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Expandable Module Technologies

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> "Within the next 10 to 15 years, the Earth will have a new companion in the skies. An artificial moon, from which a trip to the moon itself will be just a step, carried into space, piece by piece, by rocket ships."
>
> *Wernher von Braun*

INFLATABLE SPACE STATIONS

The idea of inflatable space stations may sound revolutionary, but this technology has a history stretching back even before the birth of NASA. The von Braun reference dates back to the great man's 1945 study for an American manned space station. The toroidal station (Figure 2.1), which spun to provide artificial gravity, became familiar to the American public over the next six years, and the design, which was elaborated at the First Symposium on Space Flight on October 12th, 1951, at New York's Hayden Planetarium, was popularized in *Colliers* magazine, and illustrated by famed space artist, Chesley Bonestell. The 1946 version used 20 cylindrical sections, each about three meters in diameter and eight meters long, to make up the toroid. The station spanned about 50 meters in diameter and guy wires connected and positioned the toroid to the central power module, which was fitted with a solar collector dish, designed to run an electrical generator. The 1952 version, which was enlarged to 75 meters in diameter and housed 80 crew, was

2.1 Von Braun's inflatable space station. Courtesy: NASA

improved by making the station's toroid out of smooth donut-shaped, inflatable sections made of reinforced rubber.

Inflatable technology was just one of many new technologies featured on the station.[1] The orbiting outpost would rotate to produce artificial gravity at the crew levels, which would feature two crew-height living and working areas, while the outer level would be dedicated to utilities. Space taxis would move from docking ports at the center of the station to arriving shuttles, and to conduct assembly operations of Moon-bound spacecraft near the station. Protecting the station's inflated torus would be a metal meteorite shield. The station would be in a 1,730-kilometer circular two-hour pseudo-Sun-synchronous orbit, meaning it would always be in sunshine as Earth revolved below it. Sporting a total volume of 18,400 cubic meters, the station would require 24 metric tonnes of a nitrogen/oxygen air mixture for pressurization, although use of a helium/oxygen atmospheric mixture would reduce the total mass of atmosphere aboard the station to 16 metric tonnes while eliminating the risk of bends in case of depressurization.

While von Braun's prediction that the station would become a reality in a few decades was not realized, the prospects of a space station did not pass unnoticed at NACA (National Advisory Committee for Aeronautics) Langley, where researchers speculated about the technology needed to develop an orbiting outpost such as the one von Braun had proposed. Then, in 1958, with the ink still drying on the Space Act that created NASA, interest in a space station ratcheted up considerably, and preliminary working groups concerned with space station concepts came alive within the newly founded agency and the aerospace industry. One of the working groups was NASA's inter-center Goett Committee, which met for the first time on May 25th–26th, 1959, to propose ideas for the next manned spaceflight objective after Project Mercury. One of the most enthusiastic members was Langley representative Larry Loftin, whose Project AMIS (Advanced Man In Space) presentation recommended "NASA undertake research directed towards the following type of system: a permanent space station with a 'transport satellite' capable of rendezvous with the space station". In his presentation, Loftin explained how the space station could serve as a medical laboratory to study the effects of space on astronauts, how researchers could study the effects of the space environment on materials, and how NASA could use the station to develop new stabilization, orientation, and navigational techniques. The minutes of the Goett Committee do not record the immediate reaction to Loftin's presentation, but several members of the committee had a strong feeling that a manned space station should be the project after Mercury.

To that end, the Manned Space Laboratory Research Group was formed. It consisted of six subcommittees responsible for the study of various aspects of space station design and operations: (1) Design and Uses of the Space Station; (2) Stabilization and Orientation; (3) Life Support; (4) Rendezvous Analysis; (5) Rendezvous Vehicle; and (6) Power Plant. The Group's goal was to send an astronaut to the Moon and back using an orbiting station as a launch pad for the lunar landing mission. By the fall of 1959, work had progressed to the

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[1] Writer Arthur C. Clarke and director Stanley Kubrick borrowed the torus design for their classic 1968 movie *2001: A Space Odyssey*. In one of the most iconic scenes of the film, the space wheel turns majestically to the waltz of Johann Strauss's *The Blue Danube* while a Pan Am shuttle with passengers aboard approaches the station.

point where Loftin made a three-point statement of purpose: Langley would study the psychological and physiological reactions of man in space over extended periods of time, provide a means for studying materials, structures, and control and orientation systems, and study means of communication, orbit control, and rendezvous.

SATELLOONS

At about the same time as the Manned Space Laboratory Research Group was formed, work was already underway developing inflatable structures for space—satelloons.[2] As the civilian agency responsible for US space activities, NASA has had a program of technology development for satellite communications ever since the agency was established in 1958. One of the agency's first projects—Echo—was to develop a passive communications satellite that reflected radio waves back to the ground. The Echo project began in 1956 as a NACA experiment to test the effects on large lightweight structures in orbit. Then, in 1958, when NASA was created and NACA dissolved, Echo (Figure 2.2) became a NASA project.

Built by the G.T. Schjeldahl Company (Grumman built the dispenser), the Echo satellite was a 31-meter-diameter aluminized-polyester balloon that inflated after orbital insertion. The balloon's development was enabled by a 12.7-micrometer-thick metalized biaxially oriented polyethylene terephthalate (PET) film material known as Mylar® (see sidebar). During ground inflation tests, up to 18,000 kilograms of air was needed to fill the 68-kilogram balloon but, once in orbit, several kilograms of gas were all that was required to fill the sphere. To ensure the balloon remained inflated in the event of micrometeorite strikes, a make-up gas system using evaporating liquid was integrated inside the satellite. It was also fitted with 107.9-megahertz beacon transmitters for telemetry purposes, powered by five nickel-cadmium batteries charged by 70 solar cells mounted on the balloon. Following the failure of the Delta rocket carrying Echo 1 on May 13th, 1960, Echo 1A[3] was placed into a 1,519–1,687-kilometer orbit by another Delta rocket on August 12th, 1960, and two-way voice links were set up between Bell Telephone Laboratories in Holmdel, New Jersey, and NASA's Jet Propulsion Laboratory (JPL) facility at Goldstone, California. The program was successful, since Echo demonstrated satellite tracking and ground station technology that was later applied to active satellite systems. Buoyed by the success of the world's first inflatable satellite, it wasn't surprising that Echo 2 was built. Managed by NASA's Goddard Space Flight Center in Beltsville, Maryland, Echo 2 was launched on January 25th, 1964. Fitted with an upgraded inflation system, which improved the balloon's smoothness, Echo 2's investigations were concerned more with the dynamics of large spacecraft.

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[2] The satellite was nicknamed a "satelloon" by those involved in the project, as a portmanteau of satellite–balloon.

[3] It finally re-entered Earth's atmosphere and burned up on May 24th, 1968.

2.2 Echo satelloon. Courtesy: NASA

Echo 2 was a 41.1-meter-diameter, metalized PET film balloon, which was the last satelloon launched by Project Echo. Launched on January 25th, 1964, on a Thor Agena rocket, it used an enhanced inflation system to improve the satelloon's sphericity, and sported a beacon telemetry system that provided a tracking signal, monitored spacecraft skin temperature (between −120°C and +16 °C), and measured the spacecraft's internal pressure. The system consisted of two beacon assemblies powered by solar cell panels and had a minimum power output of 45 milliwatts at 136.02 megahertz and 136.17 megahertz. In addition to the passive communications experiments, Echo 2 was used to assess the dynamics of large spacecraft and for global geometric geodesy. After the satelloon re-entered Earth's atmosphere and burned up on June 7th, 1969, NASA abandoned passive communications systems in favor of active satellites.

Mylar

Boasting a diameter close to the height of a 10-storey building, the Echo satelloons have been described as perhaps the most beautiful objects ever to be put into space. The challenge NASA engineers faced was how to place such a large structure into the tiny Thor-Delta fairing—a challenge that was to later inspire the TransHab invention. The solution was to use an inflatable system, which led to the satellite being made out of Mylar®. Mylar® polyester film was invented in the early 1950s and its use in the Echo project was just the first of many firsts in the space industry, with variants being used in space blankets and as linings in spacesuits.

INFLATABLE SPACE STATIONS: THE SATELLOON LEGACY

As the Langley researchers got to work examining the feasibility of various space station configurations in 1960, they soon agreed that the most promising design was a self-deploying inflatable. Thanks to their satelloon experience, Langley engineers already knew first hand that a folded station packed snugly inside a rocket would be protected during the rough ride through the atmosphere. That's not to say the Langley space station office didn't consider other concepts. They did. Among the non-inflatable concepts considered were designs for orbiting cylinders, and for a cylinder attached to a terminal booster stage, but these were rejected as dynamically unstable because they tended to roll at the slightest disturbance. A version of Lockheed's elongated modular concept was turned down because it required the launch of several boosters to place all the elements into orbit, and proposals for Ferris wheels in space were rejected because of Coriolis effects (see sidebar). While the Langley space station team had sound technical reasons for doubting the feasibility of these proposals, it perhaps wasn't surprising they favored the inflatable option because the technology was developed at Langley! The concept also happened to make good engineering sense because the inflatable option meant a light payload and, with hundreds of kilograms of propellant required to put just one kilogram of payload into orbit, any plan that lightened the payload was a winner.

Coriolis Effects: A Primer

A rotating space station will produce the feeling of gravity because the rotation drives any object inside the station towards the hull. This "pull", or centrifugal force, is a manifestation of objects inside the station trying to travel in a straight line due to inertia. From the perspective of astronauts rotating with the station, artificial gravity behaves similarly to normal gravity, but there are side effects, one of which is the Coriolis effect, which gives an apparent force that acts on objects that move relative to a rotating reference frame. This force acts at right angles to the motion and the rotation axis, and tends to curve the motion in the opposite sense to the station's spin. If an astronaut inside a rotating station moves towards or away from the axis of rotation, they will feel a force pushing them towards or away from the direction of spin. These forces act on the inner ear and can cause nausea and disorientation. Slower spin rates (less than two revolutions per minute) reduce the Coriolis force and its effects, but rates above seven revolutions per minute cause significant problems.

The first idea for an inflatable station was the Erectable Torus Manned Space Laboratory, developed by the Langley space station team led by Paul Hill and Emanuel Schnitzer with the help of Goodyear. Their idea was a flat inflatable unitized torus about seven meters in diameter. Since it was unitized, all its elements were part of a single structure that could be carried to orbit on one booster, which was a major selling point. All NASA needed to do was fold the station into a compact payload. The Langley space station team was so enthusiastic about its inflatable torus that they made a presentation on the design to a national meeting of the American Rocket Society. In the months following their presentation, Langley built and tested models of the Erectable Torus Manned Space Laboratory (Figure 2.3), including a full-scale research model constructed by Goodyear.

Development of the concept appeared promising, but the design had its drawbacks. For one thing, engineers worried that if the flexible material was not strong enough, astronauts moving around vigorously in the space station might somehow propel themselves so forcefully they would break through the fabric and shoot into space! There was also the more serious engineering concern related to the dynamics of the toroidal structure. When arriving astronauts moved equipment from the central hub to a working area at the outside periphery, it was suggested the station might become unstable, thereby upsetting its orbit. So, knowing astronauts working in the station would have no weight but would still have mass, the Langley engineers conducted studies to calculate the effect of astronauts moving about in the habitat. The results showed the mass distribution would be changed when crewmembers walked from one part of the station to another, producing a slight oscillation of the station. The next step was to investigate whether it was possible to alleviate the oscillation, so the Langley engineers built a three-meter-diameter elastically scaled model of the torus. By the time the model became operational in 1961, NASA had realized it had to either develop a more rigid inflatable or abandon the inflatable idea altogether.

2.3 Erectable Torus Manned Space Laboratory. Courtesy: NASA

While still pursuing the inflatable torus concept, the Langley group also explored other ideas. In the summer of 1961, it entered into a six-month contract with North American Aviation for a feasibility study of an advanced modular space station concept, which also incorporated inflatable technology. While rigid in structure, this advanced station could still be automatically erected in space. The idea was to put together six rigid modules connected by inflatable spokes or passageways to a central non-rotating hub. The 22.8-meter-diameter structure would be assembled on the ground, packaged into a snug launch configuration, and launched into space. To ruggedize it against micrometeorites, the rigid sections of the rotating hexagon airlock doors could be sealed when any threat arose to the integrity of the interconnecting inflatable sections. The structure was designed to rotate, making it possible for astronauts to take advantage of artificial gravity, which space station designers of the day believed was an absolute must for any long-term stay. Incidentally, the 22.8-meter-diameter size was selected because it provided the minimal rotational radius needed to generate the 1 G required for the station's living areas.

As the Langley engineers continued to investigate the potential of a rotating hexagon, they became increasingly confident they were on the right track. The only problem was finding a launch vehicle capable of lofting the 77,500-kilogram structure into orbit.

The solution was von Braun's Saturn, so a team of Langley researchers tried to figure out how to mate their space station to the Saturn's top stage. After working with a number of dynamic scale models, they refined a system of mechanical hinges enabling the six interconnected modules of the hexagon to fold into one compact mass. Tests confirmed the arrangement could be carried aloft in one piece and, once on orbit, actuators located at the joints between the modules would deploy the folded structure. The cost for the space station project was US$100 million. At the time, this was too much for NASA, which only had sufficient funding to finish Mercury and US$29 million for Apollo. Also, NASA wasn't even sure it needed a space station, because Apollo entailed only a circum-lunar mission, with the possibility of building a space station as a by-product of the Earth-orbit phase. Such uncertainty is par for the course in the aerospace industry, but it put Langley in a difficult situation. Since some sort of space station was still possible in the Apollo era, the basic technology had to be ready, so Langley continued their research. On May 19th, 1961, six days before President Kennedy's lunar landing speech, Loftin updated the US House Committee on Science and Astronautics on Langley's manned space station work. He passed around a series of pictures showing Langley's concepts for the inflatable torus and the rotating hexagon, before summarizing Langley's assessment of the status of the space station. The politicians were somewhat flummoxed, many of them not understanding what a manned space station was all about or how it might be used.

Six days after Loftin's appearance, President Kennedy stunned the world—including NASA—with his lunar landing speech. For 14 months following Kennedy's speech, NASA debated various mission modes. Many in NASA were certain the mission architecture would involve Earth-orbit rendezvous, which would require the lunar spacecraft to be assembled from components put into orbit by two or more Saturn rockets. This plan would therefore involve the development of orbital capabilities that might translate into a space station. With this in mind, the Langley team continued to explore the problems facing the design and operation of a space station. One continuing issue was how to protect astronauts from micrometeorite strikes, because big hits, especially those striking the inflatable torus, could prove disastrous. In an attempt to solve the problem, structure experts at Langley and Ames searched for a wall structure that offered the greatest protection for the least weight. They settled on a sandwiched structure with an inner and outer wall—a precursor to the layered structure that was later used in TransHab. Developed by North American, the outer wall was a meteorite shield comprising aluminum, backed by a polyurethane plastic filler that overlaid a bonded aluminum honeycomb sandwich. The wall seemed rugged enough to do the job, but no one really knew because there was no way to simulate micrometeorite strikes in any ground facility. For the inner wall, Langley's engineers decided nylon-neoprene, Dacron-silicone, saran, Mylar, polypropylene, Teflon, and other flexible and heat-absorbing materials could do the job. What made these materials attractive was their ability to withstand a hard vacuum, electromagnetic and particle radiation, and large temperature changes. At a symposium in July 1962, the Langley team presented summary progress reports on their space station research, concluding that the rotating hexagon was superior to the inflatable torus. The inflatable concept was still a possibility. But not for long.

BIRTH OF TRANSHAB

In 1963, an inflatable extension was proposed for the Apollo program but, by that time, technology based on hard aluminum shells had became prevailing, although suggestions of how to use inflatable technology were still discussed. For example, when NASA embarked on the development of its second-generation manned spacecraft called Gemini, engineers considered an inflatable delta wing as an alternative to the primary landing method of splashing into the ocean with parachutes. Another suggestion was an inflatable paraglider (Figure 2.4), which promised a controlled landing of a two-seat capsule on land, but the pressures of the space race left precious little time to resolve the technical challenges of the new system.

But NASA didn't do away with inflatable technology completely: inflatable air bags (Figure 2.5) were used on the Command Module of the Apollo spacecraft to ensure a vertical position following water landing. And, on the subject of the space race, the Americans weren't the only ones who recognized the advantages of inflatable structures in space: in 1965, Alexi Leonov conducted the first spacewalk from a cylindrical inflatable airlock fitted on board the Voshkod-2 spacecraft. The event almost ended in tragedy when a miscalculation in the pressurized size of Alexi Leonov's spacesuit caused him great difficulty when re-entering through the airlock's small hatch.

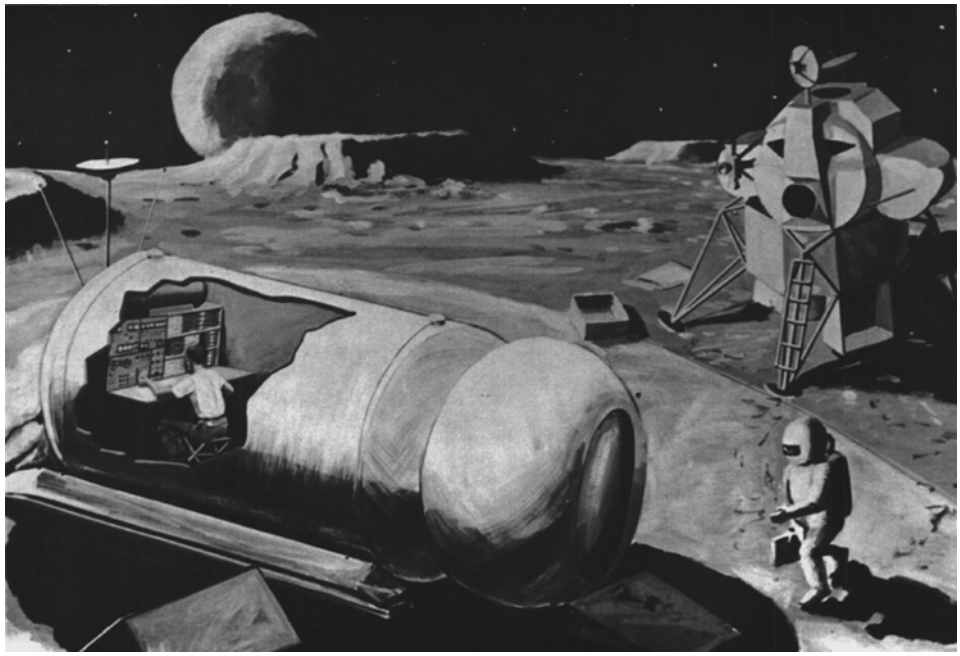
After developing its space station, Goodyear continued its research into the application of inflatable structures by proposing a lunar shelter (Figure 2.6) designed to support a crew of two for periods of 8–30 days at a pressure of 0.35 kilograms per cm^2. The shelter's outer and inner layer materials were polyaramid nylon fabric bonded by polyester adhesive to provide micrometeorite protection. A middle layer was a closed-cell vinyl foam for radiation protection and thermal insulation. The module and airlock, whose volume was 14.5 cubic meters, was constructed of a three-layer laminate consisting of nylon outer cover, closed-cell vinyl foam, and inner nylon cloth bonded by polyester adhesive layers.

Goodyear then developed a larger space module prototype for a proposed 36-meter-long lunar base habitat in 1968. The outer surface was covered with a nylon film-fabric laminate covered with a thermal control coating, and the inner layer was a gas bladder made from PET dipped in a polyester resin bath, and sealed by a polyvinyl chloride (PVC) foam. The middle layer was flexible polyurethane foam. Designed to operate at a pressure of 0.35 kilograms per cm^2, the entire structure weighed just 735 kilograms!

Next on the Goodyear drawing board was a two-meter-long inflatable airlock designed to be mounted on a Skylab-type vehicle. Developed through a joint NASA/Department of Defense venture in 1967, the structural layer used a thin filament-wound wire for tensile strength while flexible polyurethane foam provided a micrometeorite barrier, and a fabric-film laminate afforded thermal control. The compact unit weighed just 83 kilograms and fit into a snug 1.2-meter-diameter, 76-centimeter-tall cylinder. In the course of its research into inflatable applications, Goodyear also qualified a flexible fabric consisting of Nomex unidirectional cloth coated with Viton B050 elastomer. The combination offered potential applications for habitats because the Nomex/Viton structural layers could be laminated together for strength, and a flexible cable could serve as a bead to ensure structural integrity during deployment and when a structure was inflated. Another concept developed at the time was the rigidization of structures to ensure the volume of the habitat was retained

2.4 Inflatable paraglider concept. Courtesy: NASA/Smithsonian Air and Space Museum

2.5 Airbags used on the Apollo capsule. Courtesy: NASA



2.6 Lunar shelter concept. Courtesy: NASA

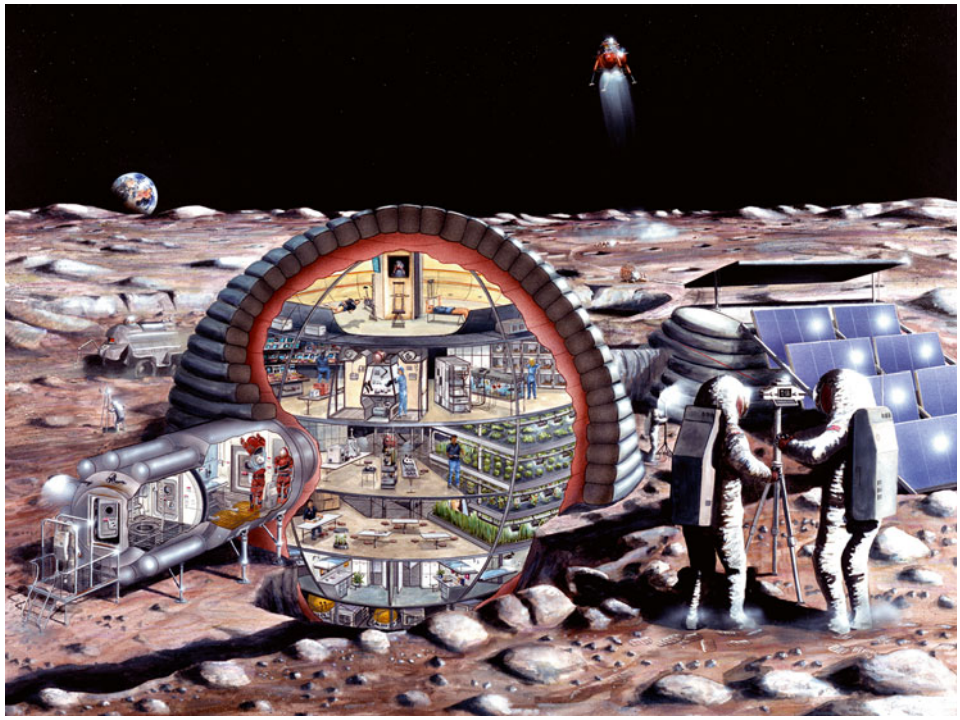
after inflation gases had been used. It was suggested rigidization might be accomplished by incorporating a flexible mesh core material impregnated with a gelatin resin between membranes of a sealed structure which expanded to harden the core when the wall cavity was vented to space vacuum during structure deployment—some of this technology laid the groundwork for NASA's Surface Endoskeletal Inflatable Modules, which are discussed in Chapter 8.

In addition to Goodyear, ILC Dover, developer of spacesuits, also became a leader developing advanced technology inflatable systems, including a hyperbaric chamber that had similarities to space habitats. The 0.8-meter-diameter, 2.1-meter-long structure included a bladder layer to retain pressure, and a restraint layer to support structural loads. The bladder comprised a urethane-coated polyester, and the restraint was a series of polyester webbings stitched to a polyester fabric substrate.

Meanwhile, Apollo came and went and very little happened in the world of inflatable structures. For many years, the Langley engineers hoped the idea of inflatable modules would catch on, but the idea was cast aside, not because people doubted the technology, but because nobody championed the cause. The result was that, by the mid-1970s, the development of inflatables had come to a halt at NASA. The concept was revived briefly in the late 1980s when the Bush Administration talked about returning to the Moon and Mars, issuing National Security Presidential Directive 6, authorizing the Space Exploration Initiative (SEI). At the time of the SEI, the fundamental advantages of inflatable structures still held true (a large amount of volume packed into a slim rocket fairing equals savings on mass and cost), which is why the technology was once again considered by NASA engineers. Faced with the same problem as their predecessors in the 1960s, NASA needed to get a significant amount of volume into space and had only a limited amount of rocket fairing room with which to do so. The solution? An inflatable crew habitat. In 1989, one of the planetary exploration concepts NASA proposed was the Inflatable Habitat Concept for a Lunar Base (Figure 2.7).

In the same year, the Lawrence Livermore National Laboratory studied the feasibility of inflatable modules to be used in a future space station (echoing the concept von Braun suggested almost four decades earlier) or possibly integrated in the space station Freedom, which was moving into hardware fabrication phase. The cylindrical and toroidal shapes investigated in the study were five meters in diameter and approximately 17 meters long. The dimensions of the deployed modules were not much bigger than the Shuttle's cargo bay, but they offered big savings on weight and take-off volume. A prototype inflatable sphere was developed in 1989 as part of the SEI initiative, but it kept tearing along the seams. Perhaps as a result of the problems encountered with the sphere, concepts for inflatable Moon lodges and construction shacks never made it much further than the proposal stage, although the inflatable cause was far from dead.

In 1996, NASA's Johnson Space Center (JSC) began to study a Moon mission that envisioned the use of an inflatable habitat to support checkout activities before a permanent habitat was established. ILC Dover was contracted to study various configurations and sub-assemblies including bladder, restraint layer, and thermal and micrometeoroid layers. The system was designed to sit atop a landing craft and expand on the surface. A number of concepts were assessed for the lunar surface module's construction. These included a rugged bladder design that was a dual-walled self-sealing silicon-coated



2.7 Inflatable Moon base concept. Courtesy: NASA

Vectran fabric with film laminates that afforded simplicity and cold temperature deployment properties. Several restraint layer concepts were also investigated, including coated single-layer fabrics, layers with circumferential and axial webbing over coated fabric, and structures with circumferential toroidal webbing over an internal axial layer. The selected wall system comprised a restraint layer that applied an outer Kevlar layer overlaying a structural denier plain weave.

Lowell Wood, a physicist at Lawrence Livermore National Laboratory, was one of the more vociferous inflatable proponents. He had been pushing inflatables as a way for this lab to take advantage of the SEI. Sadly, like so many NASA initiatives, SEI was plagued by a lack of budgetary and political support, and eventually went nowhere. But the idea of an inflatable crew habitat lived on and was revived as a crew quarters for the International Space Station (ISS). Despite the change in purpose, NASA again began focusing its attention on an inflatable habitat, conceived in early 1997 by a JSC engineering team under the direction of William Schneider, who had worked on micrometeorite protection for the Shuttle. Until Schneider's arrival, micrometeorite protection had been the inflatable's Achilles heel, but Schneider's team solved that by devising a Nextel–foam combination, which is why Schneider generally gets credit for being the Father of TransHab. The advantages of TransHab were obvious (Table 2.1). Like all inflatable systems, TransHab offered

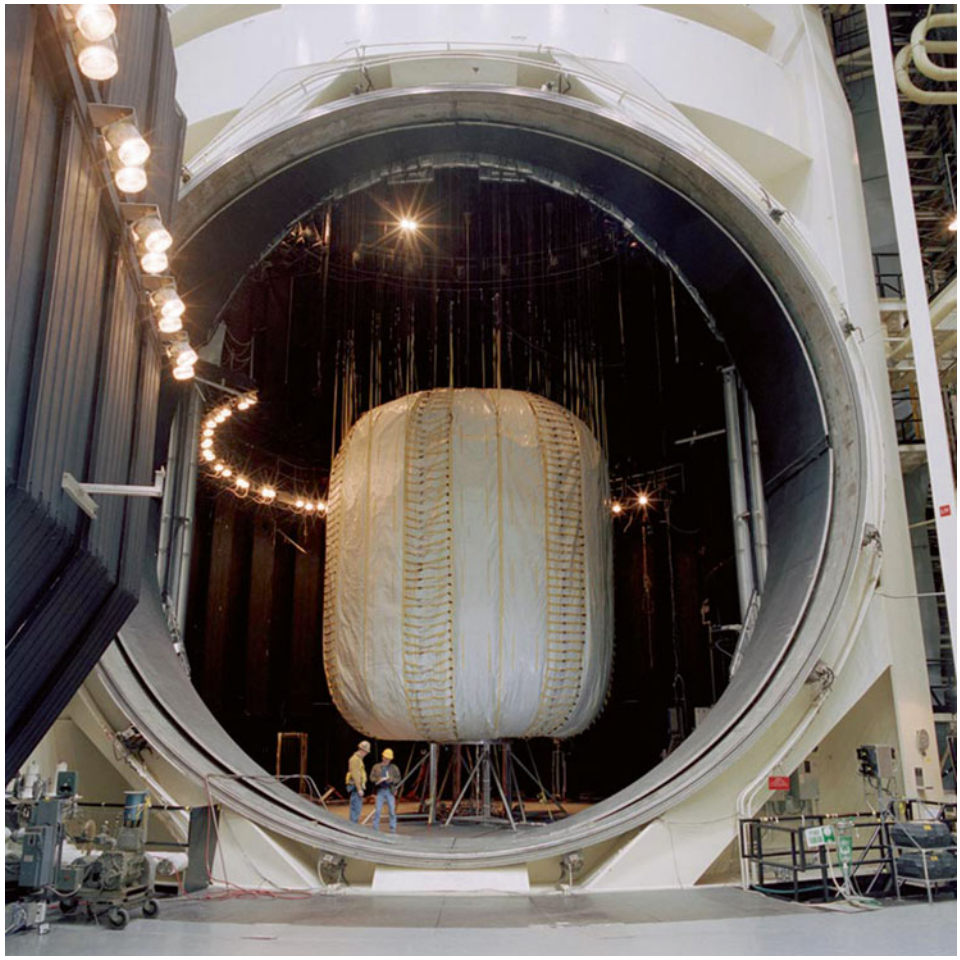
Table 2.1. TransHab by the numbers.

Weight at launch	13.2 tonnes
Length at launch	11 meters
Diameter at launch	4.3 meters
Diameter after inflation	8.2 meters
Inflated volume	339.8 cubic meters

a huge amount of on-orbit volume while taking up a small amount of rocket fairing space relative to a traditional metallic structure. Additionally, the habitat provided enhanced protection from radiation compared with traditional metallic habitats. The reason is this. When exposed to cosmic rays or solar flares, metallic habitats may suffer from damaging secondary radiation wherein the metal creates a scattering effect. In contrast, due to non-metallic material being used as the primary envelope, inflatables can significantly reduce this dangerous phenomenon. But could the inflatable habitat be adapted for the ISS? The team was given a year and US$2 million to find out. They got to work quickly, and submerged a mock-up in the Neutral Buoyancy Laboratory where it was overfilled with air and subjected to four times the maximum operating pressure of the station. It passed with flying colors. Incidentally, the space station's modules are designed to hold two times normal pressure.

Next was a vacuum test. The team assembled a test article in the Apollo-era vacuum chamber in Building 32 at Johnson (Figure 2.8). The test article was a slightly smaller version than the flight mode, which would be 8.2 meters in diameter and 11 meters high (if a human centrifuge was approved, the module would grow by another meter in height). The flight model would weigh about 11,800 kilograms empty and 15,875 kilograms outfitted with water. Compare these dimensions with Boeing's US Laboratory Module, which would have been 4.5 meters in diameter, 8.5 meters long, and weighed 14,500 kilograms. The team conducted a vacuum test that confirmed the module could fit into the Shuttle bay and unfold and inflate afterwards. The module was inflated to space station pressure of 1.04 kilograms per centimeter and, except for some restraining cords being hung up in the eyelets, it performed perfectly.

At the time of the tests, the price of a TransHab was US$200 million, compared to the US$300 million it had cost Boeing to build the Unity node. One of the reasons NASA didn't commit to the inflatable option was Boeing. As a prime contractor, the aerospace behemoth wasn't going to give up easily, which, for the astronauts and cosmonauts, was a shame. The sleeping quarters in TransHab would have been 25% bigger than those in the Boeing habitation module and the quarters could have been used as a storm shelter thanks to the surrounding water. Apart from the cost savings (a poor man's way of getting more volume), TransHab also represented pioneering technology and a bridge to exploration down the road—a philosophy that sat particularly well with the astronauts. Sadly, despite showing great technical promise, when it was revealed that the ISS program was US$4.8 billion over budget, the TransHab/crew habitat program was canceled by Congressional bean-counters in 2000.



2.8 Vacuum chamber with TransHab test article. Courtesy: NASA

THE RUSSIAN AND EUROPEAN INFLATABLE EXPERIENCE

Despite Leonov's harrowing experience with the inflatable airlock, the Soviets pressed on with developing the technology. In 1966, after many failures, the Soviet Luna-9 unmanned probe soft landed on the Moon thanks to the use of inflatable air bags that softened the impact onto the lunar surface. This method played a lasting role in planetary exploration in the USSR and in the US, and to date remains the most significant application of inflatable technology for space exploration.

In 1984, Soviet scientists placed instrument-carrying balloons on a pair of Vega spacecraft heading to Venus. Following their flyby of the planet, Vega probes dropped re-entry capsules, which in turn released a pair of traditional landers and inflatable balloons to float

in the atmosphere. Then, in 1996, the landing system first proven during the Luna-9 mission was resurrected in the post-Soviet Mars-96 mission. A pair of landers carried on board the main spacecraft were to land on the surface of Mars. Shortly before reaching the surface, a pair of airbags would inflate around each lander to soften the impact. The spacecraft would bounce and continue to bounce until they finally came to rest. Lines holding the two bags would be cut and the lander would free fall to the ground. In addition to landers, the Mars-96 spacecraft also carried a pair of penetrators—needle-shaped vehicles designed to strike the surface of the planet and penetrate four to six meters into the soil. After braking in the Martian atmosphere with the help of an inflatable heat shield, the penetrators were expected to strike the surface at a speed of about 60–80 meters per second. Unfortunately, Mars-96 was stranded in Earth orbit and neither the inflatable bags nor the inflatable heat shields on its penetrators had a chance to prove themselves.

In the same launch window for Mars-96, NASA launched the Mars Pathfinder mission, which utilized inflatable bags to ensure a soft landing. The spacecraft completed a flawless trip to Mars and the inflatable airbag system successfully delivered a lander and a small rover on the surface of the Red Planet in July 1997. Seven years later, NASA used the inflatable cushioning system again, delivering a pair of Mars Exploration Rovers onto the surface of the Red Planet.

Back in Russia, many space projects faced a budget crunch in the wake of economic problems of the post-Soviet period, but the European Space Agency (ESA) reckoned the Russian inflatable heat shield system from the Mars-96 project had potential, possibly as an affordable method of returning cargo from the ISS. To that end, ESA co-funded the Inflatable Re-entry and Descent Technology (IRDT; Figure 2.9) project together with the European Commission and Daimler Chrysler Aerospace, DASA, and, in February 2008, a pair of IRDT devices were launched on a Soyuz rocket. The smaller IRDT device was to return an experimental package from orbit, while the larger IRDT device was attached to the Fregat upper stage to protect the Fregat during its re-entry. After the flight, both IRDT devices successfully inflated and re-entered, but a radio beacon failure on both payloads coupled with bad weather at the landing site hampered search efforts and only the small device was recovered.

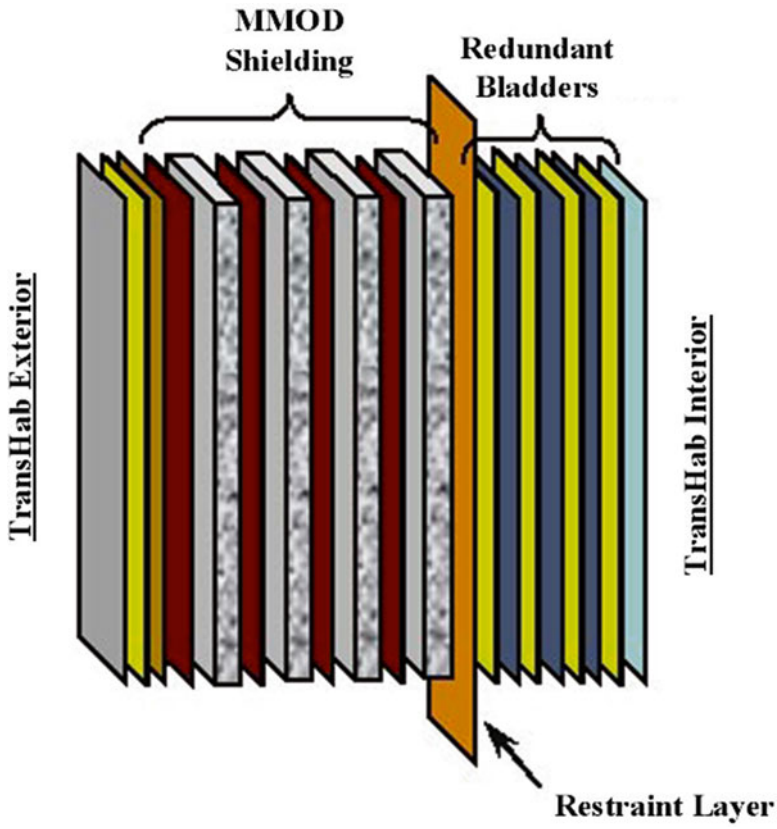
More recently, the company that built Leonov's spacecraft has jump-started work on multilayered inflatable structures. In its annual report for 2012, RKK Energia said the new project might pave the way for a new generation of space station modules, interplanetary spacecraft, and interplanetary bases. According to RKK Energia, inflatable modules will not only provide three times more volume and one and a half times more surface area per unit of mass than metal structures, but also promise lighter micrometeorite and radiation shielding. On the Russian ISS segment, an inflatable module could increase comfort for the crew and also provide increased volume for science experiments, including a centrifuge to create artificial gravity. RKK Energia began development of the inflatable module in 2011 using its own funding, in the hope of getting a future contract for such a structure from the Russian space agency, Roskosmos. During 2012, RKK Energia evaluated two sizes of the module, which could be launched on the Soyuz-2-1b rocket or on the Proton-M and Angara-A5 rockets. In the course of the project, RKK Energia procured domestically produced materials suitable for the inflatable module and developed a structural design and composition of the module's flexible skin. Samples of the materials were tested and a

2.9 Inflatable Re-entry Descent Technology. Courtesy: NASA

scale model was used to assess the module's skin. The troublesome issue of micrometeorite protection was dealt with by a research center at Roskosmos (TsNIIMash research institute), which developed an undisclosed protective material that was tested alongside traditional AMG-6 aluminum alloy used in the aerospace industry. According to the company, the new materials provided 95% of the required level of protection. During 2014, RKK Energia and its contractors planned to build a one-third-scale prototype of the module for ground tests.

TRANSHAB: A PRIMER

Going back to the late 1990s, practically everyone thought TransHab was cool, and potentially very useful, but it didn't fit into NASA's plans for the space station and was abandoned. We'll get into the technical aspects of this invention in the next chapter but, before we do, it's useful to have an understanding of the basic structure, so what follows is an overview of this inflatable technology. At its most basic, TransHab is a unique hybrid structure combining the packaging and mass efficiencies of an inflatable structure with the advantages of a load-bearing hard structure. TransHab's inflatable shell comprises multiple layers of blanket insulation, protection from orbital and meteorite debris, an optimized restraint layer, and a redundant bladder with a protective layer (Figure 2.10). With almost two dozen layers, the structure's inflatable shell is as unique and tough a design as they get: the outer layers are layered to break up particles of space debris and micrometeorites that may hit the shell at speeds of several kilometers per second, while the shell provides insulation from temperatures in space that can range from +121°C in the Sun to –128°C in the shade.



2.10 TransHab layers. Courtesy: NASA

The inflatable shell, which is TransHab's primary structure, is composed of four functional layers: the internal scuff barrier and pressure bladder, the structural restraint layer, the micrometeoroid/orbital-debris shield, and the external thermal protection blanket. The shell is folded around the core at launch and deployed once on orbit. Its function is to provide the crew with living space, and provide debris protection and thermal insulation. The key to the rugged protection is successive layers of Nextel, a material used as insulation under the hoods of many cars, spaced between several-centimeter-thick layers of open cell foam, similar to that used in chair cushions. Particles hitting at hypersonic speeds expend energy and disintegrate on successive Nextel layers, spaced by the open cell foam. For extra protection, the shell includes a thin layer of Kevlar. The layering has been tested extensively and repeatedly,[4] including having projectiles fired at the fabric sandwich at speeds of seven kilometers per second.

Underneath the outer shell is the restraint layer, woven from 2.54-centimeter-wide Kevlar straps. This layer is just as tough as the outer shell but it's a different type of toughness because the restraint layer's job is to contain pressure—four atmospheres of it. Under the restraint layer is an inner liner of Nomex that provides fire retardance and abrasion protection, and then there are three Combitherm (a material commonly used in the food packaging industry) bladders that form redundant air seals.

TransHab is a fabric construction, so it's hardly revolutionary, but the idea of launching such a structure into low Earth orbit (LEO) strikes many people as pretty radical—perhaps it's because the word "inflatable" is often used when describing the technology: NASA discouraged use of the word because it conjures up images of balloons. But let's focus on the fabric element. Many thousands of years ago, cavemen created temporary housing using animal skins stretched over bones while following herds of animals in their search for food. Over the centuries, other fabrics were developed to enhance similar structures and to fashion tents. More recent is the appearance of tensile fabric structures, which are now at the forefront of architecture with their dynamic shapes, sweeping boldness, and technological flexibility. If you watched the 2012 Olympics, chances are you saw several examples of what can be accomplished using tension fabric structures: the basketball arena was the largest temporary structure of the Games: the velodrome featured interior permeable fabric screening, and the press bar was an exterior canopy shelter. NASA understood the value of fabrics more than 50 years ago, just as it understood the value of the inflatable concept but, as is often the case when developing radical technology, the concept was mothballed not once (when the Moon program was halted), but twice (following the SEI). NASA didn't stop work developing fabric habitats; it just decided to rely mostly on aluminum because it was a known, safe, and reliable material. But, eventually, inflatable habitats made their way back to the table with the idea of attaching a module to the ISS. Over the years, NASA engineers continued to refine their ideas and concepts for inflatable structures until, one day in 1997, a Tiger Team was formed to design an interplanetary vehicle habitat for a crew of six to travel to and from Mars. The team, which comprised half a dozen engineers and a space architect, was led by Dr. William Schneider. The team identified one major challenge: how to deliver the habitat into space using

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[4] These tests were so dramatic that the cable-TV show *Scientific American Frontierp*, with host Alan Alda, included the test shots as part of a television series on Mars mission technology.

existing launch vehicles. Because of the considerable volume required per crewmember, for food, equipment, and consumables, the only viable solution was to use an inflatable structure. One member of Schneider's Tiger Team was Kriss Kennedy, a space architect at NASA's JSC. He had been working on the Mars Mission Studies and had already helped design various types of habitats as transit and surface habitats. When the team began designing the inflatable transit habitat, it was Kennedy who coined the name TransHab (short for *transit habitat*).

The original ISS TransHab—had it been approved—was to be carried in a compressed state on board a Shuttle and inflated once the Orbiter reached the outpost. TransHab would have provided a huge amount of space compared with traditional hard-shelled modules. The interior (Figure 2.11) would have featured three spacious levels—the lower level holding a dining area, the middle level a mechanical room and living quarters, and the top level an exercise room and shower. Water tanks would surround the middle level where the living quarters were and two portholes allowed views of Earth and the stars. With all these fancy options, you may be wondering why the technology didn't catch on, especially since NASA had been studying them for decades. One of the biggest hurdles was psychological because most people just didn't—and some still don't—believe it was possible for fabric to be as strong or stronger than metal. Even astronauts were among the early skeptics although, once they saw what TransHab had to offer in the way of living space, they became more supportive of the project. It was the concern over the use of the word

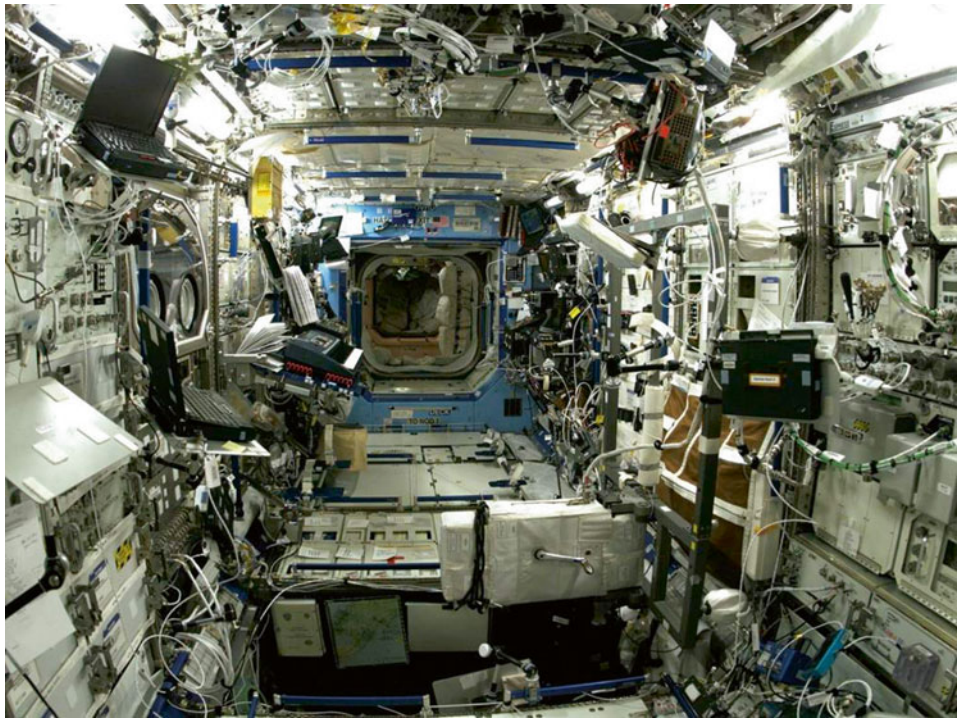
2.11 Deputy NASA Administrator Lori Garver next to the interior of a BA-330, a descendant of TransHab. Courtesy: Bill Ingalls/NASA

"inflatable" that perhaps caused the most concern, prompting Kriss Kennedy to pull out a balloon and pop it whenever he gave a public talk about the project. The popping was mainly to get the audience's attention, after which Kennedy would patiently explain that a balloon is a balloon and an inflatable structure is *not* a balloon. Horacio de la Fuente, the project's deputy manager for technical development, preferred a football analogy. He would explain that a football and TransHab have bladder systems to hold air. In fact, TransHab has three bladders covered by alternating layers of ceramic fabric, polyurethane foam, and Kevlar.

While talks by Kennedy and de la Fuente helped persuade skeptics TransHab was safer than it appeared, people really started to wake up to the integrity of the inflatable's space worthiness following the ballistic tests. The target of the tests was TransHab's outer layer, comprising mustard-colored Kevlar webbing (woven by hand to reduce the number of seams, thereby adding strength) and sheets of ceramic fabric (Nextel) separated by layers of foam. To test the module's ability to protect the crew from micrometeorite strikes, the TransHab team fired marble-sized aluminum balls at the shell at velocities of seven kilometers per second. Each time, the Nextel decimated the balls before they reached the air-containing bladders. Then the team turned their attention to the reinforced aluminum plates used in the ISS and performed the same test. The result wasn't pretty: the balls ripped chunks off the back of some of the plates, which were more than three centimeters thick, and left craters that left little to the imagination of an astronaut.

Many people were disappointed when development ceased on TransHab, but the project was just one of several trade studies performed to determine which habitat choice was best suited for ISS budgetary constraints. To that end, the TransHab project was intended to perform the design studies and engineering tests necessary to prove an inflatable module was viable for the ISS. Nothing more. And the project was extremely successful because it proved the viability of an inflatable option. So why was TransHab canceled? After all, in terms of long-term and operational costs and needs, there was no question the module would have saved the program tens of millions of dollars over the first decade, and would have given the outpost several modules that it could not otherwise have had. These included a safe-haven shelter for solar storms, on-orbit water-recycling capability, more than double its current total stowage volume, and the ability to test new exploration-class technologies like a human centrifuge, advanced medical facilities as well as the orbital-debris shielding for which TransHab has become famous. TransHab would also have furthered the progress of a manned Mars mission because NASA's Human Exploration and Development of Space (HEDS) roadmap defined these technologies as essential developments for any long-duration expeditions beyond Earth orbit.

Unfortunately, in early 2001, there was a US$4.8 billion shortfall in the ISS budget which had wide-ranging effects on NASA's space program, almost all of them damaging. One of the first things to be cut from the program was the habitation module and the Crew Return Vehicle which would be necessary to allow the crew to grow from three to seven. It was a shame, because the TransHab group had overcome major obstacles that had frustrated earlier attempts to build large inflatable modules. For example, the group developed the specialized weaving pattern that permits straps of woven Kevlar to withstand remarkable amounts of stress. For astronauts, the biggest attraction of living in a TransHab would have been the space. Lots of it. Take a look inside the current ISS (Figure 2.12) and what



2.12 The cluttered interior of the ISS. Courtesy: NASA

do you see? Modules packed with electronics racks, cables streaming everywhere, piles of manuals laying all over the place, and loud cooling fans running constantly. Equipment scattered all about, bulkheads covered with stuff attached to Velcro. "Cluttered" is perhaps the most apt word to describe living on board the ISS. Not exactly great working conditions! Now imagine living in that kind of environment 24 hours a day for several months and compare that living experience with the luxurious confines of a TransHab, which had a layout that would have encouraged a more orderly, productive, and pleasing environment to live and work in. It wasn't to be. Not in the late 1990s at any rate.

To be fair, part of the reason for the cluttered ISS is a legacy of the basic ISS architecture, which dated to the mid-1980s. Another problem is engineering. Ask any engineer which is more important—clutter and noise or dealing with a hard vacuum and 500-degree temperature fluctuations of space—and you realize where most of the money went. So, today, the ISS has done little to alter people's perception that working in space is little different from living in a submarine—dark, dank, and claustrophobic.

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