Inflatable technology: using flexible materials to make large structures

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ABSTRACT

Space structures are one of the most critical components for any spacecraft, as they must provide the maximum amount of livable volume with the minimum amount of mass. Deployable structures can be used to gain additional space that would not normally fit under a launch vehicle shroud. This expansion capability allows it to be packed in a small launch volume for launch, and deploy into its fully open volume once in space. Inflatable, deployable structures in particular, have been investigated by NASA since the early 1950's and used in a number of spaceflight applications. Inflatable satellites, booms, and antennas can be used in low-Earth orbit applications. Inflatable heatshields, decelerators, and airbags can be used for entry, descent and landing applications. Inflatable habitats, airlocks, and space stations can be used for in-space living spaces and surface exploration missions. Inflatable blimps and rovers can be used for advanced missions to other worlds. These applications are just a few of the possible uses for inflatable structures that will continued to be studied as we look to expand our presence throughout the solar system.

Keywords: Deployable structures, inflatable structures

1. INTRODUCTION

The dream of human exploration beyond our home planet has excited and inspired generations across the world. The dreams of taking vacations to the Moon, visiting cities on Mars, or traveling through black holes to discover new life in other galaxies have been described in fiction stories for decades. Science fiction has always depicted these space missions with relative ease, using large scale, crewed space colonies. In reality, one of the biggest constraints to space exploration is size and volume of space structures. Given the size of current space launch vehicles, large structures cannot be delivered to space in fully assembled configurations. Modular designs, with in-space assembly, like the process used to construct the International Space Station (ISS), is a viable method to construct large assemblies, but requires a large number of launches. Utilizing deployable structures, however, a large scale structure can be put into space with a single launch.

1.1 Deployable Structures

Deployable structures are adaptive systems that can expand from its packaged, launch configuration, to its operational, expanded state. These devices have been used for many years on satellites and habitats to deploy solar arrays, antennas, and camera booms, for example. They fall into three main categories, depending on their use and construction: 1) deployment mechanisms, which are typically switches and latches that unfold rigid structure to lock into a straight position, like antennas or pointing devices; 2) expandable booms, which are commonly collapsed truss members that are linearly expanded using springs or motors, like those used on the ISS solar arrays and the Cassini spacecraft; 3) inflatable structures, which are multi-dimensional pressure vessels that are rigidized by being inflated with air and have been used as linear booms, spherical satellites, and habitable modules.

Achieving the dreams of deep space exploration and colonization will require the use of all three of these types of deployable structures on any future vehicle. With many occupants in a single vehicle, however, an inflatable habitat, offers the most significant benefit to a deep space vehicle. With a small, packed, launch configuration, an inflatable can fit into a launch vehicle and expand once in orbit, offering increased habitable volume over metallic designs for future deep space habitats.

While this paper is not a comprehensive list of all inflatable structures projects and concepts, it highlights applications for deployable structures used in the past and conceptualized for the future.

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2. LOW-EARTH ORBIT INFLATABLES

2.1 Project Echo

The first inflatable space structure was developed at NASA Langley Research Center in the late 1950's as an orbiting satellite known as Echo. The Echo satellites were a pair of spherical balloons that acted as passive reflectors for microwave signals. The Echo 1, shown in Figure 1, launched in 1960 and orbited the Earth until it reentered in 1968. Its first microwave transmission after its inflation was from JPL in California to Bell Labs in New Jersey. The balloon satellite, referred to as a 'satelloon' was a 100-ft diameter metalized balloon that could be seen as a bright, shiny object in the sky at its ~1,000-mi orbit. It was made of 0.5-mil thick Mylar and inflated with sublimating powders that turned to gas in space. As an inflatable structure, the potential damage from micrometeorite and orbital debris (MMOD) was a concern for the entire life of the satellite, but excess gas was provided to overcome any minor leaks.

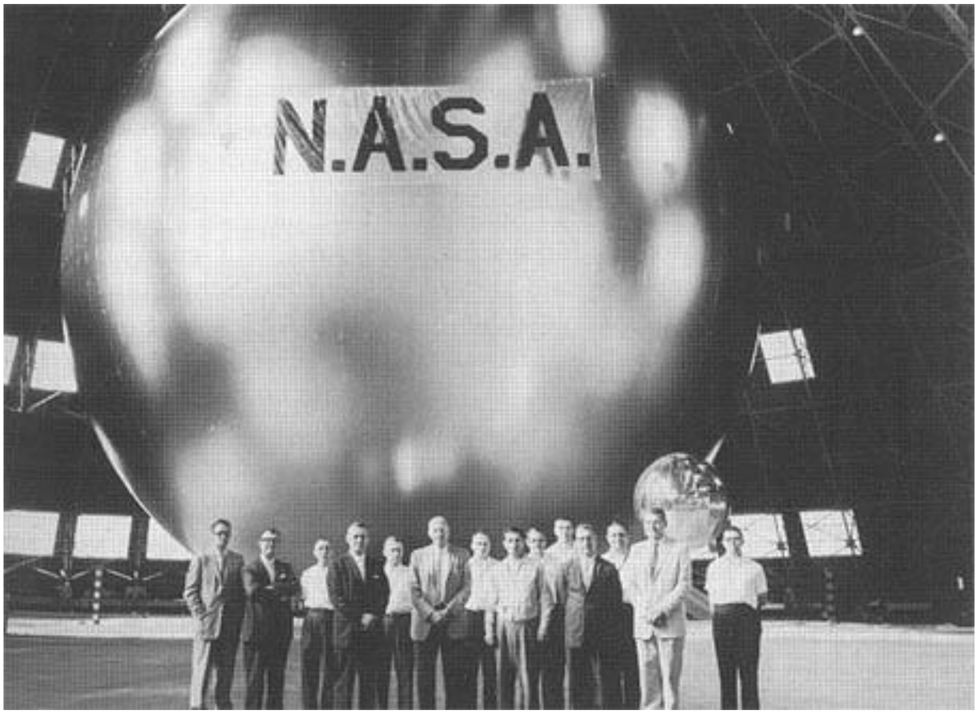

Figure 1. The Echo 1 team stands in front of their 100-ft diameter balloon in a hangar in Weekesville, North Carolina.[1]

The Echo 2 satelloon was put into a similar orbit in 1964 and was used until it burned up in 1969. It was larger than Echo 1, with a 135-ft diameter, and rigidizable in nature. The skin was made from 0.35-mil thick Mylar sandwiched and bonded between 0.18-mil thick layers of aluminum foil. The aluminum layers became rigid upon full inflation and allowed the satelloon to maintain its shape without a constant internal pressure. This allowed MMOD impacts to be tolerable without losing the satellite's shape. The Echo project showed engineers that inflatables were viable options for volume constrained space missions[1].

2.2 Inflatable Torus Solar Array Technology

Inflatable space structures have been more commonly used for non-habitable structures. Large, tubular structures can be constructed in space using inflatable booms that get their rigidity from internal pressure. They can be packaged and folded for launch and inflate to provide large, lightweight structures. In 1993, the Inflatable Torus Solar Array Technology (ITSAT) project was founded to create a solar array with inflatable booms. The booms were made of an aluminum foil sandwiched between two layers of thin plastic that became rigidized at low temperatures, below the material's glass transition temperature. A 12-ft long protoflight unit was constructed, as shown in Figure 2, and successfully tested at low temperatures.[2]

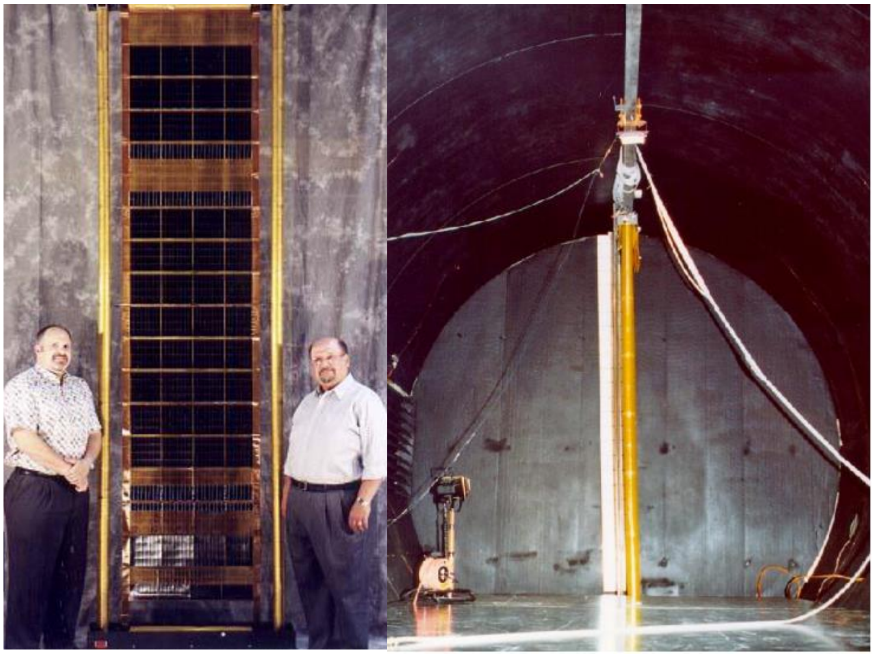

Figure 2. (Left) ITSAT prototype unit fully deployed[2] and (Right) test unit in thermal vacuum chamber[3].

2.3 Inflatable Antenna Experiment

In 1996, the STS-77 space shuttle mission deployed the Inflatable Antenna Experiment (IAE). The experiment was part of the Shuttle Pointed Autonomous Research Tool for Astronomy (SPARTAN) series that provided short duration, free flight opportunities for a variety of scientific studies. The IAE was a separate unit, attached to the SPARTAN satellite, which ejected after the SPARTAN tests were complete. The inflatable consisted of three, 92-ft booms, connected to a 45-ft diameter circular sheet of reflective fabric. The booms were made of neoprene coated Kevlar, while the reflector was composed of 62 sheets of 1-mil aluminized mylar[2]. The antenna was inflated by the crew and maintained its shape for a complete orbit, performing as expected. Figure 3 below shows its final inflated configuration[4].

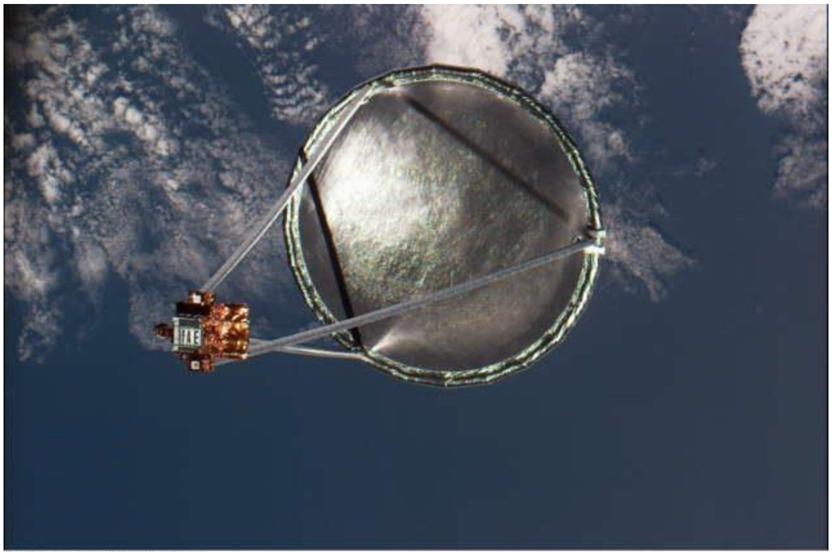

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Figure 3. Following its deployment from the Space Shuttle Endeavour, the IAE payload is fully inflated[2].

3. INFLATABLES FOR ENTRY, DECENT AND LANDING

3.1 Mars Pathfinder Airbags

Airbag systems are considered deployable structures and have been used as impact attenuation for Mars landers and rovers since 1997. The Mars Pathfinder lander was too large to land under parachute alone, so a landing system was needed to get it safely down to the surface. The airbag system was made of silicone coated Vectran fabric covered in multiple abrasion layers, made of uncoated Vectran. The overall system was composed of four large sections with six bags in each section. Each bag section was 17-ft in diameter and 17-ft tall, as shown in Figure 4. The bags were inflated at the end of the entry, descent, and landing (EDL) sequence, after parachute and backshell separation. At about 330-ft above the ground, the bags were inflated in a matter of seconds using gas generators powered by solid rocket motors. Retro-rockets then slowed the vehicle to 70-ft above the ground, where the vehicle fell at 18 g's deceleration. Upon impact, the assembly bounced 51-ft off the surface and continued to bounce another 15 times until coming to a complete stop. The airbags then deflated and were retracted towards the lander. The airbag system successfully protected the spacecraft and allowed the Sojourner rover to start its mission. Its success led to similar airbag systems being used on subsequent Mars rovers including the Spirit and Opportunity[5].

Figure 4. Mars Pathfinder's large, multi-lobed air bags are inflated and tested in 1995[5].

3.2 Inflatable Re-entry and Descent Technology

For EDL, the larger the diameter of the aeroshell, the bigger the payload can be, so by utilizing a deployable, inflatable aeroshell, you can increase your drag area and allow for large payloads to be delivered. Deployable structural decelerators can help deliver large payloads to Mars, by saving system mass and volume over a rigid aeroshell. Similarly, inflatable heatshields can deliver large payloads on re-entry at Earth from high speed Mars returns.

In 2000, the Russian and European Space Agencies tested the Inflatable Re-entry and Descent Technology (IRDT) demonstrator to put a payload in a 370-mi high Earth orbit and return it to land using an inflatable heatshield. The test launch ran into issues and did not achieve all of its objectives, but the inflatable heatshield was successfully deployed in space. The IRDT is shown in Figure 5 below[6].

3.3 Hypersonic Inflatable Aerodynamic Decelerator

NASA also began working on inflatable heatshields around the same time, with the Hypersonic Inflatable Aerodynamic Decelerator (HIAD) project. The HIAD structure is composed of inflatable stacked torus rings that are covered with a flexible thermal protection system. Over the past decade, the HIAD project has developed ground test articles from 10 to 20-ft diameters[7]. In 2009, a 10-ft test article was successfully launched and deployed in space at a 124-mi altitude as part of the Inflatable Re-entry Vehicle Experiment (IRVE) project[8], as shown in Figure 5.

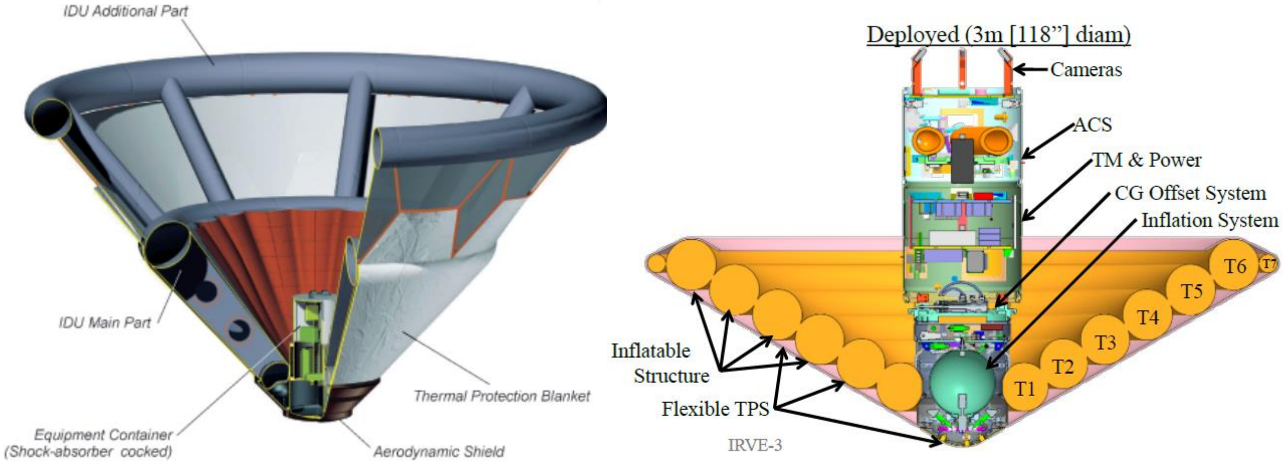

Figure 5. (Left) Fully deployed Inflatable Re-entry and Decent Technology heatshield[6] and (Right) HIAD inflatable aeroshell diagram in the IRVE flight configuration[8].

3.4 Low Density Supersonic Decelerator

For Mars EDL, the Low Density Supersonic Decelerator (LDSD) project has developed an inflatable aeroshell to carry large payloads through the atmosphere. Current Mars EDL systems can carry no more than 1-ton payloads, but larger landers will be required for human landings. The LDSD project seeks to develop a device to slow 2 to 3-ton payloads from the supersonic speeds of Mars atmospheric entry to the subsonic ground approach speeds necessary for a safe landing. The inflatable aeroshell has been designed using Kevlar materials in a torus shape with a 20-ft diameter. In 2014, the LDSD completed an Earth orbit flight where it was successfully deployed at an altitude of 190,000-ft, traveling at Mach 4.08. It traveled through a powered flight phase and slowed to Mach 2.54. The test of the inflatable was fully successful and lead to an additional test of a larger 26-ft diameter version in 2015[9]. An image of the LDSD in flight is shown in Figure 6.

Figure 6. An artist's rending of the LDSD fully deployed in the powered flight phase[9].

4. HABITABLE INFLATABLE STRUCTURES

Inflatables were conceptualized for habitable modules since before NASA itself. In the 1950's, scientists began proposing configurations for Earth orbiting space stations, and the concept of an inflatable laboratory was developed by Werner von Braun. His 'wheel' station was an early concept of a rotating space station to provide artificial gravity to the crew. The station was made of inflatable sections there were connected and deployed in orbit. Although this project never flew, it sparked the idea of using deployable modules that continues today.

4.1 Erectable Torus Manned Space Laboratory

In 1960, the Erectable Torus Manned Space Laboratory concept was proposed with Goodyear Aircraft Corporation. The laboratory was a 24-ft diameter torus that had the major advantage of being a single unit, not requiring in-space assembly of multiple modules. It could be carried into orbit by a single booster, use a deployable solar array, and have a life support system for six crew members. It could also spin around its central axis to provide artificial gravity for the crew. The flexible torus was constructed out of three-ply nylon cords, held together by a butyl elastomer rubber. A full scale test model was constructed by Goodyear and deployment tests were conducted to show that the fabric layers could be packaged around the hub to occupy only 2% of its inflated volume, as shown in Figure 7.

The biggest concern for the inflatable was related to the potential MMOD damage of the habitat in space. Small pinhole impacts were not a concern for the Echo satellite, but for a crewed habitat, a small hole would cause a leak that could turn catastrophic for the crew. This concern, coupled with the large price tag, led NASA to abandon the concept and solely chase the Moon with the Apollo program[1].

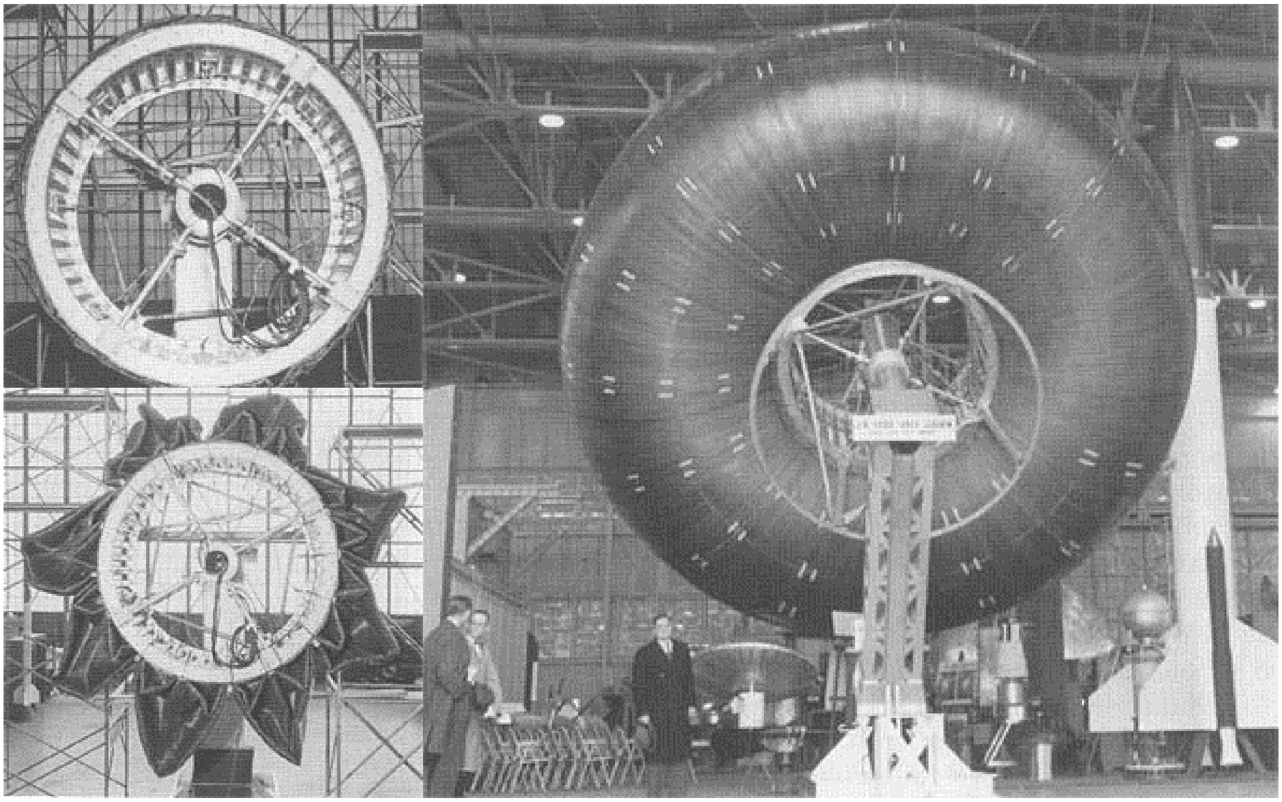

Figure 7. (Left) Testing indicated that the inflatable torus could be packaged around the hub so that it occupied only 2% of its inflated volume and (Right) a full size test model of the space station receives a visit from NASA Administrator James Webb in December 1961[1].

4.2 Volga Airlock

While NASA was studying large scale inflatables, the Soviet space program was attempting to conduct the first ever spacewalk, in 1965, using an inflatable airlock. An airlock is an integral part of moving between a pressurized spacecraft and the vacuum of space. Early Gemini and Apollo spacecrafts utilized a single chamber airlock for extra-vehicular activity (EVA) where the entire habitable volume was depressurized and acted as the airlock. For this design to work, all electrical components in the vehicle need to be designed to withstand the vacuum and temperatures of space. The inflatable airlock of the USSR, known as Volga, was designed out of necessity, because the Voskhod spacecraft was not capable of going to vacuum. The Volga was added over the main hatch of the vehicle to add EVA capability, as shown in Figure 8. It was a cylindrical shape, 8.2-ft in length and 3.9-ft in diameter when fully pressurized. It was packed on the side of the spacecraft with only 2.5-ft packaged length. It was made of a fabric layer with rubber airbooms to maintain its rigidity during the EVA. It supported a single crew member, Alexei Leonov, and was jettisoned after use. While the EVA was successful, the USSR did not use it again after this mission, as their subsequent vehicles had single airlock capabilities.[10]

During this same period, the US looked at inflatable airlocks as well with both the Goodyear and Whittaker companies proposing designs to NASA. Early designs were funded and developed, but none ever flew.[10]

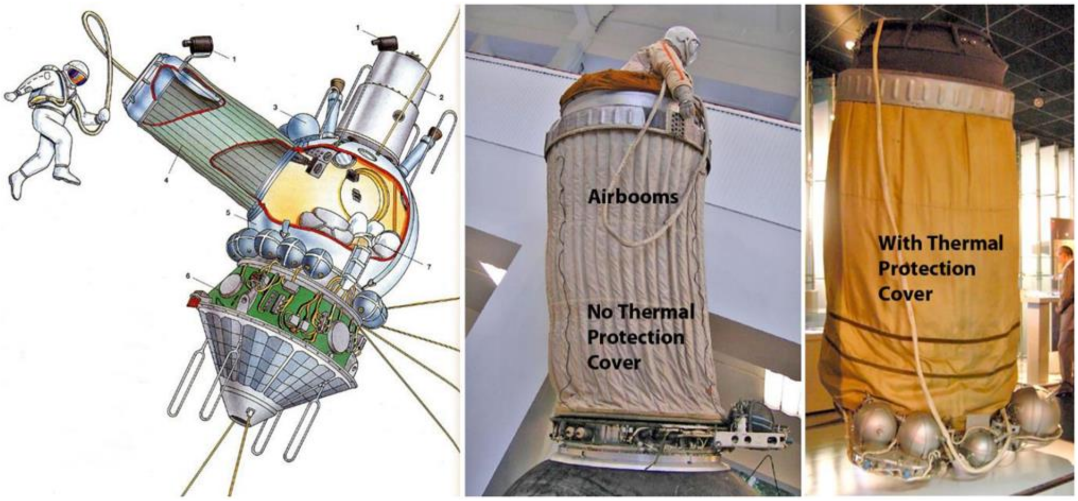

Figure 8. The Volga airlock, shown in a graphic attached to the Voskhod spacecraft. Test mockups are also shown with and without the thermal protection cover[10].

4.3 TransHab

The modern habitable inflatable module design was developed by NASA in 1997 with the Transit Habitat (TransHab) program. The TransHab was a 3 level, 27-ft diameter by 36-ft long inflatable habitat designed as a living space for missions to Mars and later for habitation on the ISS. With modern high strength materials, inflatables could be constructed using all fabrics that included a bladder, restraint layer, and MMOD layer, solving the major downfall of the previously designed inflatable space stations. The work that was done through this program led to several patents and advancements in the state of the art of inflatable structures. The design of the multi-layer fabric shell, which included the structural, thermal, pressure, and MMOD shields was the first of its kind, as shown in Figure 9. Sub-scale and full-scale tests were completed to prove out the design in its packaging and deployment process[11].

4.4 BEAM

Although TransHab never flew, it pioneered the work that led to the Bigelow Expandable Activities Module (BEAM) demonstration on the ISS. The BEAM module was developed by Bigelow Aerospace and installed on the ISS as the first ever human occupied inflatable module. BEAM is 13-ft in length and 10-ft in diameter when fully inflated, offering 565-cubic ft of living volume. The module was attached to the aft port of the Tranquility node of the ISS on April 2016 and remains in operation today. An image progression of its inflation process is shown in Figure 10. The demonstration has performed as expected and proves that inflatable habitats are feasible and applicable for future use[11].

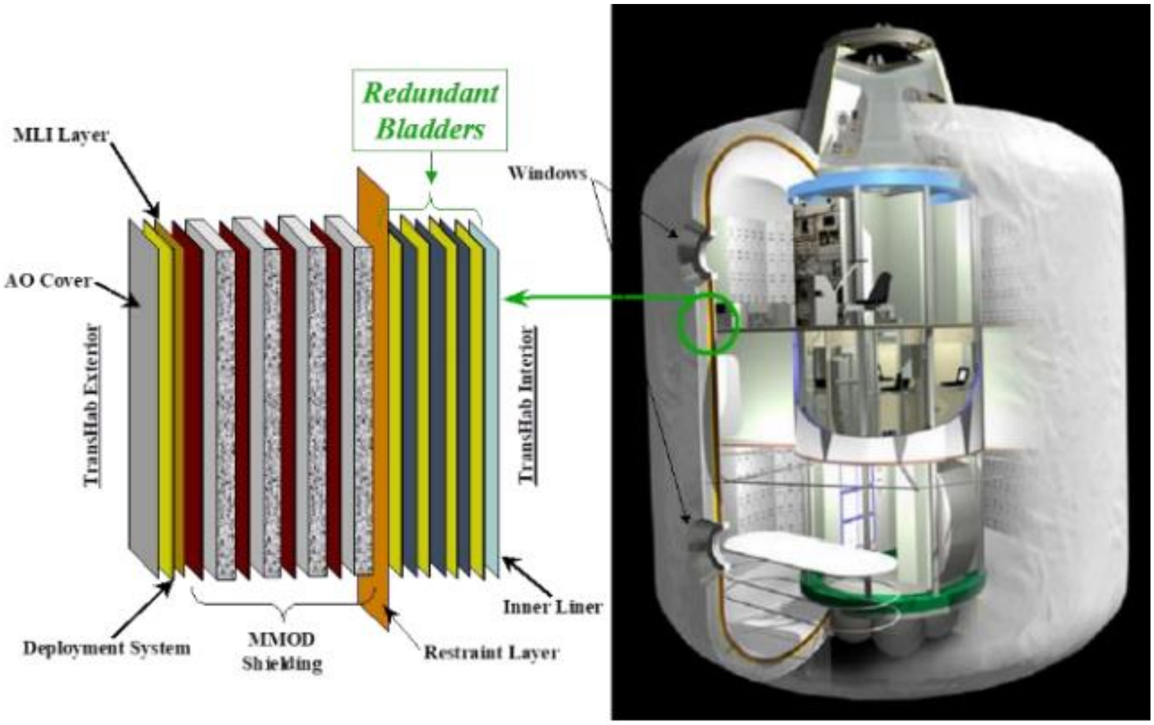

Figure 9. TransHab cutaway image with shell layer breakout[11].

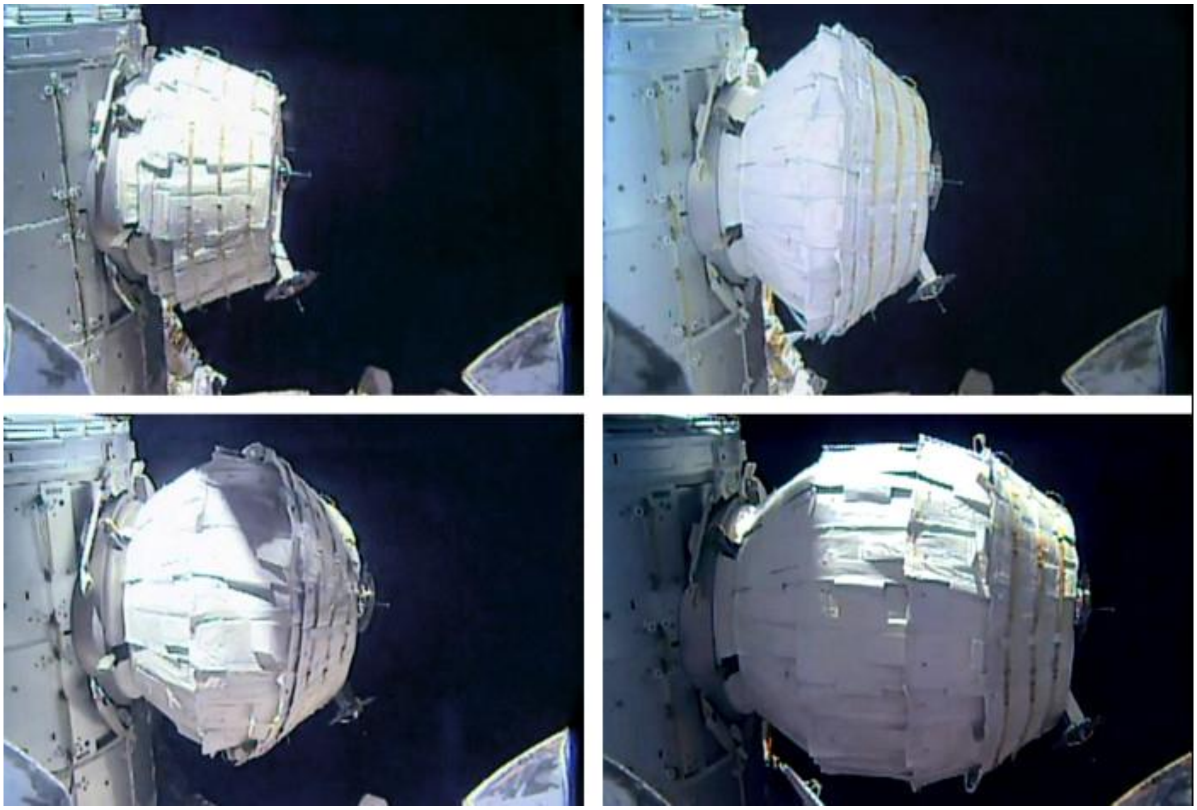

Figure 10. BEAM module inflation progression shown from top left to bottom right[11].

4.5 Surface Exploration

As we look towards the future of exploration, we look at surface exploration missions to the Moon or Mars. In these environments, inflatable structures have a great potential to provide livable volume. Artists and writers have been conceptualizing for years on what a surface habitat would look like and many concepts include inflatables. The same advantages previously discussed would apply on the surface, that a habitat could be packaged and launched in a small volume and inflated once on the ground. To protect against radiation, the module could be inflated in a hole or tunnel underground. The inflatable could be used as a habitat or an airlock, or a connecting tunnel between the two. During the Constellation program, starting in 2005, NASA developed concepts for lunar surface exploration using inflatables. Figure 11 shows some of these concepts including a concentric torus habitat, an expanding cylindrical tunnel, and a softgoods airlock[11]. While these are just a few of the potential applications, there are many more options yet to be envisioned.

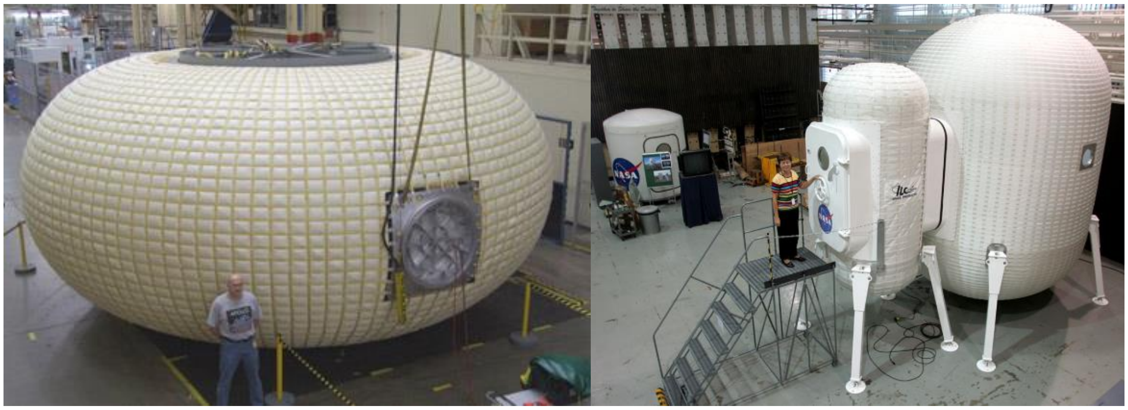

Figure 11. NASA lunar surface inflatable habitat design (left) and inflatable airlock design (right). [11]

4.6 Advanced Exploration Concepts

Some additional advanced concepts are worth noting for human exploration of Titan, Venus and Mars. The High Altitude Venus Operation Concept (HAVOC) for example, uses an airship with habitable gondola to explore the atmosphere of Venus with a crewed mission. The study led to a proof of concept model and analysis work, but was not funded for further development[12]. A similar blimp type vehicle was studied as an aerobot or surface rover for exploration of Saturn's moon, Titan. An inflatable wheel at the bottom of the blimp would be used to cushion a landing or act as a floatation device. Additional concepts were developed using inflatable wheels for surface exploration as an inflatable rover. The wheels were 5-ft diameter spherical inflatables that rotated around the central axis like a wheel. The size allows them to traverse well over 99% of the Martian surface. Figure 12 below shows test configurations of the inflatable rovers and the Titan Aerover blimp=13. While these designs only reached the conceptual stage, they prove that inflatable structures can be adapted to a variety of applications and provide a unique solution to volume and mass constraints for space exploration.

Figure 12. (Left) Titan Aerover blimp with inflatable wheels and (Right) inflatable rover concept vehicles[13].

5. CONCLUSION

Inflatable structures have a long history with space applications. From inflatable booms to planetary habitats, the unique advantages of deployable structures can be accomplished using fabric materials and internal pressure. As NASA looks towards human exploration in deep space, the need for larger livable volumes increases. With crews spending months and years on a transit to Mars, a large habitable volume is required. Traditional metallic modules cannot meet this need using current launch vehicles. Expandable, inflatable structures will be required for long term exploration. The ground tests, concept analysis and development work described in this paper have paved the way for deep space modules and the work on inflatables will carry on into the future.

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