simplicity of design and operation and the minimal burden on mass and packing efficiency.

STRUCTURE

The main habitat and the airlock were modeled as an inflatable double wall structure with mitered cylindrical sections that approximate a semicircle. Figure 6 shows the details of the dimensions and design rationale for the habitat and airlock also depicts the modeling methodology. The inflatable structure is a double walled structure with a wall thickness of 48.76cm upon inflation. The inflatable structure is designed in accordance with US Army Natick Laboratories Technical Report 69-59-GP, Design Manual for Ground-Mounted Air Supported Structures (Single and Double Wall)[11]. The analysis of dynamic pressure on the structure at a wind velocity of 100 miles/hr is shown below.

The dynamic pressure is indicated by q, v is the wind velocity and ρ is the density of air

$q = \rho v^2 / 2$

$\rho_{air,\ -40°F,\ Sea\ Level}$ = .094 lb/ft^3 =1.49 kg/m^3

v = 100 miles/hr = 146.67 ft/sec =44.7 m/s

$q = (.0029)(146.67^2) / 2$

q = 31.424 lbs/ft^2 = .218 lbs/in^2 = 6.04 iwg

=15.04 Pa

Basic pressure coefficient P_c/q = 3.10. Cell pressure corrections factors C_q = 1.00 and C_w = 1.25

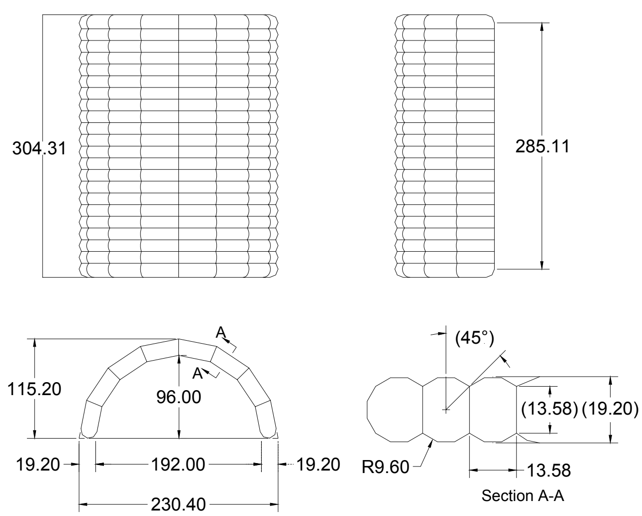

Figure 6 - Geometry of the Habitat Used in Modeling

Required cell pressure is calculated as:

$C_q\ C_w\ (P_c/q)\ q$ = (1.00)(1.25)(3.10)(6.04) = 23.41 iwg
= 0.846 psig = 58.3 Pa.

The operational cell pressure was set as1.25 psig (+/- 0.25 psig) to include a factor of safety, above the calculated pressure of 0.85 psig. The cell pressure value was also corroborated with cell pressures of comparable double walled structures designed and used in military applications. The requirements on the structure imposed due to aerodynamic impact are calculated as shown below.

Lift = L = $C_L q A_p$

C_L= .54

A_p = planform area = 45.23m^2

q = 1.50 kPa

L = (.542) (31.4) (486.9) = 3761.64 kg

Drag = D = $C_d q A_p$

Where: C_d= .34

D = (.34)(31.4)(486.9) = 2338.72 kg

Where: C_m= .54

The overturning moment (M) on the structure is calculated as follows:

$M = C_m q A_p$
D = (.54) (31.4) (486.9) =11,284.48 N-m

The loading on base anchor (P_{BL}) is calculated as:

$P_{BL} = C_{BL} q A_p$ Where: C_{BL}= .75

P_{BL} = (.75) (31.4) (486.9) = 5,204 kg

Assuming an allowable anchor load of 680.38Kg/anchor, number of anchors required for the structure was calculated as follows:

5204.9 kg / 680 kg = 7.65 anchors

TR 69-59 recommends a value for 10.16cm arrowhead ground anchor. Therefore a minimum of 8 ground anchors are required in accordance with the above analysis. A total of 10 ground anchors were employed for the inflatable structure. Additional anchors were installed for the airlock.

To counteract the loading on the habitat structure due to wind force on its sides, guy lines were installed. The load of each guy line (P_{GL}) was calculated as:

$P_{GL} = C_{GL} q A_p$ Where: C_{GL}= .43

P_{BL} = (.43)(31.4)(486.9) = 2,963.30 kg

The total number of guy lines required was calculated by assuming that each guy line would be attached to a 680.38 kg anchor:

2963.3kg / 680.38kg/guy line = 4.36 guy lines

A minimum of 5 guys lines were selected to be installed on the sides of the structure. The loading on each guy line due to wind across the end of the habitat is calculated as follows:

$P_{GL}End=CdqA$

For end wall, assume Cd = 1.2 (flat plate on ground plane)

P_{GL} End = (1.2) (153.30kg/m2) (13.09m2) = 2411.75 kg

The load of the corner guy lines was calculated with the assumption of a 45 degree inclination from the vertical.

sin 45(680.38 kg) x 2 guys = 962.06 kg

The materials used in the fabrication of the inflatable were selected based on requirements generated by the structural analysis. Material properties such as tensile strength tear strength puncture resistance, flexibility of the fabric coating at low operating temperatures and fabric permeation rate were the critical factors in fabric selection. However, the robustness of the fabric and low seam leakage were deterministic in the final selection of a fabric leading to the selection of a fabric with higher coating thickness than warranted by the theoretical analysis.

Several different fabric coatings including polyurethanes, silicone, thermoplastic coatings and vinyl coatings were considered. Polyurethane coating was selected due to its relative flexibility at low temperatures, low cost, easy availability and manufacturing simplicity. The coated fabric used in fabrication is a polyamide with polyurethane coating on both sides of the fabric. The properties of the fabric used in the construction of the main inflatable structure are given in Table 1.

Specifications	Standard -Test	Direction	Result (Imperial)	Result(Metric)
Surface Mass	NF EN 22862 FSTM 191/5041		20.9+/- 1.8oz/yd^2	710 +/- 60 g.m^2
Tensile Strength	NF EN ISO 1421 ASTM D751/B	CH (W) TR(F)	>337.1 lbs/in >325.8 lbs/in	> 300daN/5cm >290daN/5cm
Elongation at Break	NF EN ISO 1421 FSTM 191/5102	CH (W) TR(F)	25%	35%
Tear Resistance	NFG 37 129 ASTM D751 /A	CH (W) TR(F)	>11.2lbs >11.2 lbs	> 5daN > 5daN
Permeability (Helium) Zeppelin Test	NGF 37 774			< 2l/m^2
Abrasion Resistance	En en ISO 5470 - 1 1kg, H-18,5000 cycles		< 0.0106 oz	< 0.3 g
Peeling Test Adhesion	NFG 37 107 ASTM 751		>/= 11.2 lbs/in	>/= 10 daN/5cm
Adhesion (HF welding - peeling test)	ASTM D 751		61.8 lbs	>55 daN/5cm
Low Temperature Resistance	NF EN 1876-2 ASTM 751		< -58 F	< -50 C
Hydrolysis Resistance	40 semaines a 80 C 90 hr 40 weeks 176 F 90 hr		PASS	
Ozone Resistance	ISO 3011		NO AFFECT	

Table 1: Properties of urethane coated nylon used in the construction of the inflatable structure

The inflatable structure was made of mitered sections which formed large single volumes as shown in figure 7. The structure was assembled by heat sealing cut patterns of coated fabric. The doors and the non-inflatable walls with windows were assembled separately and then attached to the inflatable sections by thermal sealing. Zippers were installed via sewing and sealing. Figure 8 shows the fabricated door and integrated window components.

Figure 7 - Mitered Sections of the Habitat (Two Joined Sections Shown – Front Entrance)

INSULATION

An insulation cover was designed and integrated to the habitat structure to provide thermal and environmental protection and also maintain a constant temperature on the inside of the habitat. The flexible/packable design and the operational environment imposed stringent requirements on the design of the thermal cover. The goal in this effort was to attain a consistent R value through the structure. The critical requirements for the insulation cover included low mass, high flexibility & compressibility for high packing efficiency, complete recovery of thickness after packing and retention of thermal conductivity and structural integrity in the temperature range of -50 ^oC to 8 ^oC.

Figure 8 – Airlock, Door and Window Details

The insulation blanket is analogous to the micrometeoroid and orbital debris layer and the thermal cover on a habitat structure for planetary exploration and hence this terrestrial demonstration serves to prove the feasibility of deployment of such a structure under inclement and harsh conditions. Materials that are conventionally used for insulation in polar environments include foam and fiberglass. These materials did not meet the requirements of the project. Other state of the art insulation materials such as microfibers and aerogels were also considered. These materials have a very high value of R in comparison to fiberglass and polyurethane foams for a similar thickness. Mass analysis of aerogel candidate (Aspen Spaceloft™ 6200 0.13g/cc) materials revealed that the high density of these would significantly increase the total mass of the system when compared to the mass of other insulation materials (EPS P2000 Foam 0.023g/cc, Thinsulate™ G200 0.01g/cc), and Fiberglass 0.016g/cc) and their incompressible nature reduced packing efficiency. Cost and particulate contamination were also considerations.

The use of fiberglass entailed a thermal blanket with a minimum thickness of 10.16cm, and need to preclude particulate shedding and hence fiberglass was dismissed due to inefficient packing and complexity of integration. Thinsulate ™ type G insulation was selected for the blanket due to its easy availability, light weight, high packing efficiency and retention of insulation properties under damp conditions. Insulation blanket was fabricated by sandwiching the two layers of Thinsulate™ between coated fabric layers to provide a flexible integrated laminate. Figure 9 shows the cross-section of the insulation blanket. The fabric envelope around the insulation material was used to heat seal indexing tie tabs and load distribution guy patches.

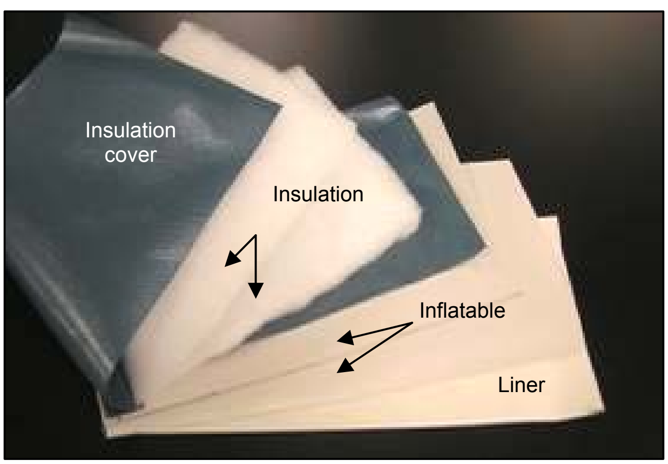

Figure 9 - The Insulation, Structural, and Liner Materials

The total thickness of the insulation was 3.81cm and the calculated R value of the insulation blanket was 6. The R-value offered by the air gap in the inflatable wall and trapped air gaps under the insulation was approximately 1-2. Therefore, cumulative insulation around the structure during its deployment and operation is concluded to be an R value of 7-8. The integration of the insulation over the inflatable structure can be seen in Figure 10.

Figure 10 - Integration of the insulation blanket to the main inflatable habitat

INFLATION & POWER DISTRIBUTION SYSTEM

The Habitat is equipped with an automated inflation system that maintains the inflation pressure to 6.894kPa +/- 0.1. A bulkhead fitting on the habitat contains a 1.27cm air inlet port and a 0.64cm pressure sense port. Both ports are plumbed to the Inflation System enclosure which contains three pressure switches and a mechanical pump capable of topping-off the pressure within approximately 120 seconds (Figure 11).

The inlet port has been fitted with a check valve to prevent backflow through the pump. Two of the pressure switches are used as high and low set-points which turn on the pump when the pressure decays below the low set-point and turn it back off when the pressure reaches the high set-point. The third pressure switch, with a set-point of 4.83 kPa, monitors for gross leaks or pump failure. If the pressure drops below this last set-point, the power to heaters is shut off and an audible alarm sounds to warn of the low pressure condition. The inflatable structure is also fitted with several pressure relief valves to preclude inadvertent over-pressurization during deployment with a pump system failure.

In addition to the inflation controls, this enclosure houses the power distribution system, which both routes and monitors all power in the habitat. The main power cable passes through a bank of circuit breakers which branches the power to the sensors, electrical outlets, lighting system, and the two ceramic heaters. The enclosure houses 6 electrical receptacles into which the heaters, lighting system, and utility outlets are plugged. The system is equipped with battery operated power monitors; one monitors all power into the habitat and the other monitors the inflation pump. From this data the energy usage of the habitat system can be monitored. Also, the health of the inflatable can be determined by detecting how often and for how long the inflation pump runs. An increase in either would indicate increased leakage in the structure.

The internal ambient lighting is powered and controlled through this system as well. The lighting is comprised of a string of 10 standard sockets which plug into an outlet on the power distribution system. There is a spare lighting outlet that is currently unused. The power to these two lighting outlets is controlled by a wired remote switch located by the entry door. Several lighting technologies were provided in the habitat to evaluate the usefulness of each. Two styles of clustered LED bulbs and a Halogen bulb. The halogen bulbs were most useful to provide a lot of light while detailed work was going on in the habitat. For general, low level lighting, the LED clusters worked well alone.

Figure 11 – Inflation System Components - Internal Make-up Pump & Power Distribution System Door open & Closed and Orange External Inflation Blower

ELECTRICAL SYSTEMS

The Habitat has been fitted with various and multiple sensor packages in order to monitor the health of the structure and the internal and external environment (Figure 12). The sensor systems were designed and constructed by NASA JSC personnel along with the monitoring system. NASA implemented both high Technology Readiness Level (TRL) systems along with experimental (lower TRL) sensor packages. The sensors packages included the following:

<u>External</u>

- Light impingement
- Surface temperature (RuBee Tags)
- Weather station (wind speed/direction/temperature)
- Web camera

<u>Internal</u>

- Temperature (RuBee Tags)
- CO_2 Monitor
- Internet controlled web camera
- System, heater, and air pump power consumption

<u>Embedded within the inflatable structure</u>

- Temperature
- Pressure

The external and embedded sensors, as well as some of the internal temperature sensors are wireless devices. Each embedded sensor has a dedicated antenna, while the surface mounted temperature "RuBee" tags are RFID type tags and are all linked to the monitoring system via a single loop antenna that is routed around the inside perimeter of the habitat.

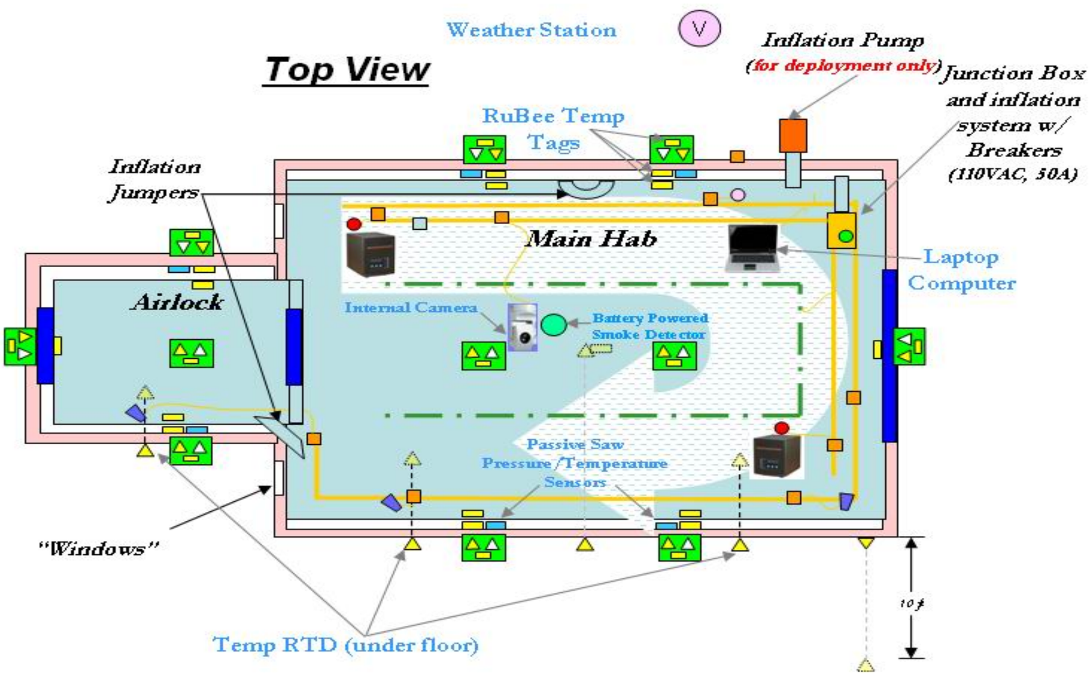

Figure 12 – Sensor & Electrical Systems Plan View

Several of the power monitors are hardwired to the data system while the balance are connected through a wireless USB hub. All data is logged to a local computer and is accessible with a local laptop computer system. These computers are connected to the McMurdo Local Area Network and then via internet protocols to NASA's Johnson Space Center for data collection and review

REGOLITH HOLDERS

The inflatable habitat is also designed to be equipped with storage bags on the exterior sidewalls of the habitat structure (Figure 13). These enclosures could prove very useful for NSF Antarctic habitat application by serving as storage space, water generation devices, and when filled with snow, they could aid in stabilizing the structure. The operational data obtained during packing, deployment and long term function of this demonstration unit can provide design guidelines for habitat architecture for exploration. These pockets could be used to scoop up and store large quantities of regolith that can provide radiation protection to the inhabitants and equipment during long duration missions. Systems that capture regolith piled on the inflatable structure during system deployment are being studied by NASA and ILC. This would allow simple equipment to be used to create radiation shields. The regolith pockets helped demonstrate aspects of this work and how the expandable structure would react.

Figure 13 - Deployed habitat with regolith pockets being filled and assessed

A simple design was developed for the regolith pockets with attachment features that enabled the contents of the bags to be removed easily. The habitat was equipped with 10 regolith containment bags, each designed to provide an inlet opening of 1.21m and a depth of about 0.91m. A closing flap was attached to each bag with a webbing and D-ring system that serves as a simple mechanism for removal and draining.

TEST RESULTS

Testing was conducted at the material level, component level and system level. Material and component level testing were conducted to ensure survivability of the system throughout its anticipated lifecycle. System level testing produced data to meet the objectives of the program.

COMPONENT TEST RESULTS

Extensive testing was conducted for material quality assurance, design verification, sub- assembly validation and material survivability. The testing and results are summarized below.

Material

The seam design was evaluated for all different configurations of seams used in the structure. The seam validation was conducted at room temperature as well as in the extremes of the operation temperature range. Figure 14 shows the test set up for deal loads at -50 ^{o}C .

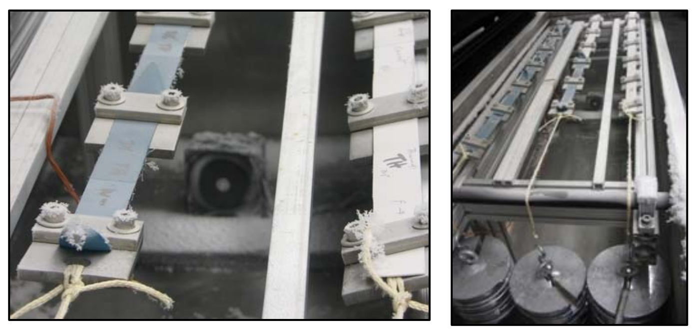

Figure 14 - Test set up for low temperature long-term dead-load testing

The coating adhesion of the fabric used in the construction of the inflatable was tested to assure the ability of the inflatable sections to survive the stress induced during operation. The survivability of the fabric on the outside of the habitat due to prolonged exposure of ultra violet radiation was determined by exposing the fabric to the UV radiation representing Antarctica for a period of 500 hrs. The continuous exposure was designed for accelerated aging study of the material. Tensile strength of the fabric registered a minimal reduction which was well within the design requirements. However, a significant discoloration of the fabric was observed.

The function of the zippers, which were critical to the installing and operation of the system, was verified at lower operating temperatures. The hardware components, such as the guying systems used in installation and sustained function of the system, were also evaluated for their ability to retain their function in the operational environment.

Subassembly Testing

The load bearing capacity of the fan patches used in transferring and distributing the load from anchors into the structure was also evaluated. A test was devised to simulate loading the fan patches during installation and operational lifetime, and verify factors of safety were met. The fan patch assembly was tested to 861.8kg and met operational needs.

The ability of the inflatable to retain the operational pressure of 6.9KPa was verified by testing a sub assembly that emulated the basic design of the habitat. Several pattern verification units were fabricated and tested to determine the burst pressure and factor of safety. Results indicated the required factor of safety of 3 over ultimate was easily achieved and no creep rupture issues were anticipated for long term operation. Figure 15 shows two of the test articles. The completed system was also proof tested (1.5 times operational pressure) and leak tested before and after proof test. One of the hose junctions was found to leak and was sealed and no delta-leakage was noted, indicating the structure underwent no change during the test.

The resistance to damage and compression set due to multiple packing and deployment cycles was verified by subjecting a representative layup of the habitat to repeated folding and unfolding cycles. There was no damage to the materials and the material layup was able to regain its original dimension after the compressive force (folding) was removed.

Figure 15 - Pattern verification unit test articles

SYSTEM TEST RESULTS

The 453.6kg system was packed and deployed approximately 20 times throughout the course of manufacture and test prior to deployment in Antarctica. The final packing event was conducted by 5 people in 1 hour and yielded 2 soft packed packages approximately 2.43mx1.21mx0.76m. The airlock was included with one of the packages. The units survived handling and shipping vibration and environments without issue. The two packages and a small electronics package were shipped by truck from ILC in Delaware to Port Hueneme Naval Base in California. At that point it was repacked and shipped to Long Beach where it was put on a cargo ship bound for Christchurch New Zealand (the NSF Antarctic staging base). The system was then loaded on a C-17 and flown to McMurdo Station. After offloading from the C-17, it was moved by truck and fork-truck to the deployment site.

The system was erected in 50 minutes by 3 people in a snow storm with winds gusting to 32km/hr. Inflation was 12 minutes of the set-up time and due to the integrated nature of the layers, the materials did not flutter in the wind. The deployment team wore full body Extreme Cold Weather Gear (ECWG) during the set-up to simulate wearing space suits. Mobility was comparatively better in ECWG, but still gave some idea of human interface issues astronauts might face. The only task that was somewhat difficult was zipping the multiple zippers of the habitat halves together. Lanyards were used but material handling was still difficult in aligning the zippers because of the mass of material involved.

The system was deployed several times at ILC in the factory and outside on tarp ground covers. Positioning and indexing of layers was at times difficult because of friction. Thus moving the habitat half took several people and the insulation sometimes didn't fit the habitat perfectly when deployed. In McMurdo, one person could easily position and move the habitat half on the snow because of the low friction. The insulation also fit the inflatable structure very well because it slipped into place easily under low humidity and cold materials.

The ground was relatively even at the deployment site having been prepared by Raytheon Polar Services using snow/earth moving equipment. However, there was some undulation to the surface especially after the snow (7.5cm-15cm) which was noticeable in the habitat. The structure adapted well to the surface and no unusual disturbances in the system were noted. It was noted that the exact locations of the ground anchors near the habitat and the positioning of the regolith pockets were altered due to the habitat slightly altering shape while adapting to the ground. This highlighted the need and importance for compliant structures and attachments.

After a few days the snow under the habitat would still "crunch" in areas away from normal walking paths indicating the insulated floor was working well. At this time the temperature inside the habitat was 10 ^{o}C -21 ^{o}C and the sun was not out. Once the storms passed and the sun warmed the surface of the habitat and the ground surrounding it, the snow under the structure melted. This took approximately 5 days. During this time the guy lines had to be re-tensioned to account for the vertical position difference.

Operation of the doors and windows was simple with gloves on. The zippers did not get clogged during the intensive use over 10 days (hundreds of people in and out). This may be attributed to the large zippers used or the fact that the McMurdo soil had very low adhesion since is was crushed volcanic rock with no cohesive matter in it. Even if it got on the zipper it would become dust quickly in the dry environment and dislodge easily.

Dust migration studies were conducted over seven days to assess the amount of material that would be tracked into the habitat. Results do not correlate well with the lunar surface because of the differences in soil properties, but general operational characteristics were gathered for comparative purposes. For 4 of the 7 days of study, no snow was on the ground in front of the habitat door. Snow did tend to clean the soil from boots prior to entry. No provisions were made to remove boots in the airlock, but this would have eliminated the movement of soil into the habitat (and was demonstrated during outdoor testing at ILC prior to shipment to McMurdo). This finding is consistent with work previously conducted on removable space suit covers for lunar dust mitigation[8]. On the days when occupants stepped from wet soil into the airlock and habitat, visible deposition was easily noticeable in the form of small rocks and mud which turned to fine dust when dry. The dust migrated everywhere in the habitat and slightly reduced in concentration away from the door. A boot cleaning station (upside-down straw broom) was installed in the airlock to attempt to reduce inflow, but with little noticeable impact. The cleaning station was better with snow removal than dirt.

The structure was habitable for working and sleeping. The team of six from NASA and ILC slept in the habitat over night to assess performance. Some observations included: the floor was not cold, the window covers accommodated internal darkness in the 24 hr daylight, and the insulation and liner provided some sound attenuation from the external environment. The lighting system provided ample light for standard office operations with four 60W Halogen bulbs and 6 LED (5W) cluster bulbs (Figure 16).

Figure 16 – Expandable Habitat interior

Localized lighting was used where applicable to reduce system power consumption. The arch shape used in the habitat provided good vertical clearance near the walls and enabled most of the floor space to be utilized. The multitude of attachment locations on the structure and the cord suspension system provided locations to hang equipment and partitions as required.

CO_2 build-up tests were conducted with six occupants in the space and the system completely closed. Within 2 hours with the inhabitants working normally, the CO_2 readings climbed from a baseline of 1000ppm to 4500ppm. A small portion of the zippered doors on either end of the habitat were opened (~ 58cm^2) and the problem was alleviated. The test was conducted to determine if the zippers provided enough air exchange during normal operation to maintain comfort and thermal balance while minimizing power consumption. Results indicated more prescribed air exchange systems were required for habitation as the internal volume was more air-tight than expected.

The pressurized volume performed very well. Multiple inflate-deflate tests were performed in the cold environment (~ -17.7^{o}C-1.6^{o}C) with no damage to the inflatable structure. The blower used to inflate and evacuate the structure was sized to accomplish the task within 0.1hr-0.16hr. Once up to pressure and properly sealed-off, the small internal make-up pump cycled 3-6 times per day to compensate for pressure variation from permeation, leakage around fittings, and temperature swings.

The insulation package packed well and returned to shape and normal lofting in minutes. Several smaller blankets were vacuum packed for three weeks and showed no compression set or change in performance. Thermal images were taken periodically and studied to identify heat-leaks or issues with the insulation (Figure 17).

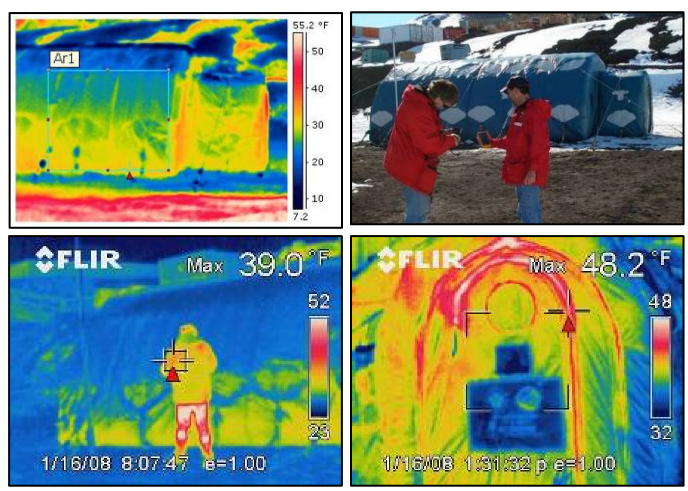

Figure 17 – Thermal images of habitat (~30oF Difference between interior and exterior)

Some images revealed that subtle differences in insulation performance were noted where the insulation was under greater compression such as on the upper roof at the apex of the inflatable tubes. Solar loading must be taken into account when reading the thermal images. Studies are ongoing regarding verification of insulation performance and thermal model verification. Power consumption data is also being collected for the heaters and other systems.

The sensor systems performed well after installation and through remote operation. The sensors that were embedded within the structure during manufacture survived installation, shipping and deployment. Data is being continuously collected from McMurdo and studied to assess performance of the system. The internal camera has been operated from JSC and used to monitor the system pressure gauge on the inflation system and verify pressure maintenance. All functions from the weather station have also been proven.

SUMMARY

The expandable habitat which was deployed and tested in Antarctica has provided information regarding processing and performance to support NASA's definition of lunar architecture for the Exploration Program. The system has demonstrated, through testing in the analog environment, that expandable systems have high packing efficiencies, are rugged and durable, and can withstand extreme environments. The habitat showed the reusable nature of these structures and their ability to be reconfigurable. The fully instrumented structure will be monitored over the 2008-2009 seasons in Antarctica to develop long-term data.

The habitat also provided information to the NSF Office of Polar Programs to show how this technology can aid in achieving their missions via transportability, rapid deployment, and structural stability. For the polar environment, expandable systems were found to pack like a tent but act like a building once deployed.

The Innovative Partnership Program was very successful in bringing together NASA, NSF and industry (ILC Dover) to address a broad series of study interests in a fast-paced team approach.

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Figure 18 – The Team in Antarctica (Cole, Toups, Scheir, Cadogan, Delaney, Hong, Valle, Hafermalz)

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

AIAA: American Institute of Aeronautics & Astronautics

CO_2: Carbon Dioxide

ECWG: Extreme Cold Weather Gear

IPP: Innovative Partnership Program

ILC: ILC Dover LP

JSC: Johnson Space Center

LaRC: Langley Research Center

LED: Light Emitting Diode

NASA: National Aeronautics and Space Administration

NSF: National Science Foundation

OPP: Office of Polar Programs

RFID: Radio Frequency Identification

TRL: Technology Readiness Level

SAIC: Science Applications International Company