Inflatable Habitat Health Monitoring: Implementation, Lessons Learned, and Application to Lunar or Martian Habitat Health Monitoring

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NASA's exploration mission is to send humans to the Moon and Mars, in which the purpose is to learn how to live and work safely in those harsh environments. A critical aspect of living in an extreme environment is habitation, and within that habitation element there are key systems which monitor the habitation environment to provide a safe and comfortable living and working space for humans. Expandable habitats are one of the options currently being considered due to their potential mass and volume efficiencies. This paper discusses a joint project between the National Science Foundation (NSF), ILC Dover, and NASA in which an expandable habitat was deployed in the extreme environment of Antarctica to better understand the performance and operations over a one-year period. This project was conducted through the Innovative Partnership Program (IPP) where the NSF provided the location at McMurdo Station in Antarctica and support at the location, ILC Dover provided the inflatable habitat, and NASA provided the instrumentation and data system for monitoring the habitat. The outcome of this project provided lessons learned in the implementation of an inflatable habitat and the systems that support that habitat. These lessons learned will be used to improve current habitation capabilities and systems to meet the objectives of exploration missions to the moon and Mars.

I. Introduction

ONE of the tasks outlined in NASA's Vision for Space Exploration[1], necessary to return to the moon, is to develop a reference lunar exploration architecture concept to support sustained human and robotic lunar exploration options. Using expandable modules is one of the options that NASA is currently looking at in order to take advantage of potential mass and volume efficiencies. By utilizing expandable modules and minimizing weight and packed launch volume less launches may be required in order to get an equivalent usable volume to the lunar surface. The overall objective of this project was to design, construct, and test a proof of concept inflatable structure to understand the utility and durability of this type of habitat over long durations. NASA's element within the project was to design and deploy a data system to monitor and transmit performance data using existing instrumentation, and then to remotely monitor the habitat over one year. This data will help to assess the durability, performance, and operability of this inflatable habitat concept. Additionally, NASA will use this instrumentation system to validate the use of various sensor systems for data acquisition and management. The National Science Foundation benefits similarly with low mass and lower packed volume efficient structures that can easily be deployed in remote locations in extreme environments that meet performance and operational requirements. The following will highlight NASA's component and the experience and lessons learned in the development, deployment, and operations of this system.

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II. Habitat Overview

The habitat structure was designed and developed by ILC Dover, a company with extensive knowledge of inflatable structures for space environments. The design was a series of tubular segments that inflated to form structural arches, as shown in the figure below. These segments were inflated to one pound per square inch and the entire structure was designed to withstand winds up to 100 miles per hour.

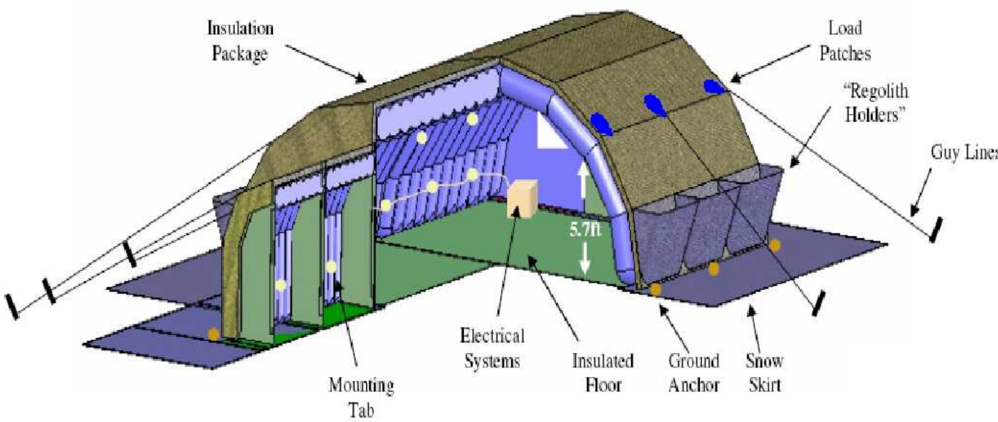

Figure 1: Inflatable habitat design by ILC Dover.

The habitat was made of two areas: the main habitation area and the simulated airlock. The main habitat area was separated into two halves that were connected with zippers, and had internal dimensions of 16 feet x 24 feet x 8 feet when fully inflated. The inflated tubular walls of this area were 19" in thickness. The simulated airlock was also connected to the main habitation area with zippers, and the inflated tubular wall thickness was 12". The simulated airlock area when fully inflated was 4 feet x 6 feet.

Surrounding the habitat structure was an insulation package made of Thinsulate™ Type G insulation to protect the habitat from the extreme thermal exterior environment, as shown in Figure 2. The habitat was also anchored to the ground using guy lines to secure the structure.

Figure 2: Fully inflated habitat at McMurdo Station.

Additionally, the habitat was fashioned with "regolith holders" to investigate one method of radiation shielding that may be used on the lunar surface (shown in Figure 1).

III. Instrumentation Overview

The instrumentation system was designed and developed by NASA, using commercial and NASA developed sensor systems, to monitor the habitat environment over a long duration mission and to investigate several methods of implementation, and to demonstrate remote monitoring over the calendar year. The instrumentation system architecture developed is shown below.

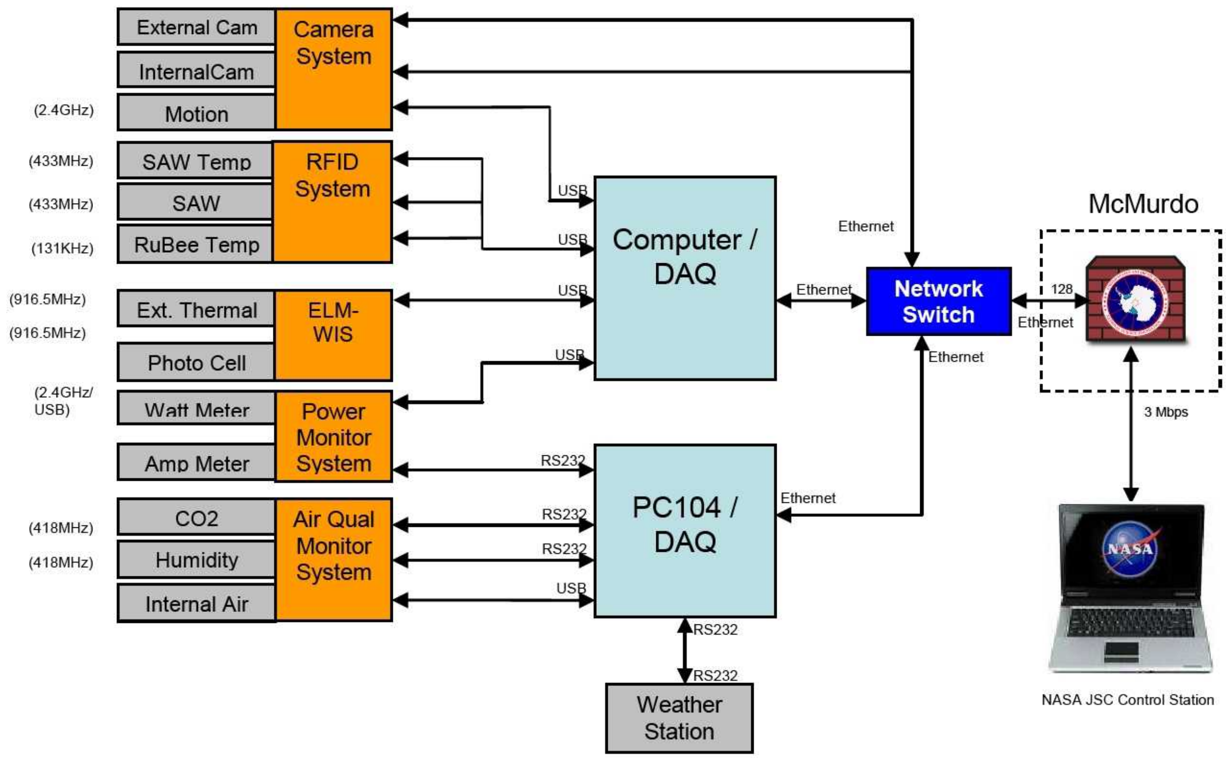

Figure 3: Instrumentation System Architecture.

The instrumentation system focused on monitoring temperature, pressure, power consumption, air flow, and air quality in the interior of the habitat and light intensity, temperature, and weather on the exterior of the habitat. There were also cameras for visual observation and a hand-held leak detector for identifying and locating small leaks within the habitat.

The sensors were located in various interior and exterior locations (shown in Figure 4) within the habitat to understand different implementation methods. Some sensors were embedded within the inflatable bladders of the habitat. Others were strapped to cords on the walls and ceilings, or placed under the floor inside the habitat. The exterior sensors had pockets built into the habitat to position the sensors and to provide exterior information in specific locations of the habitat.

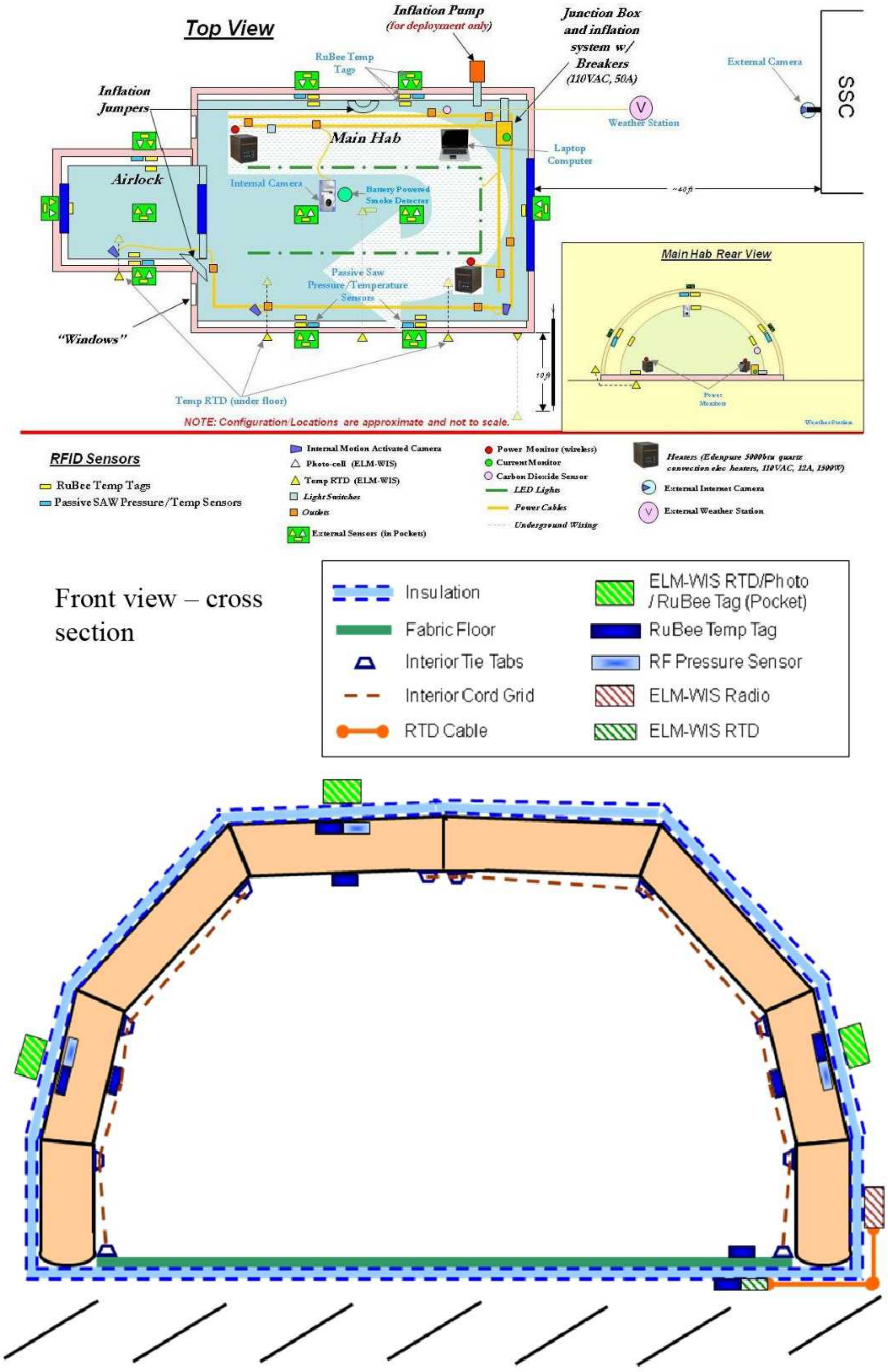

Figure 4: Sensor locations within and around the habitat.

These sensors provided the background information for evaluating the implementation of a wireless and remote habitat environmental monitoring system. The data from these sensors was wirelessly transmitted to a central computing system on-site and then transmitted via the internet from McMurdo station in Antarctica to NASA – Johnson Space Center (JSC) in Houston, TX. The instrumentation system could then be remotely accessed from JSC to investigate remote monitoring capabilities and habitat environment.

IV. Data Collection Example – Preliminary Data

An example of one type of data that was monitored by several of the sensors was the thermal efficiency of the habitat. This was done by gathering temperature data (shown in Figure 5) from sensors inside the habitat, embedded within the inflatable bladder, and outside the habitat, and combining that with the heat input from the heater to calculate what is known as an R value.

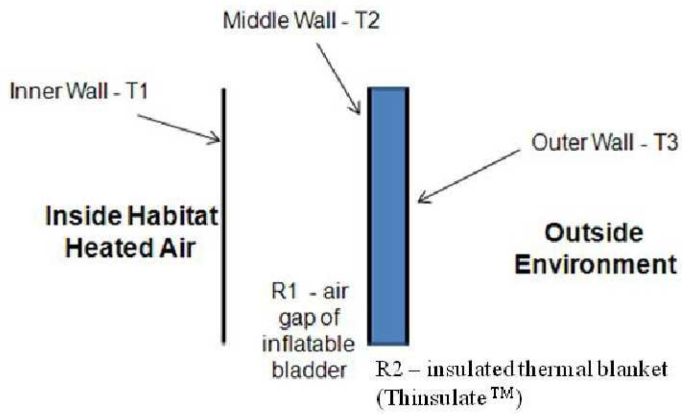

Figure 5: Diagram of habitat cross-section showing temperature sensor locations

The R value is a measurement of the thermal resistance of the habitat, which encompasses the heat flow and change in temperature through the materials. This value is defined mathematically below, where Q is the heat flux, q is the heat input from the heaters, and A is the internal area of the habitat.

$$Q = \frac{q}{A}$$
$$R_1 = \frac{(T_1 - T_2)}{Q} \quad (1)$$
$$R_2 = \frac{(T_2 - T_3)}{Q}$$

An example of this temperature data and R value collection is shown in the following table. The data in this example was gathered from the overhead front location. This type of data was collected at many locations from several sensors placed throughout the habitat, under the floor of the habitat, and outside of the habitat under the ground. This allowed for an understanding of the thermal gradients throughout the habitat and in the ground around the habitat. In this table, it is assumed that the heat flux is uniform throughout the habitat.

Table 1: example of temperature data collected at the overhead front location.

Overhead Front Location - Imputed									
Date	R1	R2	R Total	Heaters	Exterior temp(F) (T3)	Embedded temp(F)(T2)	Internal temp(F)(T1)	delta T_R1	delta T_R2
4/26 - 5/2	1.05	2.91	3.96	1.62	10.41	30.49	37.74	7.25	20.08
7/2 - 7/8	1.21	3.36	4.57	2.00	-12.17	16.48	26.76	10.27	28.66
9/6 - 9/8	1.06	3.01	4.08	1.71	7.43	29.37	37.12	7.74	21.95
10/11 - 10/19	1.05	3.58	4.62	1.40	12.01	33.42	39.68	6.26	21.41
11/1 - 11/4	0.90	4.53	5.44	1.18	16.27	39.06	43.60	4.54	22.78

Some preliminary data from the habitat is plotted, as shown in Figure 6 below. This plot shows that when the temperature decreases, or is low, the heaters are on. It also shows the difference in temperature between the exterior, the bladder, and interior of the habitat.

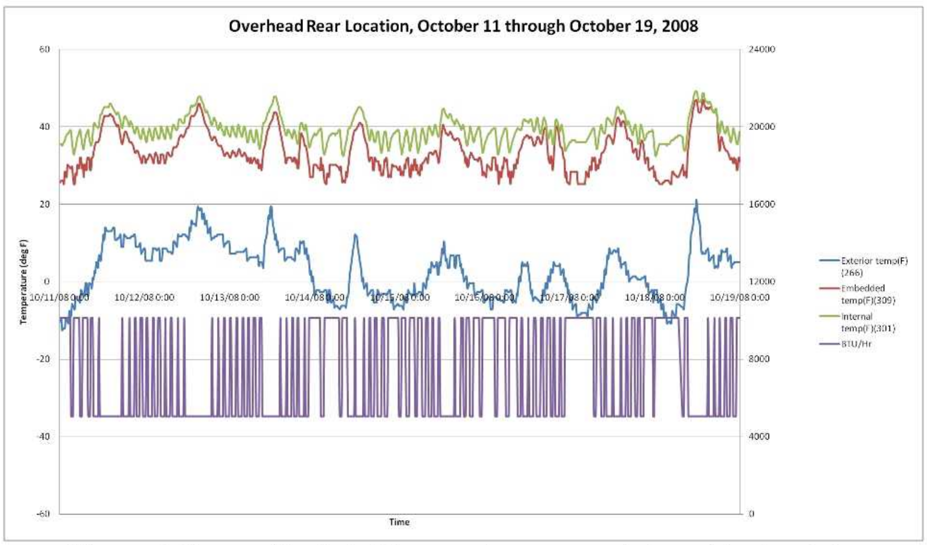

Figure 6: Composite plot of temperature sensor data and heater data.

V. Deployment – Sensor Implementation Methods

There were essentially three types of locations for the sensors: interior, exterior, and embedded. Each of these locations used different deployment methods, some of which required more set-up time than others. Additionally, each location offered its own challenges, which will be discussed below.

The interior deployment of sensors provided a unique challenge in that they could not be affixed to walls using conventional methods (i.e. screws into drywall). Rather, a network of cords throughout the interior of the habitat was employed and the sensors needed to be attached to those cords. An example of one of the motion cameras installed to the wall is shown in the following figure.

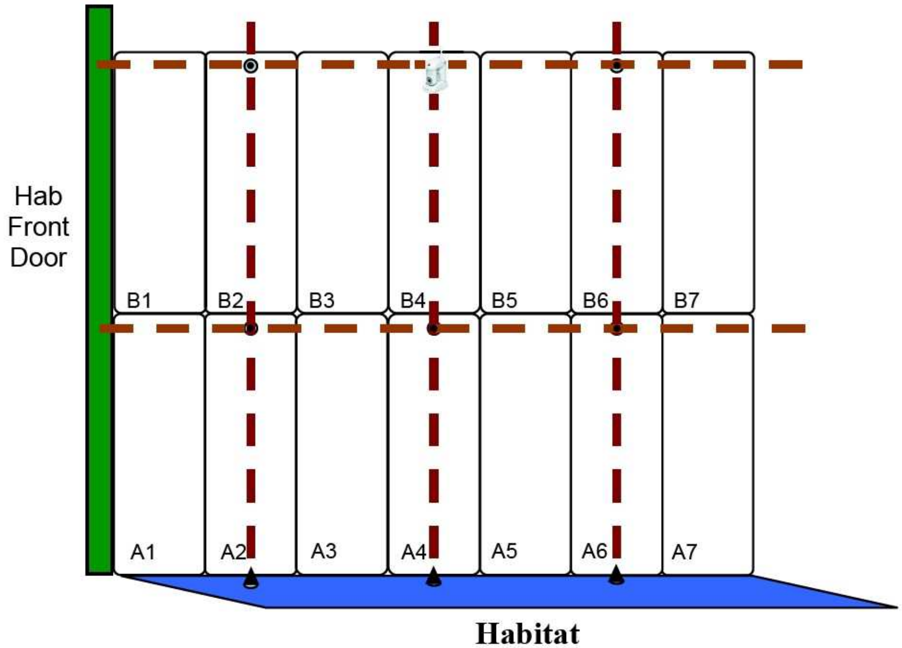

Figure 7: Representation of cord assembly within habitat and deployment of internal motion sensor.

This camera was held to the cords using Velcro straps. Foam was also placed between the Velcro and the walls to hold the camera upright as well as protect the walls from the edges of the camera. This setup is shown below in Figure 8. These cameras were relatively lightweight and did not place too much strain on the cords. There were also carbon dioxide sensors and airflow monitors that employed the same method for installation.

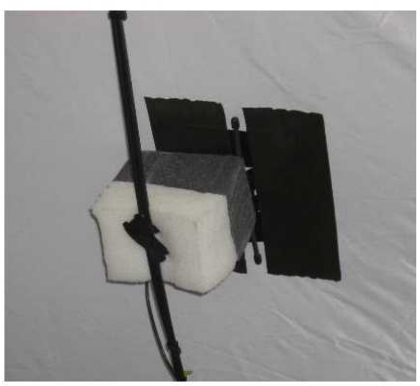

Figure 8: foam and Velcro under cord assembly (on left) and motion camera held to foam with Velcro (on right).

Another example of interior installation was a large camera with rotation and zoom capability that needed to be affixed to the ceiling. This camera provided a 360 degree view of the interior of the habitat and allowed monitoring of events within the habitat from a remote location. The challenge with this instrument was to provide rigidity so that the camera rotation created minimal movement of the instrument. Thus, the camera was mounted to a Lexan plate to provide that rigidity, and the plate was then sandwiched between the cords and the ceiling of the habitat, as shown below.

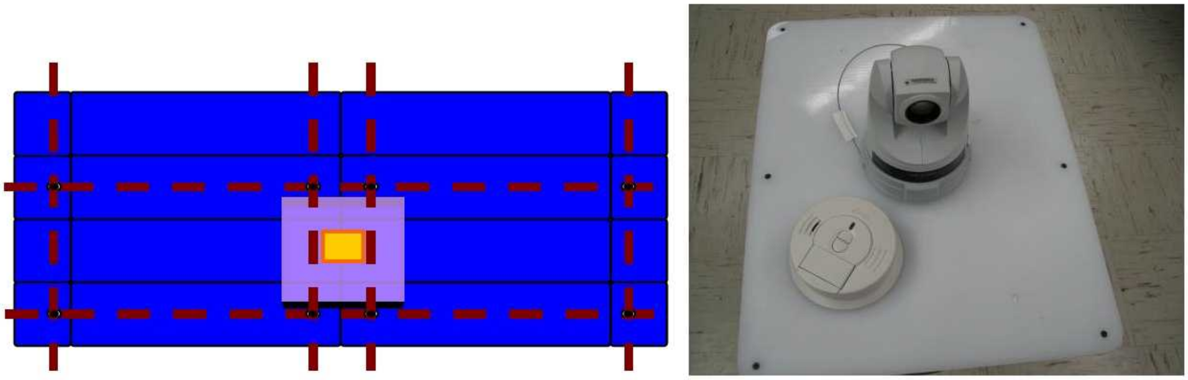

Figure 9: Representation of cord assembly on habitat ceiling and large camera deployment (on left) and camera assembled to Lexan plate (on right).

In this figure, the camera is represented by the orange box and the plate is represented by the purple square. The plate is tightly held by the cords shown going across the plate (Figure 10).

Figure 10: The internal camera assembly installed to the ceiling through cord assembly.

Another interior implementation method was of the wireless temperature sensors. These were installed in enclosed pockets that were adhered to the walls of the habitat as shown in the image below.

Figure 11: image of internal temperature sensor adhered to wall.

The exterior deployment of sensors on the habitat also had the same challenge as the interior in that the habitat could not be penetrated and had to be protected from the sensors. The added challenge to the exterior deployment is that the sensors also had to be protected from the harsh external environment. This was accomplished by vacuum sealing the sensors and placing them in pockets that were pre-sewn into the habitat exterior layer. This pocket and sensor assembly is shown in Figure 12 and Figure 13 below.

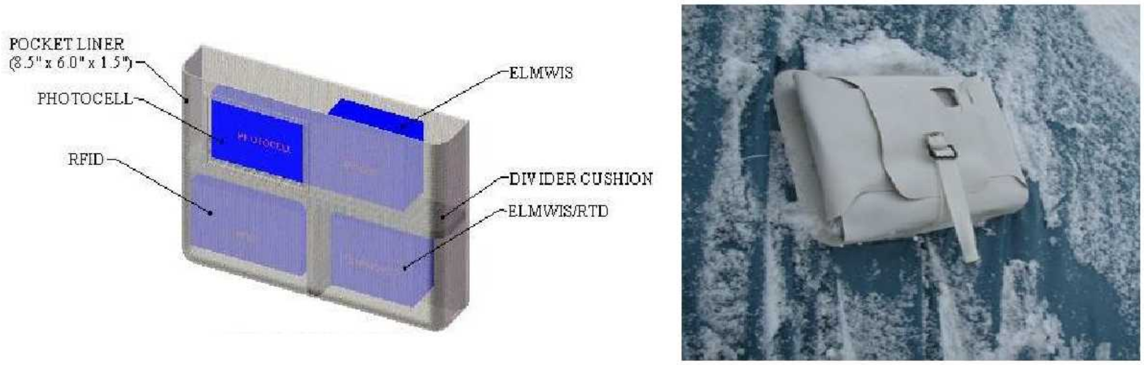

Figure 12: External sensor pocket schematic (left) and installed pocket on habitat exterior (right).

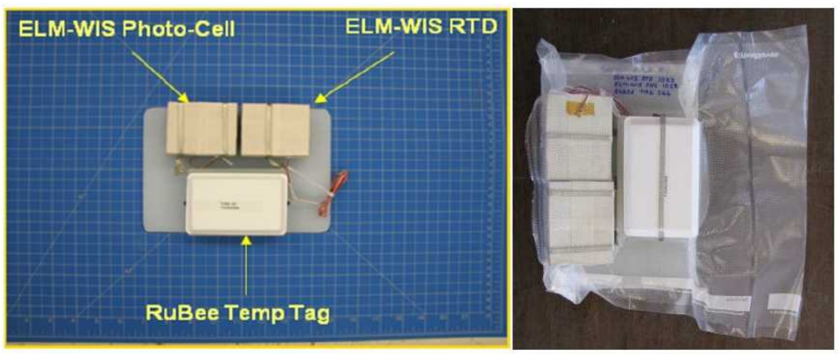

Figure 13: External sensor installation on plate (left) and sensors within vacuum sealed bag for protection from environment (right).

As can be seen in the figure, there were several sensors placed in one pocket to increase packing efficiency. The pockets were then distributed across the habitat to give a representation of the external environment over the entire habitat. These external locations are shown below.

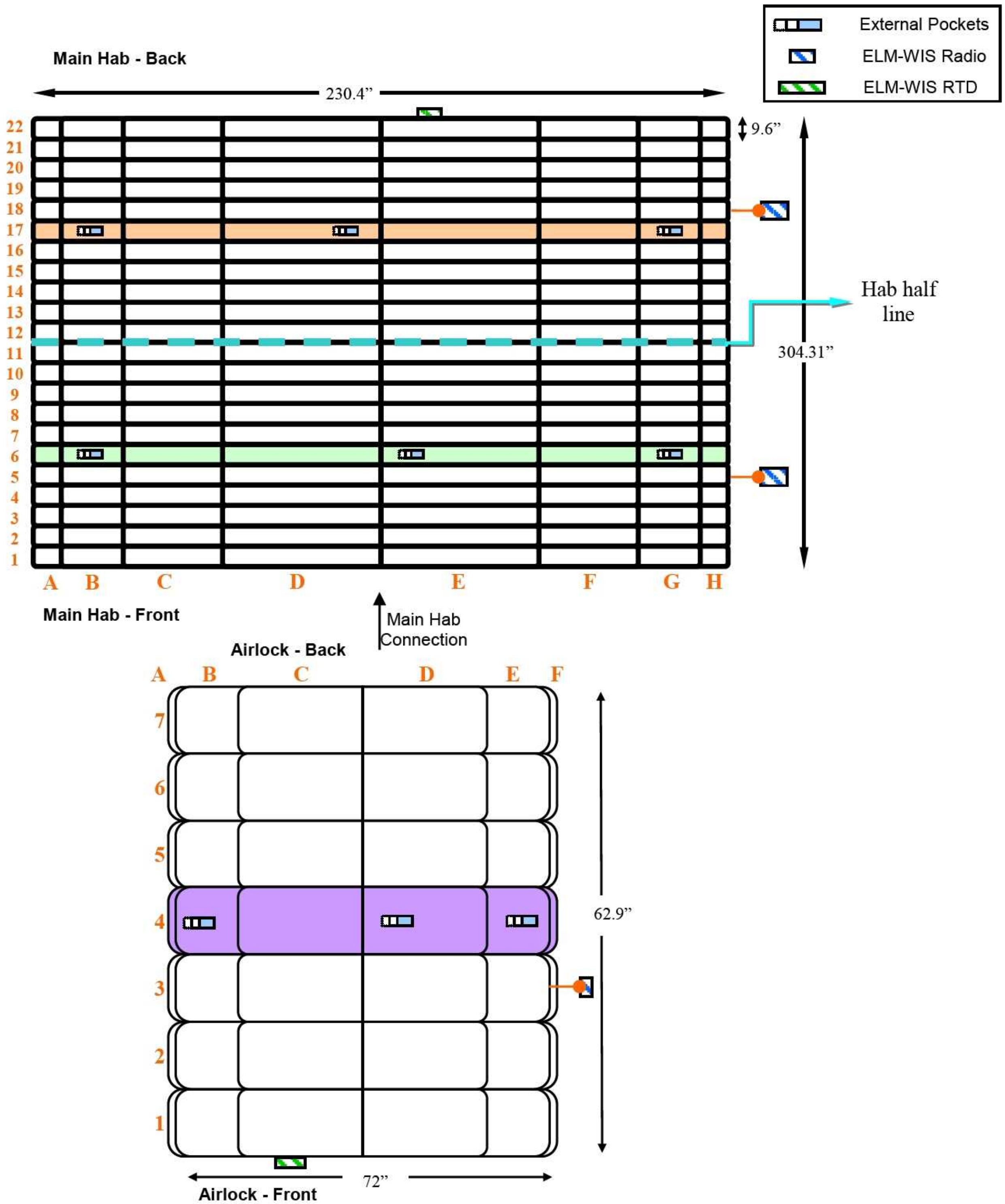

Figure 14: External pocket and sensor locations.

Operationally, the sensors were placed into the pockets before the habitat was inflated (Figure 15). This made deployment very simple and eliminated the need for ladders if deployment was to be post-inflation.

Figure 15: Installation of external sensors into habitat pockets.

Other external sensors were a weather station and external camera (Figure 16). The weather station gathered weather conditions and the external camera provided visual information on the external conditions of the habitat. The weather station was mounted on a pole a few feet from the habitat. The external camera was mounted to an adjacent building about 100 feet from the habitat and could be controlled remotely back at NASA/JSC. The deployment of these instruments was with the assistance of the NSF crew, as it was much more operationally intensive than the other sensors for the habitat.

Figure 16: Weather station mounted on pole external to habitat (left) and external camera (right).

The embedded sensors were perhaps the easiest operationally to deploy. These were temperature and pressure sensors (see Figure 17 below) that were affixed to the interior bladder of the habitat material using a bonding agent, and were installed during the development of the habitat.

Figure 17: Embedded pressure and temperature sensor antenna attached to cord assembly (left) and a close up of the pressure and temperature sensor (right).

These sensors were passive sensors and transmitted information via RF. By using these types of sensors for embedding into the habitat, the concern over wires was eliminated. However, after the sensors were embedded, it was necessary to ensure the sensors were not damaged during packaging, transporting, and deployment of the habitat.

VI. Implementation of a Wireless System

The instrumentation system designed for this project was based on a wireless network to provide quick communication, quick deployment, accessibility during remote operations, and the reduction of wires within the habitat. The system was designed so that the sensors connected wirelessly to a primary computer and PC104 (see Figure 3). The PC104 was redundant to the primary computer in case the primary computer failed, and also helped distribute the sensor data load. This data system was created such that a network switch allowed access to either the primary computer or PC104, making data collection and operations simpler.

Figure 18: The primary computer (laptop) and PC104 (box on right hand side of image).

While there were many benefits to implementing this type of wireless system, there were still some challenges. One of the main issues with these sensors is that each one operated differently and used varying wireless frequencies. Overall, there were few interference issues amongst the sensors because of the careful sensor selection. Additionally, there were few interference issues of the instrumentation system with the facility due to pre-coordination efforts with the United States Antarctic Program (USAP). However, there was one case where the RF system interfered with some of the camera signals. This interference was discovered during an integrated dry run that was completed of the wireless system in the lab. Without these integration efforts before transportation of the system to McMurdo, there would have been much more complexity during deployment.

Figure 19: Habitat mockup at JSC to integrate and test instrumentation system before transportation to McMurdo.

These integration challenges are due to the lack of a standardized wireless network system, and having this type of standardization would remove interference issues and greatly simplify implementation of wireless sensor networks in the future.

VII. Remote Habitat Environmental Monitoring Operations

Remote operations are one of the key aspects of this instrumentation system. Given the availability of the internet, it made remote monitoring of the habitat very easy to accomplish. Primarily, this setup allowed for the sensor data to be transmitted back to Johnson Space Center (JSC) from McMurdo, where it then would be processed and analyzed. Additionally, video data from the cameras allowed for monitoring of the sensors and weather conditions on the exterior of the habitat and gave a visual assessment of the habitat conditions. The interior cameras also gave visual data on the interior habitat conditions, allowed one to see if there was something defective with one of the sensors when gathering erroneous data, and allowed visual examination of who or what is moving within the habitat.

While there were several benefits to remotely monitoring the habitat through these sensors, there were still some challenges in maintenance of the sensors and security of the data during transmission. For instance, if there was a significant amount of snow that fell on the habitat roof, the external sensors would not necessarily be able to collect the necessary data. Given that there was no remote option for clearing the snow from the sensors, the operations involved having someone available at the site to clear the snow from the sensors. These interactions required active communication between those monitoring the data at JSC and those at McMurdo. Additionally, there were times when instruments were giving erroneous data and needed to be reset. The current implementation did not have an autonomous reset and required manual reset of the system from McMurdo. Manual intervention was also needed if there was any troubleshooting of the system.

VIII. Value of Testing in a Harsh Environment vs. Testing in a Lab

One of the interesting aspects of this project is that the implementation and deployment was tested in a harsh environment. While the crew did not have to don an entire space suit for life support while at McMurdo, they did have to wear Extreme Cold Weather Gear (ECWG) during set-up (Figure 20). While it was easier to maneuver in ECWG the deployment team still received an understanding of some of the issues that astronauts might face. Set-up of the inflatable habitat structure was completed in 50-minutes by a three man crew. The inflation took approximately 10-minutes.

Figure 20: Deployment of external sensors during different environmental conditions.

Thermal images in and around the habitat were taken to determine heat-leaks or issues with the insulation. Subtle differences were noted in areas where the insulation had been compressed and on the upper roof at the apex of the inflatable tubes[2]. Subtle differences due to external solar heating were also noted.

Once the inflatable habitat was erected, the instrumentation set-up and check-out began. Although the set-up and check out had been dry run in a laboratory environment at NASA/JSC, it was extremely valuable to conduct the actual set-up in an extreme environment. Setting up the network required for year round monitoring of the habitat required strong coordination between the NSF and NASA IT Security. NASA has to coordinate transmission of data during remote hours to meet NSF bandwidth requirements. Structural health monitoring and performance data was taken throughout the year and occasionally some of the sensors or equipment would experience off nominal readings, drop outs or malfunction. NASA would evaluate the data and working with ILC Dover and the NSF put together appropriate field test and evaluation plans to determine the issue and resolution. This strong coordination was conducted throughout the calendar year and gave valuable insight into the requirements for long term monitoring in an extreme remote environment.

IX. Ideal habitat monitoring system

As a result of the real-world experience in the implementation of this project and developing the lessons learned, an ideal habitat monitoring system for lunar and Martian habitats should encompass several features.

The key feature of an ideal habitat monitoring system is that it should be as autonomous as possible, minimizing crew input and maintenance. One way to accomplish this in terms of deployment would be utilize embedded and wireless sensors as much as possible. This would essentially integrate the monitoring system with the habitat, making it one system from the point of manufacture. Of course, the system should also be very robust, having multiple redundancies in both the instrumentation and the remote operations capabilities.

Another feature of this system would be to have a communications system from the Moon to the Earth, similar to the current internet infrastructure on Earth. This would require physical infrastructure to develop this type of system, and also tackling the challenges of bandwidth and speed between the Earth and the Moon. With this type of system implemented, most of the data could be provided to the public via websites to allow for additional data analysis beyond operational interests. The challenge would be in making the communications secure while still providing this type of access to the general public.

X. Conclusions and Future Work

To reiterate, the main objectives of the project were to design, construct, and test a proof of concept inflatable structure to understand the utility and durability over long durations. The portion of the work that was focused on by NASA and discussed in this paper was the deployment and operations of the instrumentation system used to monitor the performance of the habitat. The system discussed here was tested, integrated and implemented under a compressed schedule in order to deploy before the Antarctic winter, and this work was performed with minimal funds, such that resources had to be leveraged to accomplish this work. Thus, given the success of the deployment and the continued monitoring of the habitat, the conclusion is that an inflatable habitat with a structural health monitoring system can be quickly deployed in a harsh environment and monitored remotely. However, this concept was simplistic in nature and there is still much work to be completed before this type of system will be feasible on the lunar surface or on Mars.

An ideal habitat health monitoring system was discussed, and to begin to meet the requirements of that ideal system there is further work that needs to take place. It was mentioned that embedded sensors would be ideal for a structural health monitoring system, as they would essentially combine the health monitoring system into the habitat structure. To do this, it would be beneficial to invest more research into embedded sensor technology and increase the type of sensors that may be embedded into structures. Along with embedded sensor technologies, it would be necessary to also develop new manufacturing techniques to embed the sensors directly into the structural materials.

Additionally, it would also be beneficial to look into methods by which one would affix items to the walls or ceilings of inflatable habitats. In this study, a cord system was developed and Velcro and foam was used to affix items to the cords. In a lunar or Martian habitat, it is quite possible that the operating environment will be at a higher oxygen concentration and several of the items used in this study will be highly flammable. Thus, it would also be advantageous to consider other methods by which to affix items to walls and ceilings.

It will be necessary to implement a wireless system, as it reduces cables and mass. One of the challenges in this study was to eliminate interference amongst the different sensors and to work with the different frequencies. To remove this complexity, development of some sort of standardization is needed for wireless systems.

One disadvantage to the current system was that it was only able to remotely monitor the habitat, and not able to remotely operate any of the instrumentation. Thus, it was required to have someone available on site for any troubleshooting of the system. To eliminate this dependency, it would be advantageous to develop some sort of remote system in which an operator can have control to power cycle instruments within the system or do active troubleshooting. This, of course, would also require the development of a communications network around the lunar surface or Martian surface that was near real time.

This project provided invaluable experience in understanding the process of developing, deploying, and monitoring an inflatable habitat in a harsh analog environment. In conducting this exercise, several "lessons learned" were developed and will be implemented in the development of future habitats and habitat monitoring systems that will meet the mission requirements for living and working safely on the lunar and Martian surface.

References

[1]NASA Vision for Space Exploration, NASA-TM-2005-214062.

[2]Cadogan, D.P., Scheir, C., "Expandable Habitat Technology Demonstration for Lunar and Antarctic Applications", AIAA 2008-01-2014. 2008 SAE International.