LIGHTWEIGHT STRUCTURES IN SPACE

by
Jerome Pearson
Ball Aerospace & Technologies Corp.
Mount Pleasant, SC 29466-8513

and

Keith Denoyer
Air Force Research Laboratory AFRL/VSDV
3550 Aberdeen Ave. SE
Kirtland AFB, NM 87117-5776

ABSTRACT

Building structures for operation in space represents the ultimate need for lightweight structures. The building material must be lifted a few hundred kilometers into low earth orbit, where the International Space Station will be constructed; several thousand kilometers into medium earth orbit, where many voice communication and military navigation satellites are located; or all the way to geostationary earth orbit (35,800 km above the equator), where giant television, environmental, and military data satellites are located. The weight of satellite structures is highly constrained by the cost of launching them into orbit, currently about $20,000 (US) per kg into low earth orbit. In addition, the operational and environmental constraints of our current launch vehicles severely limit space construction. The international Space Station, the largest space structure ever designed, is now under construction and being prepared for launch. Precision satellites with giant mirrors or antennas are being designed that must point with nanoradian accuracy. Microsatellites are being designed that use the latest in miniature circuits and instruments, and weigh only a few kilograms. All these new examples of lightweight space structures must address difficult issues of automatic deployment or manual construction in orbit, long lifetimes, economy, and safety. Our future development and command of space will require unprecedented new technology in lightweight space structures.

INTRODUCTION

Spaceflight represents the ultimate need for lightweight structures. Building material must be lifted hundreds of km against Earth’s gravity into orbit, survive the launch environment while confined to small payload bays in launch vehicles, and must then survive the space environment of vacuum, radiation, and atomic oxygen that degrades the structures. Despite these problems, the need for a permanent habitat in space has resulted in plans for the International Space Station, the largest planned space construction. When finished, it will be as long as a football or rugby field and easily visible to people around the world. Scientific needs for ever-larger telescopes and antennas in space are driving us to develop ever more lightweight, compact, deployable space structures that are affordable under constrained space agency budgets. These needs and these concepts have led to a new era of lightweight space structures that will also have an effect on terrestrial designs.

LAUNCH CONSTRAINTS ON SPACE STRUCTURES

The difficulty of launching payloads into space has affected the design of space structures from the beginning of the space age. Achieving a final velocity of nearly 8 km per second requires the use of several stages of rockets, with the payload in the final stage having a small mass compared with the launch mass. To minimize atmospheric resistance, the launch vehicles are streamlined to such an extent that the payload bays are just a couple of meters across. In addition, the operational and environmental costs of our current launch vehicles cannot support the level of space construction envisioned for the next twenty years. Each space shuttle launch releases millions of kg of solid rocket fuel exhaust particles and smog-producing oxides of nitrogen into the atmosphere.

Another severe launch constraint has been the need to design structures to withstand vibration and acoustic launch loads. In many cases, this is the most severe environment that a space structure will have to withstand. If the launch environment could be reduced, great mass savings could be achieved with the same level of on-orbit performance. Currently, several systems are under development for reducing both the vibration and acoustic loads during launch.

High Launch Costs Produce Lightweight, Expensive Structures

The weight of satellite structures is highly constrained by the cost of launching them into orbit, currently about $20,000 per kg. At that rate, the cost of a simple home in the suburbs would be about a hundred million dollars! In the past, this cost was even greater per pound. This fact has led to the current spacecraft design in which weight is paramount and compactness is a virtue. Even the new X-33 vehicle, planned by NASA to represent the next generation of reusable, low-cost launch vehicles, will cost more than $2000 per kg to launch its payloads[i]. Thus, for the foreseeable future, space structures will place a premium on being lightweight.

In addition, confined payload bays require compactness and careful packing to protect payloads from damaging vibration and acoustic noise. Even the largest cargo bay, that of the Space Shuttle, measures just about 4 m in diameter and 15 m long, and is limited to less than 15 metric tons of mass. This means that space structures must be designed to fold down to much smaller dimensions than their final size.

Finally, because it is so difficult to repair or replace structures in orbit, space structures must be extremely reliable. They must be able to perform their missions even with some random failures, so they are built doubly or triply redundant to provide high reliability. The result of all these launch constraints is that current space structures become very expensive. Current satellite structures like Iridium cost[ii] more than $20,000 (US) per kg. There will be no respite from these requirements until a new generation of space launch vehicles reduces the cost of launching structures into space by a factor of 100 or more.

Launch Environment Reduction

The most severe environments that a satellite experiences during its lifetime typically occur during launch. These disturbances consist of both structure-borne vibrations and also tremendously high acoustic loads. The traditional approach to designing spacecraft against launch loads has been through structural stiffening or through individual isolation of components experiencing high vibration levels. This approach is costly and time consuming. In addition, it adds significant weight to the spacecraft that is not needed once the spacecraft reaches orbit. For this reason, several alternatives are under investigation by the United States Air Force Research Laboratory, to reduce launch loads and decrease the overall weight of spacecraft structures. One approach that addresses the launch vibration problem is to construct a whole-spacecraft launch vibration system[iii]. This is analogous to providing a suspension system for an automobile. The approach is to replace the rigid payload attachment fitting with a similar component that has a built in isolation capability. A conceptual drawing is shown in Figure 1. The first ever whole-spacecraft isolation system flew on a Taurus launch vehicle in February 1998. This system was an entirely passive design that reduced structure borne vibration levels by more than a factor of 2. Additional flights are currently scheduled to use whole-spacecraft isolation on a variety of other launch vehicles.

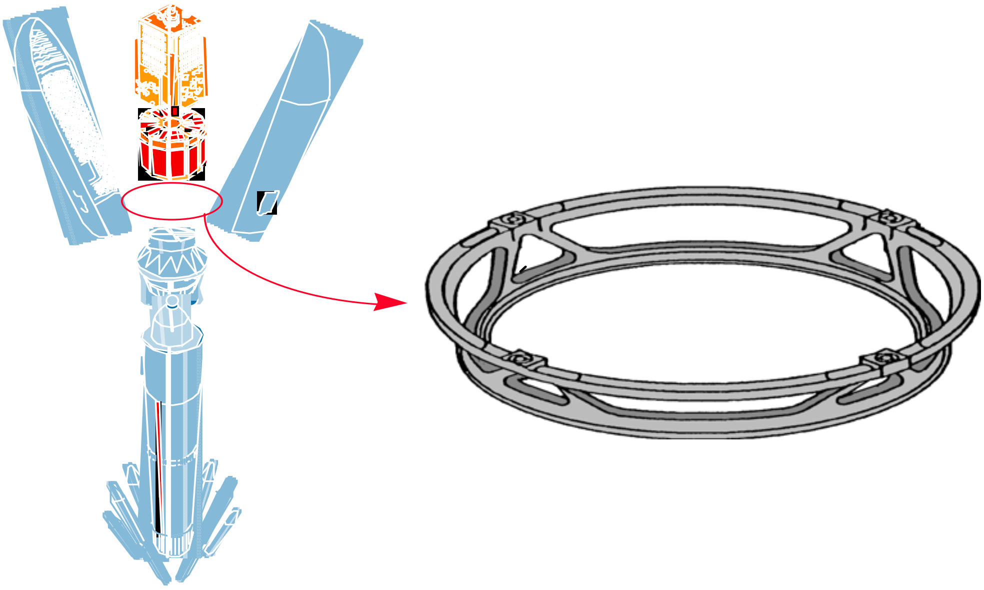

Figure 1: Launch Vehicle, Spacecraft, and Payload Attach Fitting (Adapter)

A complementary area of current research is addressing the problem of reducing acoustic loads during launch. Innovative concepts include both passive approaches as well as concepts for actively controlling sound pressure levels inside the launch vehicle payload cavity[iv]. An example of the latter is shown if Figure 2. Using this approach, sound is controlled by using a speaker mounted inside the cavity as well as piezoelectric materials bonded to the surface of the shroud. These piezoelectric devices deform when a voltage is applied to them. Therefore, a control system can be designed which both decreases the amount of sound being transmitted through the shroud as well as creating sound which interferes destructively with the existing acoustics and reduces the overall sound pressure levels.

Increasing Spacecraft Reliability through On-Orbit Servicing

Another approach for decreasing spacecraft weight during launch and increasing overall reliability is through spacecraft servicing on-orbit[v]. This is analogous to aircraft operations where aircraft are refueled during operation, inspected periodically, and have components routinely

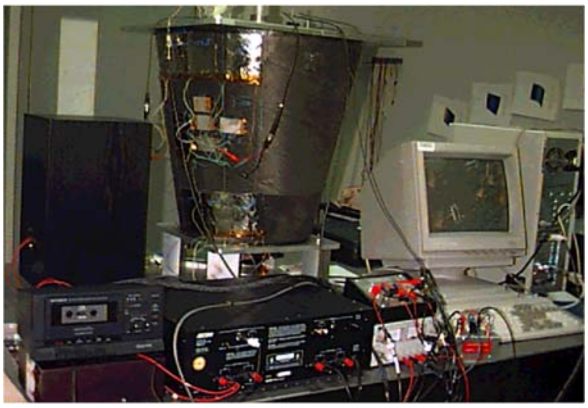

Figure 2: Sub-Scale Launch Vehicle Shroud with Active Acoustic Control

upgraded. In space, these tasks will be performed by small robotic satellites. By providing a capability to supply spacecraft with fuel in space, less fuel needs to be lifted with the satellite into orbit, greatly reducing mass. In addition, maintaining spacecraft by resupply, retrofitting, and repair can increase the life span of a satellite and result in lower life-cycle-costs. This is particularly true of geosyschronous satellites, because of the high cost of launching replacement support structure and the need to tow abandoned satellites to a parking orbit. To date, spacecraft have been maintained by extravehicular activity (EVA), limiting the set of maintainable satellites to those in the few orbits accessible to the space shuttle. Initially, astronauts or ground operators could extend their range by teleoperating robotic manipulators on spacecraft or maintenance spacecraft dispatched to aid ailing spacecraft. An extension of this idea is to automate these manipulators and craft to operate without any human intervention. This offers significant benefits when communications delays, limited communications bandwidth, or low duty-cycle would prevent a human teleoperator from working effectively.

REQUIREMENTS FOR SPACE STRUCTURES

Requirements for structures in space come from a variety of sources. The greatest number of satellites are needed to handle the exploding demand for communication, chiefly cellular phones and pagers. The most complex satellites are the scientific observatories with precise pointing. The largest single space program, the International Space Station, is driven by the need for a permanent inhabited research facility in orbit. Each of these requirements increases the demand for lightweight structures.

Satellite Complexes and Complex Satellites

The largest group of identical satellites ever launched, the Iridium complex of 66 satellites in 780-km, high-inclination orbits, was completed this year. This system is planned to be operational this fall, offering a new level of world-wide communication. Other systems for communication, such as Globalstar, is also being orbited. These systems require the manufacture, launch, and replacement of literally of hundreds of next-generation spacecraft.

These new constellations of satellites allow the economies of scale and reduced cost of satellite structures.

The NASA Hubble Space Telescope, the Compton Gamma Ray Telescope, the Space InfraRed Telescope Facility, and the AXAF X-ray telescope are giant observatories that represent a revolution in precision pointing capability. Follow-on New Millennium spacecraft are already being designed that will be even larger, with higher precision, requiring new materials, new structures, and new structural designs. Concepts for sparse optical arrays greater than 5m in aperture are also being planned. These extremely lightweight and deployable systems will require precision to the nanoradian and nanometer level to phase the components of the optical array.

Space Stations

The international space community of NASA, ESA, NASDA, and others, are cooperating in building the International Space Station, a rugby-field long, permanently occupied research facility for the next era in space. After a half century, Wernher von Braun’s vision of a space station circling the Earth will become a reality. It will not be the rotating wheels imagined in 1952 by von Braun and Willy Ley, and in 1968 by Arthur Clarke in “2001: A Space Odyssey,” but it will carry out all the same functions they recognized—microgravity research, biological experiments, Earth observations, and space operations.

The International Space Station represents the culmination of a long evolution, from the Soviet Salyut in the 1960s, the American Skylab in the 1970s, and the Russian Mir space station of the 1990s. Major modules have been designed and constructed by European countries, cooperating under the European Space Agency, by Japan, Russia, and the United States, and by Canada. The first space station module is scheduled for launch later this year, and by 2003 the International Space Station will be complete.

DESIGNS FOR SPACE STRUCTURES

To meet these requirements for new space structures, designers have used a variety of techniques. As already mentioned, compact, folded structures can be deployed on-orbit, either automatically from unmanned launch vehicles, or under human supervision from the Space Shuttle cargo bay. To further increase the ratio of final to stowed size, inflatable structures can reach extreme sizes on-orbit, and for the very largest space structures, on-orbit assembly can result in almost unlimited size. Many of these designs require new materials with even higher specific strength and specific stiffness than current high-performance composites.

Deployable Structures

By designing structures for deployment in space, satellites can be launched at much lower cost. For large, lightweight structures the principal launch constraint is volume, not mass. By making the structure deployable, the spacecraft can be launched on a smaller launch vehicle, with a smaller payload shroud. This significantly reduces cost. Two large high precision space based systems currently under investigation are sparse optical array telescopes and space based laser systems for missile defense. Concepts for these systems are shown in Figure 3 and Figure 4.

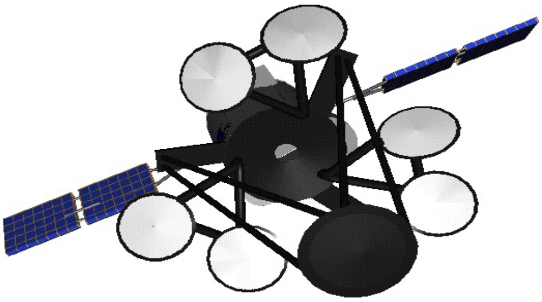

Figure 3: Concept for Sparse Optical Array Telescope

Figure 4: Concept for Space Based Laser System

To make these systems feasible, very large (greater than 5 meter) lightweight, deployable structures must be constructed with shape and position maintained to within a few nanometers. To develop the needed technologies, experiments such as the AFRL UltraLITE test article in Figure 5 are being developed and studied[vi].

The phase I UltraLITE ground experiment consists of a single deployable composite isogrid boom, which is mounted on 30,000 kg isolated granite slab. The slab is needed to reject ambient disturbances which cause motion in the structure. Extreme stability is needed because the level of motion being sensed and controlled is on the order of 10 nanometers. The size of the deployable boom is 265 x 182 x 25 cm. Advanced composite materials as well as innovative fabrication techniques are used to design a support structure which is extremely stiff, yet very lightweight. The experiment utilizes a gravity off-load suspension device to simulate a weightless environment during deployment of the test article. The experiment will consist of deploying the composite boom from a vertical position and then phasing the mirror mass simulator with respect to the top of the granite slab to a stability of 10 nanometers.

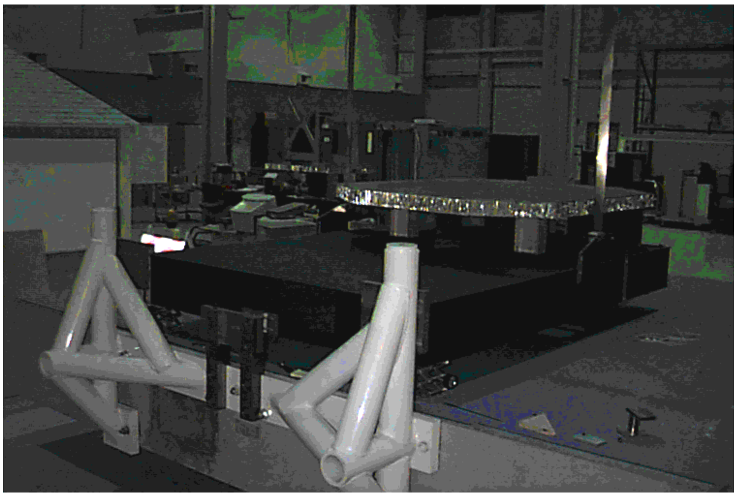

Figure 5: UltraLITE Precision Deployable Structures Experiment

Inflatable Structures

Inflatable structures can produce extremely large, lightweight structures in space[vii]. The Echo balloon satellites of the 1960s were just a few kg each, but Echo I was 30 m in diameter, and Echo II was 40 meters. Even though they deflated eventually, they proved the concept. Current designs for inflatable structures include materials that harden under vacuum and UV radiation, so that when the air is lost through micrometeoroid punctures, the structures will remain rigid.

Inflatable structures allow very large structures to be deployed in space with smaller launch vehicles. For example, large space antennas many times the size of today's mechanical orbiting antennas could provide high-performance mobile communications, Earth observations, radar, and astronomical observations.

Some specific future applications that depend on this technology include astronomy missions requiring large interferometers and lightweight optical telescopes, synthetic aperture radar systems, large antennas, large solar sails, and solar concentrators for spacecraft bound for the outer planets. This latter concept, known as the power antenna, has the potential to enable all-solar powered outer planet spacecraft, while simultaneously increasing data return rates by factors of 10 to 100 compared to missions with small fixed antennas.

Because the mass and stowed volume of inflatable components are far less than equivalent solid structures, inflatable structures can potentially reduce the cost of future missions by 10 to 100 times. The 40-meter-long Inflatable Antenna Experiment (IAE), shown in Figure 6, weighs only about 60 kilograms, and the operational version should be able to be developed for less than $10 million, compared with up to $200 million for mechanically deployable hard structures.

The IAE deploys into a 14-meter-diameter, dish-shaped antenna mounted on three 28-meter-long inflatable struts, almost the size of the space shuttle. The IAE struts are made of Neoprene-coated Kevlar and the reflector is aluminized Mylar that is only 6.4 microns thick (1/4 the thickness of a 1 mil plastic bag). Once deployed, the antenna area is about 100 times larger than its area when stowed aboard the shuttle. The IAE was developed by l'Garde, Inc. and JPL.

S77E5011 1996:05:20 08:03:03

Figure 6. Inflatable Antenna Experiment

Assembled Structures

The most challenging task in satellite assembly is the International Space Station, which will require scores of Space Shuttle flights and thousands of work hours in space suits for its construction. The design is dominated by the large solar arrays required to generate the electrical power required, but the heart of the station is the habitation modules where the crew will live, and the experimental modules where the work of the station will take place. Each of the work modules represents a marvel of lightweight structures with a maximum of work space and storage area. Major modules are being built by the Europeans, by the Japanese, and by the United States.

The International Space Station will be the site of invaluable research in biotechnology, medicine, chemistry, and microgravity. It will also be the jumping-off point for the return to the moon and the exploration of the near-Earth asteroids. To fulfill these tasks, the station is designed architecturally for efficiency in operations and ease of supply. A view of the overall station and several modules is shown in Figure 7.

SPACE EXPERIENCE APPLIED TO EARTH STRUCTURES

The development of large, lightweight structures technology for applications in space has produced a series of technologies that can also be applied to structures on the earth. Some of these technologies include active vibration control, smart structures, and new high-strength building materials.

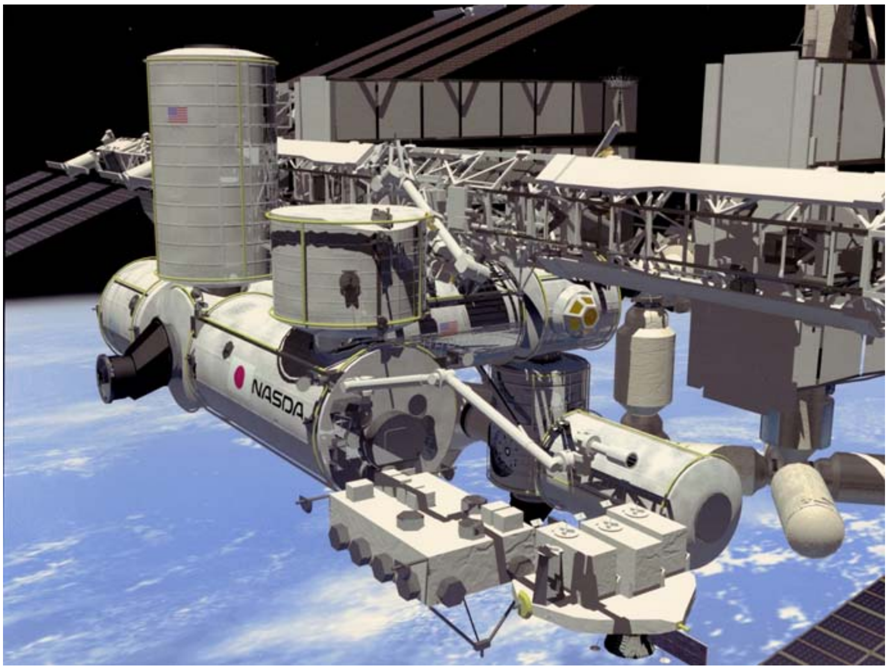

Figure 7. The International Space Station

Smart Structures for Sensing and Control

Large space structures that require accurate pointing, like telescopes and lasers, must be actively controlled to prevent vibration from interfering with their optical resolution. These active control devices take the form of fiber-optic sensors, piezoelectric crystals, and shape-memory alloys. These technologies, developed first for space structures, are now being applied to reduce damage to buildings and bridges from major vibrations during severe earthquakes and high winds.

One way of countering structural vibration caused by strong winds or seismic ground motion is to place sensors and actuators at specific locations on buildings. As sensors in the system measure the motion of the structure, actuators apply forces to counteract the structure's vibration. The actuators can be hydraulic pistons that move counterweights, or adjustable tendons along the sides of structures. The sensors in the systems can read the structural vibration patterns caused by earthquakes or high winds and adjust the tension on the appropriate tendons to reduce the excessive forces or motions of the building.

Active control technology for vibration isolation is mature and is ready now for commercial applications. There are already some actively controlled buildings in operation today, in the United States, in Japan and in Taiwan. A TV tower in Nanjing, China will also be retrofitted with active vibration control. Other new construction will incorporate the technology, particularly in seismically active regions; and, of course, it may be possible to retrofit the technology to other existing structures.

New Materials for Terrestrial Construction

Aluminum is still the most common building material for satellites and structures in space, particularly as aluminum honeycomb for high stiffness and low density, but there are more exotic materials already in use and many more that show promise. Launch vehicles such as the X-33 single-stage-to-orbit are being constructed with graphite/epoxy and aluminum-lithium propellant tanks. Superplastic-formed, diffusion-bonded titanium has allowed the production of extremely high strength structures of complex shapes. Aluminized Mylar produces gigantic reflecting surfaces with areal densities of just milligrams per square meter, and thin-film, amorphous solar cells have drastically improved the specific power output of solar arrays.

Recent advances in materials have resulted in the discovery of new forms of carbon molecules[viii]. Their structures can be like soccer balls, with 60 or more carbon atoms at the vertices of hexagons and triangles, and like saddles or tubes. These structures are called "bucky balls" and fullerene nanotubes, after Buckminster Fuller, the inventor of the geodesic dome. These new forms of carbon are the strongest material ever discovered, even stronger than diamond, and could be the basis for building extremely tall towers and buildings. The result could be the realization of far longer suspension bridges and such dreams as the "mile-high skyscraper" of Frank Lloyd Wright.

CONCLUSIONS

Space structures have high demands placed upon them for strength, lightness, stiffness, durability, and control, that are much more stringent than terrestrial structures. Meeting these demands has resulted in new structural concepts and new materials that can also be applied to terrestrial structures.

REFERENCES

---

[i] H. Hermann Koelle and Dietrich E. Koelle, "On the Cost-Effectiveness of Single-Stage-to-Low-Earth-Orbit Vehicles," IAA 96-IAA-1.1.07, 47th IAF Congress, Beijing, China, October 7-11, 1996.

[ii] Kevin Maney, "Teledesic: The Internet in the Sky," Florida Today, January 2, 1997. (Available online at http://www.flatoday.com/space/)

[iii] Eugene Fosness, Keith Denoyer, Alok Das, and David Founds, "Whole-Spacecraft Isolation Development Efforts at the USAF Phillips Laboratory," *Proceedings of the 11th Annual AIAA/Utah State University Conference on Small Satellites*, Sept. 15-18, 1997, Logan, UT.

[iv] Keith Denoyer, Steven Griffin, and Dino Scuilli, "Hybrid Structural/Acoustic Control of a Subscale Payload Fairing", *Proceedings of the 5th SPIE International Symposium on Smart Structures and Materials*, March 1-6, 1998, Sand Diego, CA.

[v] Eugene Fosness, Rich Madison, Keith Denoyer, Dino Sciulli, and David Founds, "Advanced Mechanisms for Space Applications," *Thirty-Fifth Space Congress*, Cocoa Beach, FL, April 28-May 1, 1998.

[vi] Keith Denoyer and Jesse Leitner, "Autonomous Neural Control for the Phase I UltraLITE Test Article," *IEEE Aerospace Conference*, March 21-28, 1998, Snowmass, CO.

[vii] Marvin Criswell, Willy Z. Sadeh, and Jenine Abarbanel, "Design and Performance Criteria for Inflatable Structures in Space," Engineering, Construction, and Operations in Space V, Proceedings of the Fifth International Conference, Vol. 2, pp. 1045-1051, 1996.

[viii] Boris I. Yakobson and Richard E. Smalley, "Fullerene Nanotubes: $C_{1,000,000}$ and Beyond," American Scientist, Vol. 85, No. 4, July-August 1997, pp. 324-337.