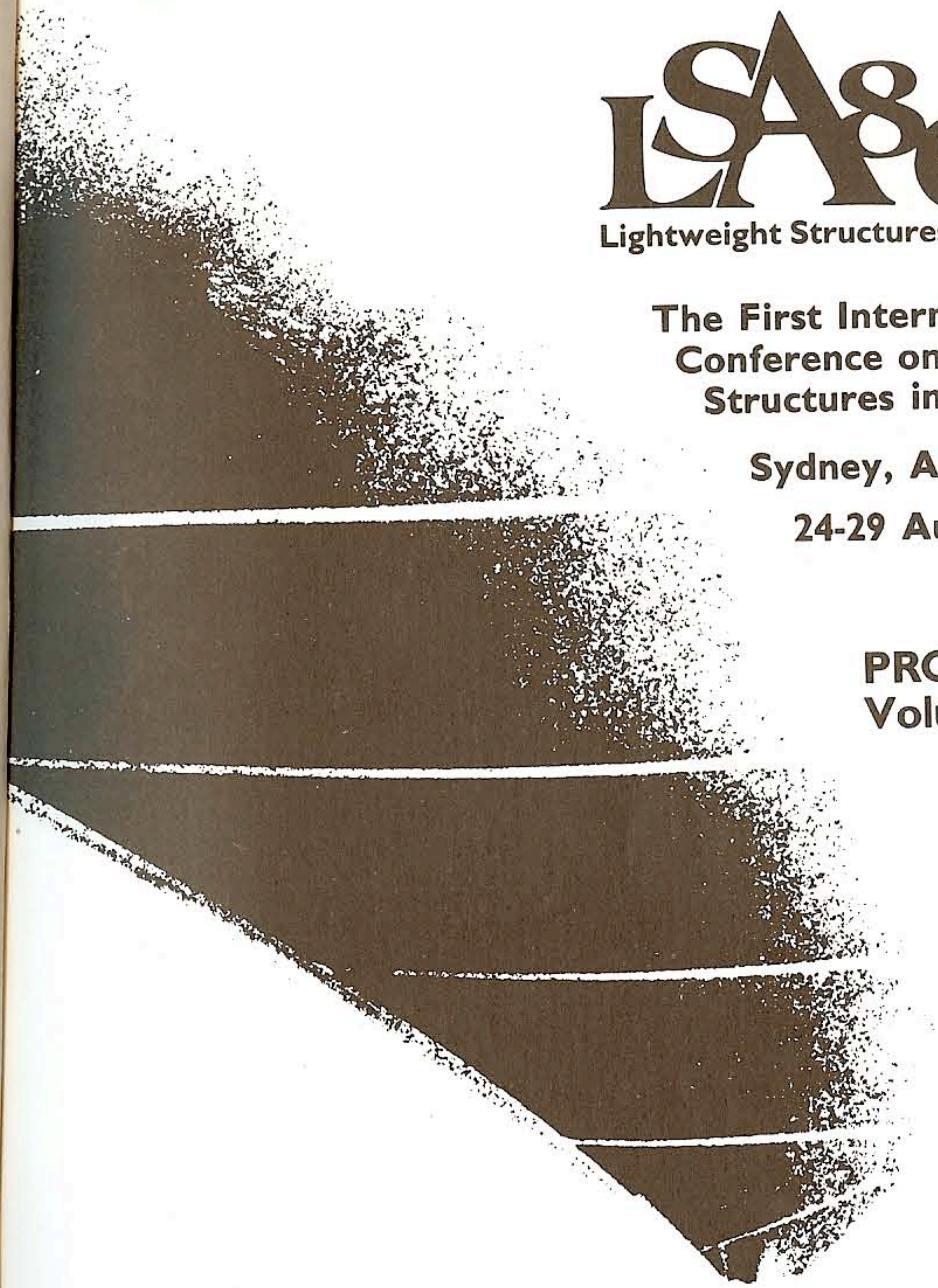
Keynote Address

Cohen, Marc M. (1986 August). Lightweight Structures in Space Station Configurations. In, *Proceedings of the First International Conference on Lightweight Structures in Architecture* (vol. 1, p. 507-541). University of New South Wales, Australia, 24-29 August 1986: Unisearch, Ltd.

Errata:

p. 509. All references to oxygen should read *free atomic oxygen*, not molecular oxygen.

p. 533. The middle image of Figure 4-7 is upside down.



LSA86

Lightweight Structures in Architecture

The First International Conference on Lightweight Structures in Architecture

Sydney, Australia

24-29 August 1986

PROCEEDINGS
Volume I

LSA86

Lightweight Structures in Architecture

Proceedings of The First International Conference held in Sydney, Australia, 24–29 August 1986 at The University of New South Wales

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TYPESETTING
Essay Composition
Hippopotamus Dreams

Assisted by the Publications Section, Department of the Registrar
The University of New South Wales

Published by Unisearch Limited, The University of New South Wales
PO Box 1 Kensington, NSW Australia 2033

August 1986

ISBN 85823 558 7 (v.1)

PREFACE

Architecture's role is the design of buildings and their environment.

The process of creative generation of internal and external spaces and their structural envelopes involves simultaneous and interactive consideration of functional, aesthetic, constructional, technological and economical aspects.

Traditional methods used for the design, construction and maintenance of buildings have shown severe limitations and do not adapt readily to change. Man's historical urge to immortalise himself through his edifices has, in fact become the very stumbling stone to the further development of the built environment: our cities and settlements have become a hotch-potch of imagery of the powerful with little regard to needs and requirements of society at large.

Not surprisingly, most of us, professionally involved with the built environment are aware of this problem, but feel powerless to change the happenings around us, we feel ill at ease but continue to contribute to the mess we have helped to create: architecture in crisis!

A new form of building, adaptable to changes in lifestyles of present and future generations is to be developed and promoted. This form of building is to become architecture in tune with it's environment, similar to a tree in a forest.

Lightweight construction facilitates adaptibility and dynamic interaction with the environment and enhances timely response to change: what becomes outmoded can be modified, the obsolete can be removed to make place for the new. Rooted in technology and nature lightweight construction is both, a contemporary technological discipline and a copious source for new types of buildings on a scale hitherto unknown: wide ranging choice of shapes, structure and envelope systems, materials and manufacture/construction technologies have opened up a new world for designers, procurers and users of buildings which is yet to be fully recognised and comprehended by all, but a few leaders and their followers.

"Lightweight Structures in Architecture" is about these new types of buildings, it addresses all those responsible for, involved and concerned with buildings: the professions, industry, government, politicians and educators.

These pre-published proceedings summarise the work of many individuals from different backgrounds and nationalities. They present the various aspects that will enable the creation of better, more humanely scaled environments through lightweight construction to be more vigorously pursued. By necessity, this summary is incomplete: architectural application and technological aspects are very well represented while other important issues, such as an architectural language of lightweight structures, user's reactions, economical and environmental aspects appear more sparingly.

At the beginning of an interdisciplinary integration process involving the work of the pioneers and their followers in various fields and disciplines of the built environment I see LSA 86 leave it's mark. It will influence future directions in architecture and building. With the help of many, here and in other countries, I have been able to arrange LSA 86 so as to provide a meeting place for the originators, the leaders and their followers, the concerned, the interested and the curious.

Vinzenz Sedlak, Convenor LSA 86

Sydney, June 1986

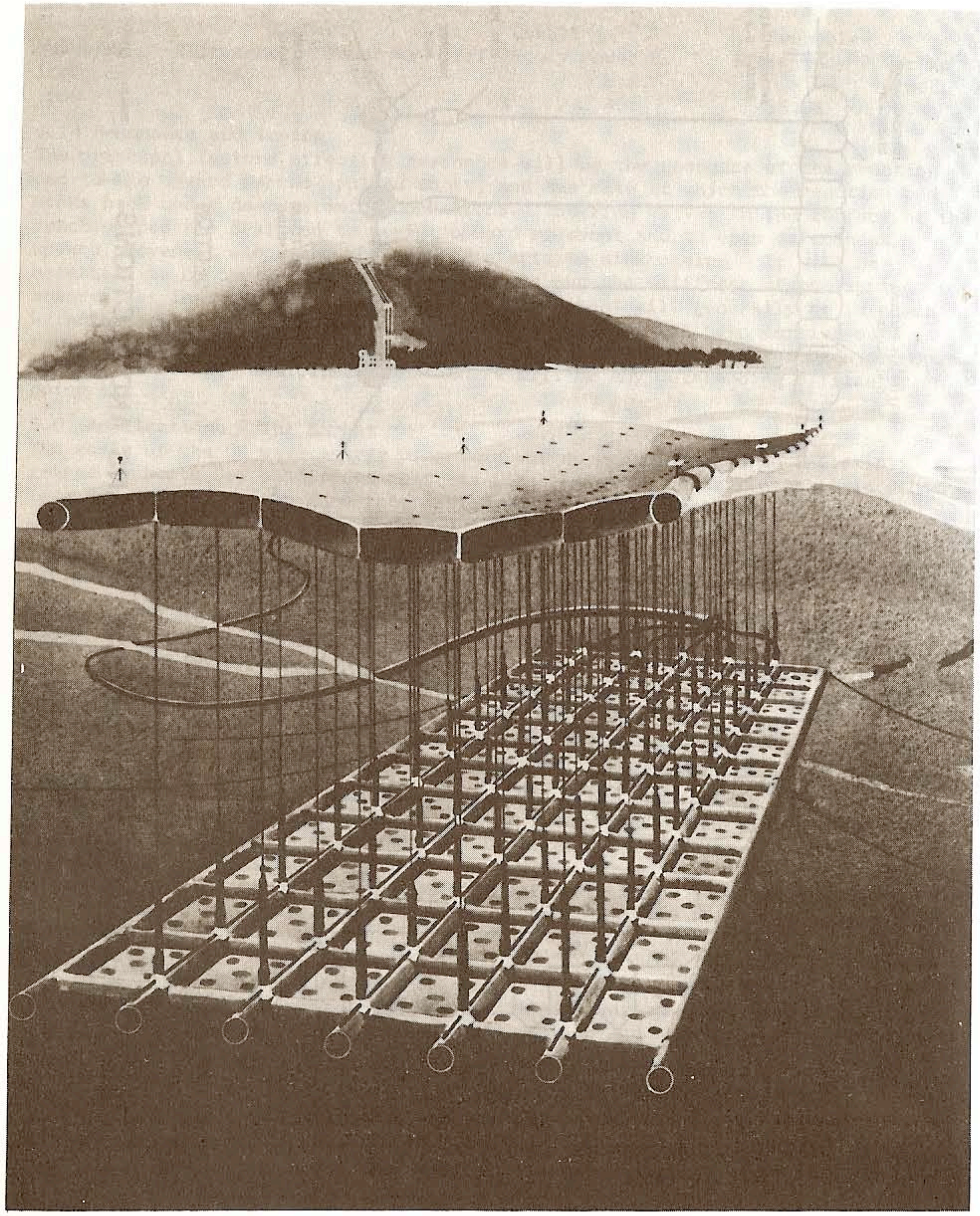

Figure 1 TWIN MEMBRANE WAVE ENERGY CONVERTER

LIGHTWEIGHT STRUCTURES IN SPACE STATION CONFIGURATIONS

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Since the beginning of manned spaceflight 25 years ago, the leading assumption about spacecraft structures has been to reduce weight as much as possible in order to minimize launch loads. The development of space technology has 'spun-off' a great number of lightweight structural techniques and materials which have contributed to a revolution in terrestrial construction techniques. However, in the coming space station era, we will not be constrained by launch loads so much as by launch payload volumes. The paper re-examines some of the traditional assumptions about lightweight structural applications in space, particularly with regard to our evolving understanding of the space environment, space station mission requirements and operations and human factors and describes the development of architectural, structural and environmental design concepts for orbital space stations.

1. INTRODUCTION

Since the beginning of manned spaceflight 25 years ago, the leading assumption about spacecraft structures has been to reduce weight as much as possible in order to minimize launch loads. The development of space technology has "spun-off" a a great number of lightweight structural techniques and materials which have contributed to a revolution in terrestrial construction techniques which we recognize today. However, in the coming space station era, we will not be constrained by launch loads so much as by launch payload volumes. While lightweight structures will continue to be vital, some of the parameters will change as we enter the era of a permanent manned presence in space when long duration missions are the norm. Hence it is necessary to reexamine some of the traditional assumptions about lightweight structural applications in space, particularly with regard to our evolving understanding of the space environment, space station mission requirements and operations and human factors.

This paper describes the development of architectural, structural and environmental design concepts for orbital space stations. Beginning with a review of the orbital environment, the discussion addresses the first fairly serious concepts presented during the 1950s and traces the maturation of configurations up to the present American, European, Japanese, Canadian and Soviet space station programs. Both the USA and the USSR have prior space station experience, with Skylab and Salyut respectively. Both space programs learned a great deal from these endeavors, and many "Lessons Learned" retain validity. The continuing debate of zero-gravity vs. artificial gravity can be examined from the biomedical, commercial and perceptual/cognitive and operational points of view. The long term practicality of small space stations can be compared to large space settlements and lunar or planetary bases. The frontier in space station design problems can be addressed in terms of technology and engineering design, although the key problem continues to be financial. For large lightweight structures and lightweight materials, suitability will depend increasingly on the human performance requirements and characteristics, especially for large space truss construction.

Before delving into space station configurations, it is necessary to define the notion of "configuration." Configuration refers to the complete ensemble of a space station orbital system, including primary structures such as truss supports for solar arrays and pressure vessel shells for habitable modules, secondary structures such as external instrument or payload attachements and internal architectural elements, and the ways in which the space station is designed to operate within its dynamic environment. These operations include a consideration of flight mode and orbital path, the orientation to the sun for solar power collectors, to the nadir for earth observations and to the orbital velocity vector for rendez-vous and docking with other space craft. All these operations imply critical view angles, particularly window and video camera observation of proximity operations, thermal radiator exposure away from direct sunlight and communications antenna links to relay satellites and ground stations. The most difficult part of any space station configuration design tends to be the interconnection and integration of all the different parts with their often conflicting requirements. A space station configuration is a set of compromises made in the hope of accommodating all functions at an adequate level, without infringing too much on any one key capability. See Figure 1-1 for an example of the full elements of a Space Station Configuration.

The evolution of space station configuration concepts follows the increasing understanding of environmental factors, mission requirements and operational characteristics of space stations. Each of these three considerations are discussed with their immediate and long-term implications for the use of light weight structures technology.

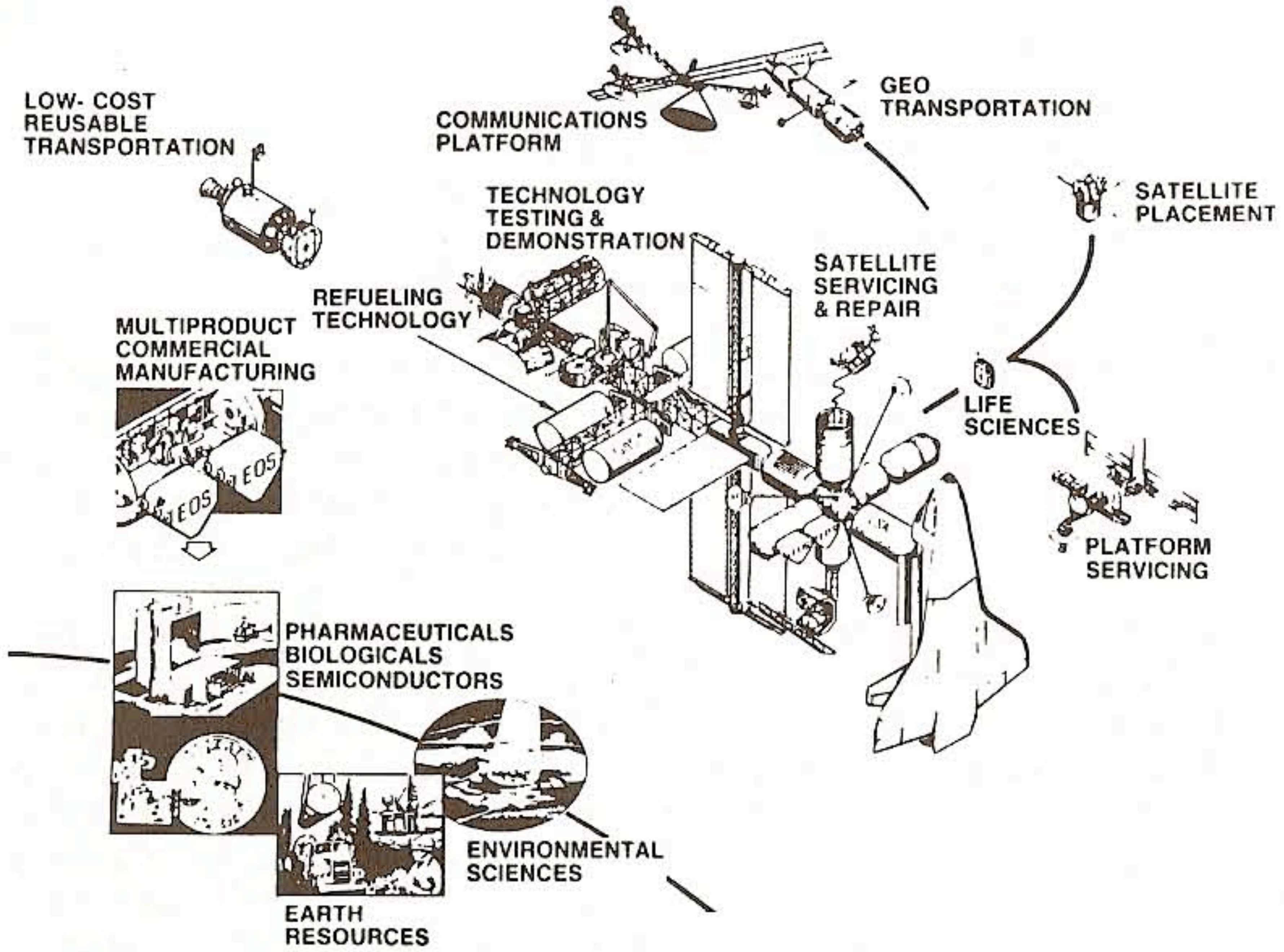


Figure 1-1. Example of a Space Station Configuration Concept.

2. THE ORBITAL ENVIRONMENT

The space station operates within a severe environment which places many demands and constraints on the materials and fabrication techniques which are available for engineering and building the configuration. While all these factors pose serious hazards to crew safety that are beyond the scope of this paper, it is possible to describe the environmental factors as an analogy to building a structure on Earth as a response to a terrestrial climate. Environmental and other external factors can be classified into two groups: the natural environment and the man-induced environment. Some immediate safety implications of these factors for space station structures and materials should be described before discussing configurations.[1]

2.1 THE NATURAL ENVIRONMENT

The natural orbital environment consists of a set of conditions, all of which must be defended against to maintain human productivity and safety. Natural environmental factors can be distinguished from the others because they are constants, over which the space station crew has no control. Natural environment factors include the vacuum of space, free atomic oxygen, micrometeoroids, radiation, thermal flux and microgravity.

VACUUM

Space at low-earth orbital altitudes (LEO) of 200 to 500 km. and beyond is essentially a vacuum, so that all habitable architecture on orbit must be pressurized with an earthlike atmosphere. Thus, all spacecraft habitats are pneumatic. However, the fact that space station modules are pneumatic does not imply that they can be inflatable. The environmental hazards are so severe and the consequences of structural failure are so unforgiving that inflatable architecture will need to come a very long way before it attains the reliablity, quality assurance, and maintainability of hard pressure vessels. Fans of inflatable structures frequently suggest that space station architecture would be less expensive and lighter in weight if made from inflatables. The answer to this suggestion is the question: "Would you trust your life to an inflatable structure in this environment?"

FREE ATOMIC OXYGEN

Although space at LEO is considered a vacuum, it is not empty. At LEO, there is free atomic oxygen, micrometeoroid flux and space debris (which will be described in a later section). The free molecular oxygen has three significant effects for space station configurations: atmospheric drag, aerotorque[2] and surface erosion.

First is the atmospheric drag effect. It is ironic to discuss this subject in Australia, in light of the reentry of Skylab, NASA's first space station, over the western edge of this continent in 1979. That reentry was due to atmospheric drag from the free molecular oxygen, a phenomenon that was not recognized or well understood at the time Skylab was launched in 1973. At that time the assumption was that an object placed in orbit would be subject primarily to the decay effects of the orbital mechanics, and the fricton effects of free molecular friction were not fully appreciated. The implication of this friction drag is that reboost thrusters on the space station must compensate for friction effects as well as the orbital mechanics decay. The consequences of this countermeasure are greater potential man-induced vibrations and external contamination and increased requirements for propellant resupply.

The second effect of atmospheric friction is aerotorque, which means that the pressure from the atmospheric drag will apply a cumulative torque to the space station configuration, for which the space station must make ongoing adjustments in flight attitude. As a general notion, the more the center of pressure departs from the center of mass, the greater the resultant aerotorque. Also, on a very large space structure, there will be an aerotorque gradient that increases toward the nadir. Some engineers propose to take advantage of aerotorque as part of an earth inertial, gravity gradient mode of attitude control and stabilisation, which could result in a reduced need for expensive and noisy control moment gyros (CMG), the conventional means of maintaining spacecraft flight mode. Although atmospheric friction and aerotorque are not direct load factors, the fact that the space station may move dynamicly as an operational response creates additional design factors especially for large space structures.

The third effect of free atomic oxygen is the erosion of surfaces subjected to long term exposure. Early test data from the shuttle orbiter have indicated a "surface recession" of 380 to

500 microns for organic films.[3] NASA recently launched a satellite called the Long Duration Exposure Facility to test various materials for free molecular oxygen and micrometeoroid exposure. The preliminary indications are that all materials subjected to the LEO environment can expect a predictable surface erosion that is linear over time. These results imply that virtually any exterior surface material will have a limiting lifetime at LEO of some period of years after which it must be replaced or the entire spacecraft lose its safety rating.

At higher orbits such as geosynchronous orbit (GEO) or at the fixed Lagrangian Point L-5, the free molecular oxygen problem is eliminated, but the meteroroid and debris problems remain and the radiation problem increases outside the Earth's electro-magnetic fields.

MICROMETEOROID FLUX AND SHIELDING

Micrometeoroid flux is one of the most serious natural environment issues for spacecraft structures, both conventional and lightweight, of all the environmental phenomena.[4] Both the space shuttle and the Salyut space station have recorded hits by sub-millimeter size particles on their windows. The damage was not serious, but at least in the case of the space shuttle, the affected window was replaced upon return to earth. The NASA space station program baseline assumes a probability of a hit by one one millimeter particle once each year. Of course, larger meteoroid particles exist, and it may be possible to protect against particles of up to ten millimeters. However, the problem of hypervelocity collisions and their consquences is receiving a great deal of attention right now. Experimental evidence in ballistic tunnels indicate that when a penetration by a particle travelling at orbital speeds occurs, the mass scattered by the failure is about 100 times that of the incident particle, resembling the explosion of a hand grenade.

The critical consideration in pressurized spacecraft is to protect the pressure vessel wall from impact. Up to the present, kapton foil in multiple layers has been the principal means of energy absorbing shielding and insulation for both manned spacecraft and for unmanned satellites. In addition, all manned spacecraft have consisted of aluminum pressure vessels, often with corrogated aluminum "bumpers" for micrometeroid protection. With the use of bumpers, if a bumper succeeds in breaking up a high velocity particle, the force of the impact by the secondary scatter is inversely proportional to the distance of the bumper from the pressure vessel shell.

The materials with the greatest promise for protecting against meteoroid and space debris impact in the future are the modern plastic composites such as kevlar, epoxy-graphite and carbon-carbon fibers. These materials are already in use in bullet-proof vests and in custom armoring for limosines. Laminated composites are excellent for the outer shielding of a space station because of the way in which that they delaminate to absorb energy rather than fracture parallel to the impact trajectory. However, for the very same reason that laminated composites make good external shielding, they may make poor pressure vessels for habitable modules on space station. Composites are in use for uninhabited pressure vessels, but the inhabited modules have the safety requirement to inspect the shell visually and non-destructively from the interior for fatigue, fracture propagation, cleaning and other maintenance. With an aluminum pressure vessel, the performance charateristics and failure modes are very well understood and non-destructive testing techniques such as radiography, ultrasonics and dye penetrants are well developed. Composites are still relatively new, and although they are in use in aircraft and some rocket booster stages today, they are not considered to be reliable enough for highly critical applications in a manned spacecraft. However, composites do present the promise of significantly lighter weight and higher strength pressure vessels in the future.

RADIATION PROTECTION

In one other respect, the aluminum pressure vessel has an advantage over plastic composites which is radiation protection. The radiation environment in space is fairly well understood. However, there is less understanding and even less agreement on the biomedical effects of radiation and the allowable dosage rates for space station crew members. LEO is a more benign radiation environment than either polar orbit or GEO, but the radiation exposure at LEO, especially from solar flares is nonetheless of grave concern. Aluminum offers a degree of radiation shielding, which the laminated composites do not. The state of the art of radiation shielding is still rather primitive and is measured principally as a function of mass, with little consideration of the energy absorbing and particle-blocking effects of particular materials. Lead, the favorite shielding material on earth presents several disadvantages for spacecraft. In a closed environment, either a factory clean room or inside a habitable pressure vessel, lead can be toxic, especially if it is subjected to fire. The low tensile strength of lead makes it difficult to work with as a foil if it must resist any significant launch loads. Finally, although lead is effective for blocking the wavelength type radiations (x-rays, gamma rays, etc.) it does not perform so well with the HZE particles which abound in solar flares and "heavy galactic ions," which tend to knock a secondary radiation scatter from the lead with a larger atomic number than the incident particle and thus the secondary scatter from lead may do more biological damage than the original particle would.

One plastic that is useful for radiation protection is a special formula of polypropelene known as "poly-z." However, poly-z has virtually no structural strength except to hold its own shape, and so it may be applied only as a lining material. Poly-z is useful principally for attenuating the energy of particle radiations by loosely bonded hydrogen atoms, in a manner similar to the radiation absorbing charateristics of water. There have been some suggestions to build a double shell pressure vessel and fill the interstice with water which would be pumped into the cavity after the module had been delivered to orbit. However, there are several practical problems with this approach, which may be solved in the future but which disqualify the water shield from current consideration.

THERMAL FLUX

Another phenomenon requiring shielding or insulation is the extreme temperature swing experienced by the space station as it passes from orbital day to orbital night. Variations of several hundred degrees over short periods of time can lead to differential expansion of materials that can be quite stressful, causing misalignments over the short term and and contributing to structural fatigue over the long term. The typical protection against these thermal effects is the kapton insulating foil, which is seen on many spacecraft. In the case of large truss structures, it will probably not be possible to apply insulation or other thermal protections, especially if the structure is to be deployed or folded out automatically. Such a structure would require materials and joints that can handle the thermal stresses of differential expansion.

While changes in external temperature must be accomodated, it is also important to control the internal temperature. In a closed environment, all electrical power is ultimately converted to heat, and that heat must be dissipated out of the spacecraft. Typically, the life support system cooling circuit collects the heat generated by people and equipment through heat exchangers into a liquid/refrigerant cooling loop and dissipates the heat through external radiators. For the US/International space station, the radiators will probably be a combination of body mounted units on the pressurized modules and remotely deployed units attached to the truss structures. These radiators would be fabricated of lightweight metal panels with a surface coating with a high coefficient of emissivity. It is conceivable that future panels might have a lightweight composite honeycomb core with a metal radiator bonded to it. Since there is no atmosphere to carry away heat, there is no effort maximize crenelated surface area for maximum air circulation. Instead, the emphasis is on maximum flat surface area with non-interfereing thermal view angles. On the space shuttle, the radiators are located on the inner surfaces of the payload bay doors. On the space station, the radiators will be located normal to the orientation of the solar arrays to minimize thermal interference from direct sunlight. Radiators might even be installed on the backside of the solar array panel except for the problem of a gimballed fluid connector. Body mounted radiators will be simpler but less efficient because they will be omnidirectional.

MICROGRAVITY

Microgravity, often referred to as "zero-g" or weightlessness has important implications all human activities on orbit. The biomedical effects of microgravity can be quite pronounced, including disorientation, space sickness, loss of muscle tone, bone demineralization and fluid shifts within the body. With regard to lightweight structures, microgravity and the vacuum of space are particularly significant for construction and assembly techniques. NASA has acquired as small amount of experience in assembling and erecting structures in space, and the microgravity aspect, combines with the pressurized space suits to create new and difficult conditions for construction work. NASA astronauts have conducted several flight experiments in the erection and deployment of large truss structures on the space shuttle. The success of these experiments shows the feasibility of space-suited astronauts assembling large structures on orbit. The assembly of large space structures is discussed in a later section of this paper.

2.2. MAN-INDUCED ENVIRONMENT

The man-induced environment around the space station is not as absolute as the natural environment in the sense that people can take actions to make it better or make it worse. Never the less, the space station designer confronts continually the need to design for the "worst case scenario," but in the case of the human induced environment, the worst case may be difficult to predict. Among the factors considered part of the man-induced environment are: space debris impact, collision with other spacecraft, vibration and external contamination. Special if temporary factors that may be included in the man-induced environment are the high gravitational, extreme noise and vibration imposed on the spacecraft structure during the first minutes of launch.

SPACE DEBRIS IMPACT PROTECTION

Probably the most serious and unpredictable man-induced hazard is space debris impact. The mechanics of space debris impact are essentially similar to the meteoroid flux, except that while the meteoroid flux appears to be a fairly constant particle population, the space debris problem appears to be growing. Some of the space debris population can be attributed to anti-satellite testing, but the great majority of it can be traced to spent upper stage rocket boosters. Both the USSR and the USA appear to have developed techniques to prevent "reservoirs" of spent upper stage debris from forming in the future, but the prospect of expanded anti-satellite testing by either side is cause for concern.

COLLISION HAZARD

The impact problem can be regarded as having one extreme case of an large piece of spacecraft hardware, possibly an entire active spacecraft colliding with the space station. The primary concern in proximity operations manuvering is not that the impact might penetrate a habitable module (although that is a possible "worst case") but that an impact might knock out a piece of equipment. For example, an impact might break one or more strut elements of a large truss structure, possibly even severing a box-truss of 5 meters square cross section. In this case, safety in redundancy has been interpreted to mean more than one truss for each of the major structural elements, as shown in the "dual keel" configuration discussed in the section: Current Space Station Programs.

VIBRATION

Collision hazard may represent the "worst case" of impact by other spacecraft on the space station, but even during routine and normal dockings, the induced oscillations can be quite significant. The undamped oscillations imparted to a large space structure by an "imperfect" but still normative docking could continue virtually indefinitely. As the combination of flexural, torque and tumbling motions is a very complex phenomenon, post-docking damping or control will need to be highly sophisticated. Levinson and Kane show an example of an "initially deformed, non-uniform" beam of 20 meters in length, which after an "imperfect docking" requires approximately 1000 seconds to "bring the system to rest relative to the local vertical."[5] One implication of this type of free body motion analysis is that a rigid structure which minimizes flexure and internal oscillations is desirable. A major application of lightweight structure technology is to the large three dimensional truss structures that will provide the skeletal system for the space station. Large, rigid truss structures are particularly appropriate for supporting large, floppy solar wing arrays.[6]

Another aspect of vibration in the space station is structure-borne noise. In the vacuum of space, noise does not dissipate out of a structure into a surrounding atmosphere as it does on earth. Instead, the noise bounces around inside the structure until it is finally converted to heat. Noise control and absorption have proved to be more complex than conditions on earth where the entire structure has the ground and atmosphere to dampen out structure-borne vibrations. Despite the best efforts of acousticians to predict and design the acoustical environment for Skylab in 1973, the astronauts' subjective responses varied considerably. "The crew's comments with respect to noise in the sleep areas are interesting in that they range from 'excellent, very quiet' to 'can't rest - there is no noise control in vehicle.'" Also, the complaints about noise levels in certain compartments appeared to increase with the length of the mission.[7]

Preliminary studies of aluminum versus composite shell module pressure vessels, for both single and double wall shells "tend to indicate that more noise is transmitted at most frequencies by a shell made from composite materials," approximately ten dB greater at most of the spectral peaks occuring from 100 to 800 Hz. In this study, the single and double wall shells are constructed of ten laminated layers, each reinforced by fiberglass and/or graphite fibers, with each layer oriented in any arbitrary direction.[8]

EXTERNAL CONTAMINATION

Perhaps one of the major constraints on the application of plastic composites to lightweight truss structures is the problem of external contamination. External contamination is caused by a variety of sources, such as the venting of atmosphere or water from the space station life support system, and the leakage of propellants. Gaseous or liquid contaminates may condense on virtually any surface of the space station, clouding windows, obscuring lenses and decreasing the efficiency of photovoltaic collectors. Of these various contaminants, the most hazardous appears to be hydrazine fuel which can attack a variety of plastics. While the greatest threat of hydrazine attack is probably to lexan which is used for outer window shields and space suit helments, other plastics may also be at risk. Extensive testing of all materials is required for resistence to chemical attack.

LAUNCH LOADS

Launch loads represent a special case of a temporary loading condition that occurs only during the high-g acceleration of launch into orbit. All presssure vessels and major components fabricated and assembled on the ground must be designed to resist the high vibration, noise and gravity forces which occur during launch. One of the great advantages of large structures which are assembled, erected or deployed on orbit is that they need not resist launch loads as completed structures. Only the knocked-down, bundled or folded packages of structural components need to resist the launch loads, which offers a major savings in weight and volume.

2.3 SUMMARY OF ENVIRONMENTAL FACTORS

The key point about environmental factors, especially when addressing the issue of lightweight structures, is that space is extremely hostile to human life. Safety and survival is always the first consideration. All configurations, materials and structures must be evaluated against this requirement. See Figure 2-1 for a variety of recent configuration concepts, each of which offer various advantages and disadvantages in the orbital environment.

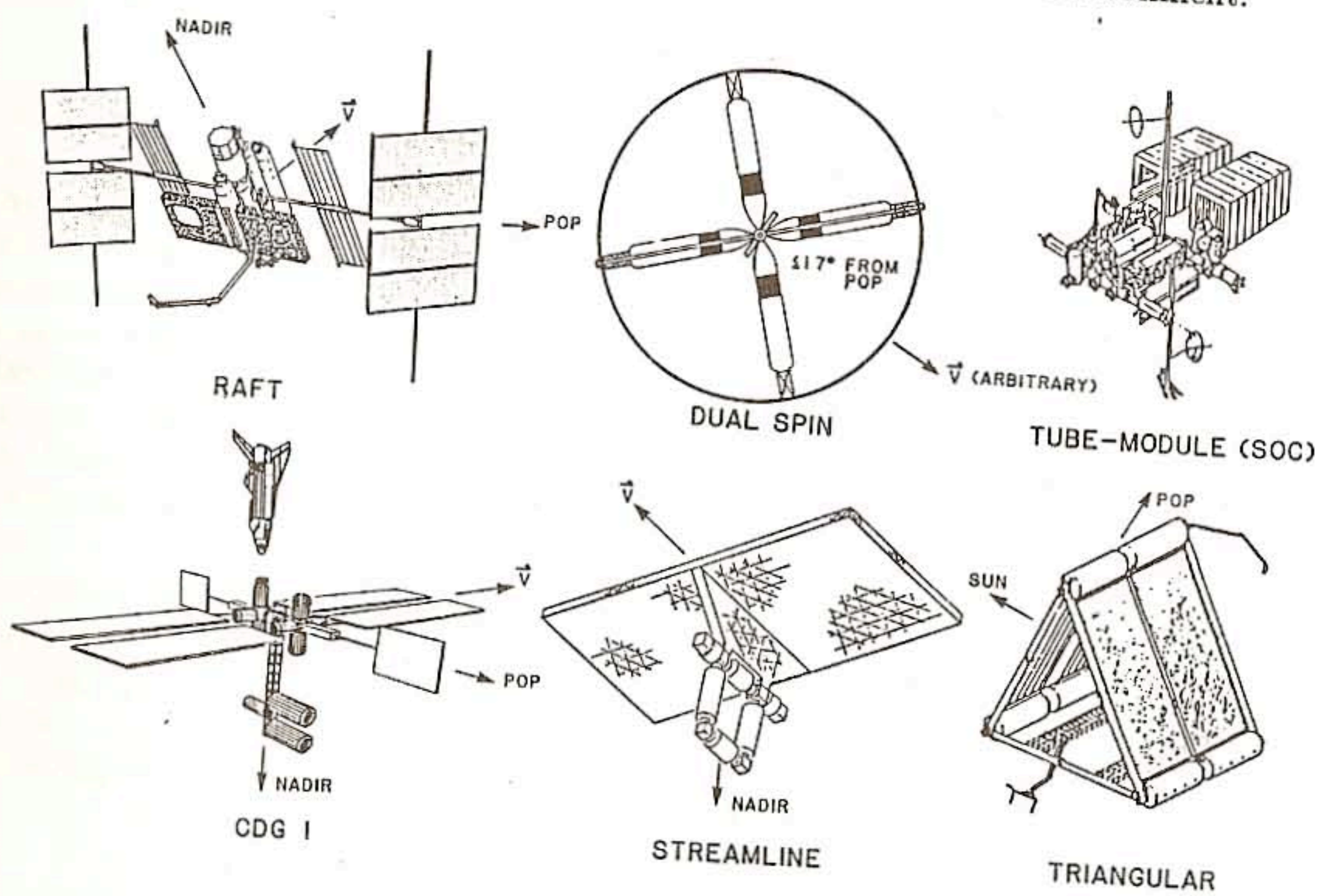


Figure 2-1. Examples of Space Station Configuration Geometries.

3. SPACE STATION CONCEPT EVOLUTION

The evolution of space station configuration concepts can be analysed largely in terms of increasing understanding of the space enviroment described above and mission requirements. Mission requirements are the reason for building a space station in the first place. The operational characteristics, the means of accomplishing the mission goals, are corollaries of the

mission requirements. Space station development can be divided chronologically into roughly four periods: early visionaries, popular concepts, the first generation (Skylab and Salyut), and current programs. Future space settlements are discussed in a seperate context which includes lunar and planetary bases.

3.1 EARLY VISIONARIES OF SPACE FLIGHT

The first period of "early visionaries" spans from 1869 to 1928 and includes the work of Hale, Verne, Lasswitz Tsilkovsky, Oberth, von Pirquet and Noordung. Most of these idealists had only vague mission requirements, and seem to have been motivated principally by their desire to show that space flight in general and artificial satellites in particular are possible. Many of the ideas associated with space stations today originated during this period.[9] The early visionaries of space flight are also of interest to this discussion because of how little they were aware of the environmental issues that are described above, and how ingenuous were their mission requirements.

Probably the earliest description of a space station is "The Brick Moon," a story by Edward Everett Hale, published in 1869, in which a brick satellite is launched in orbit by a giant catapult. The intended mission of this ceramic sphere of 60 meters in diameter was to serve as an aid to navigation. However, the spacecraft is launched prematurely with the workers still on board and it becomes a "space station" only by accident.[10] Although Hale had no notion of space as a vacuum or the need for a pressure vessel or life support system, it is interesting to reflect that a "brick" shielding might be advantageous for meteoroid and radiation protection, and that brick-like insulating tiles provide thermal protection to the space shuttle orbiter.

The first three decades of this century were a fertile period for space flight visionaries. In 1903, Konstantin Tsilkovsky presented the first space station concept incorporating a closed ecologically based life support system. Tsilkovsky's ideas have exerted enormous influence over the development of the Soviet space program.[11] Tsilkovsky was also the first to propose the idea of a space station that would rotate to generate artificial gravity. Probably the first serious study of mission goals was conducted by Hermann Oberth in 1923 who coined the term "space station" and suggested uses for earth and weather observation, communications linkages, astronomy and as an orbital refueling station for other spacecraft.[12] In 1928, Herman Noordung proposed the first rotating torus type space station, comprised of a "Wohnrad" (living wheel) crew quarters, a solar power concentrating mirror collector, and an earth-pointing observatory. The sole function of the Wohnrad appears to be earth observation and broadcasting of navigation warning signals.[13] Noordung's concept became the archtype of the rotating torus that most people envision when they think of a space station. However, all of these early visionaries had very little notion of the operational character of a space station. Never-the-less, many people are still making proposals on the basis of this one conceit of angular accelleration, that by generating a centifugal force, we could create artificial gravity. Whether that artifical gravity is useful or desirable for specific mission requirements is often overlooked.

3.2 POPULAR SPACE STATION CONCEPTS

For the next twenty years, rocket scientists and physicists devoted relatively little attention to space stations as they apparently worked on preparations for the next world war. As a side effect of that war, the rocket technology was developed that first made it practical to actually consider launching a space station into earth orbit. It is not surprising that the leading rocket engineer of that period, Werner von Braun was also the first person to write for the popular press to advocate a space station program as a national priority. In 1952, von Braun published a now famous article in Collier's Magazine, "Crossing the Last Frontier," in which he proposed a rotating torus, to be launched into a polar orbit of 1,075 miles. Von Braun explains the need to minimize weight and describes one concept for a lightweight space station:

> In at least one design, the station consists of 20 sections made of flexible nylon and plastic fabric. Each of these sections is an independent unit which later, after assembly into a closed ring, will provide compartmentation similar to that found in submarines. To save shipping space, these sections will be carried to the orbit in a collapsed condition. After the "wheel" has been put together and sealed, it will then be inflated like an automobile tire to slightly less than normal atmospheric pressure. This pressure will not only provide a breathable atmosphere within the ring but will give the whole structure its necessary rigidity.[14]

Von Braun appears to have been blissfully unaware of the meteoroid problem and he downplayed the radiation hazard as well. See Figure 3-1 for an artist's rendering of von Braun's original concept.

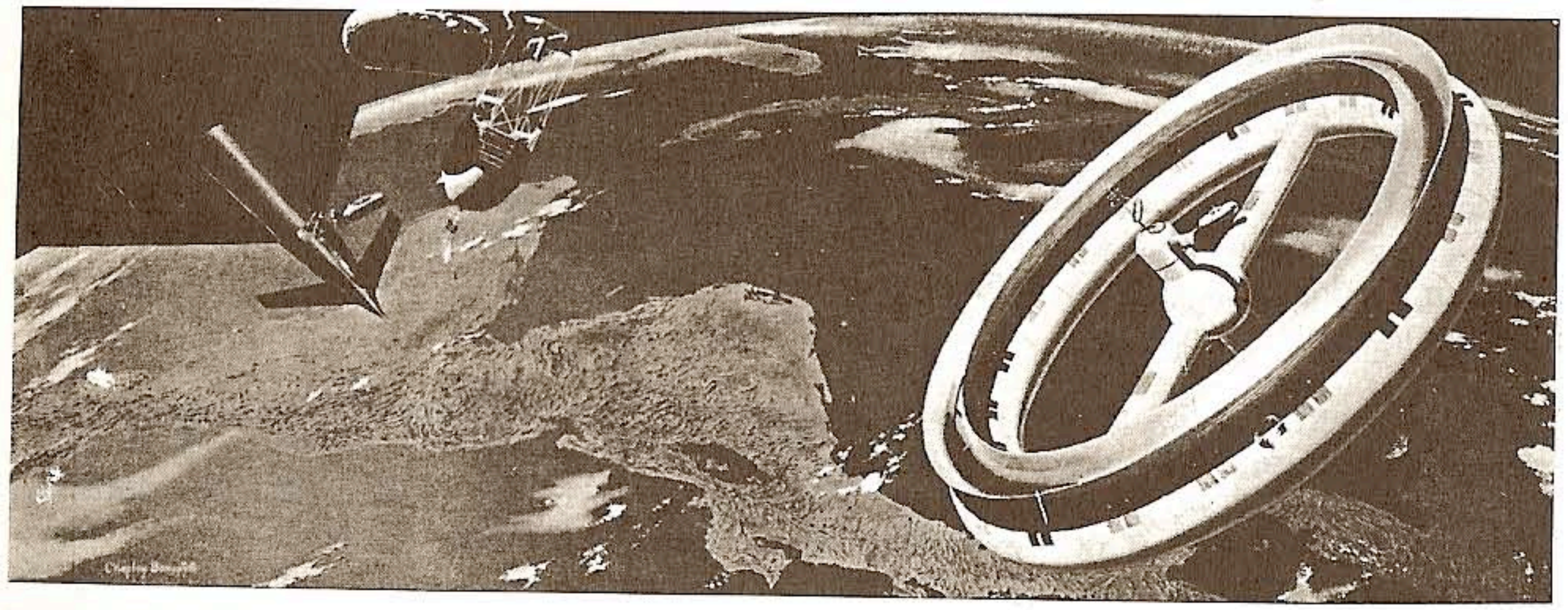


Figure 3-1. Von Braun's Rotating Torus.

As early as 1960, Carter and Bogema recognized some of the critical reliability problems of inflatable structures for space stations:

> Behavior of rubber-like materials under meteoroid attack is very uncertain. The inflation procedure for a flexible skin with internal equipment is complex; reliability of such a system would have to be given very careful consideration. . . . Complete loss of pressure will cause loss of structural stability of the station.[15]

Even with the development of modern rubber products, uncertainty continues to cloud the prospects for inflatable structures on any large scale in space. Never-the-less, proposals for inflatable structures continue to surface, and a limited application to flexible tunnels is in use in the NASA shuttle program.

In the same year that von Braun wrote for Colliers, Arthur C. Clarke published *Islands in the Sky,* the first novel about a zero-gravity space station. Clarke was more precient than von Braun in predicting a zero-gravity station at least for LEO. Clarke is also the first to describe in any detail on-orbit operations by space-suited astronauts engaged in extravehicular activity (EVA) construction activities.[16] Clarke was remarkably sensitive to the human performance characteristics of his "Inner Station" in LEO, and described the careful, slow

movements of the astronauts necessitated by the conservation of momentum problem in zero-gravity.

3.3 FIRST GENERATION SPACE STATIONS

Both the USA and the USSR have conducted programs using intermittently inhabited, temporary space stations. Both the American Skylab and the Soviet Salyut were designed as temporary facilities, derived largely from existing space flight hardware. In fact, Skylab was built principally using an Apollo program Saturn rocket upper stage casing for its principal habitable pressurized volume.

The Soviets launched and occupied the first of these temporary space stations, Salyut 1, in 1971, followed by Salyuts 3 through 7, with the longest mission duration of 237 days habitation by a crew of three on Salyut 7. The Salyut series represents small incremental improvements, with Salyut 7 being the most complex, and the largest with an overall length of 35m, largest diameter at the Salyut core of 4.15m and a total weight of approx. 47,000kg and $150.3m^3$ of habitable volume. Salyut 7 consists of an assemblage of the Soyuz-T space craft, the Salyut core, and a Cosmos 1443 "modular transport ship." Salyut 7 has approximately $100\ m^2$ of solar photovoltaic panels spanning 16m and generating 7kW of electrical power.[17] Aside from the traditional pressure vessel technologies, the only lightweight structure of significance in the Salyut series is the solar panel design. See Figure 3-2 for a sketch of Salyut 7, the most advanced of the Salvut series.

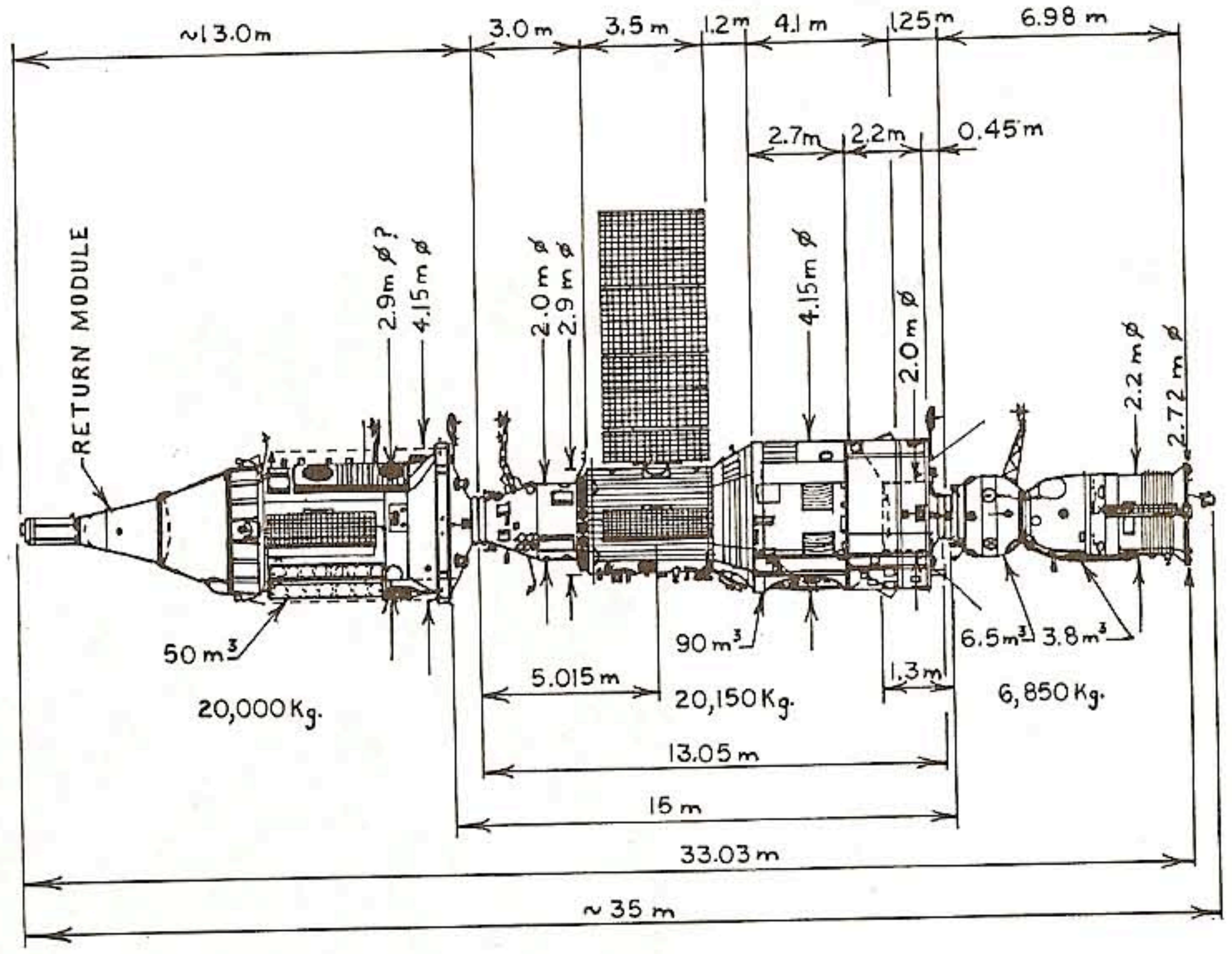


Figure 3-2. Salyut 7.

The American Skylab was launched in 1973 and was visited by three crews of three astronauts each. Skylab had approximately $354m^3$ of pressurized habitable volume, comprised of an assemblage of an Apollo command module, docking adapter, airlock and the Saturn workshop. Overall length was 40.72m, and the greatest diameter was 6.7m in the Saturn workshop, and the mass was approx. 89,000kg. See Figure 3-3 for a sketch of Skylab.

Skylab had two sets of solar arrays, one for general station power and one dedicated to the Apollo solar telescope. The Skylab general station power array was designed to deliver 10.5 kW average power, but due to the loss of one of the two "wings" on launch, the actual power was about half of this goal. The solar array consisted of a deployable open box type beam and three "wing sections."[18]

Skylab represents the first occasion on which temporary lightweight structures were deployed on a contingency basis on orbit. During the launch sequence, the outer shroud around the Saturn workshop failed to seperate properly, tearing off a large part of the thermal and micrometeoroid shield as well as one of the two solar arrays. The remaining solar array failed to deploy because of a jammed restraining strap.

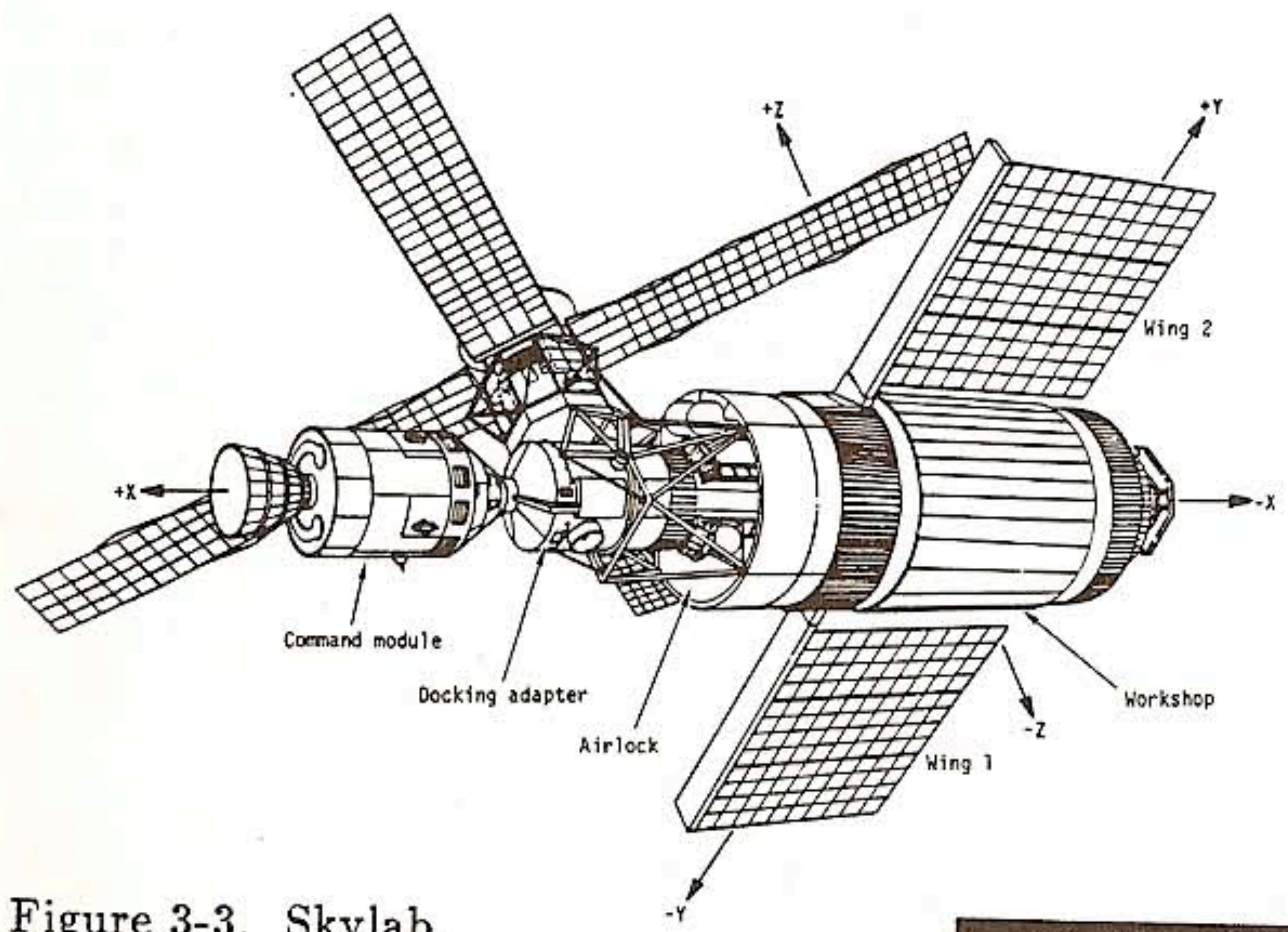


Figure 3-3. Skylab.

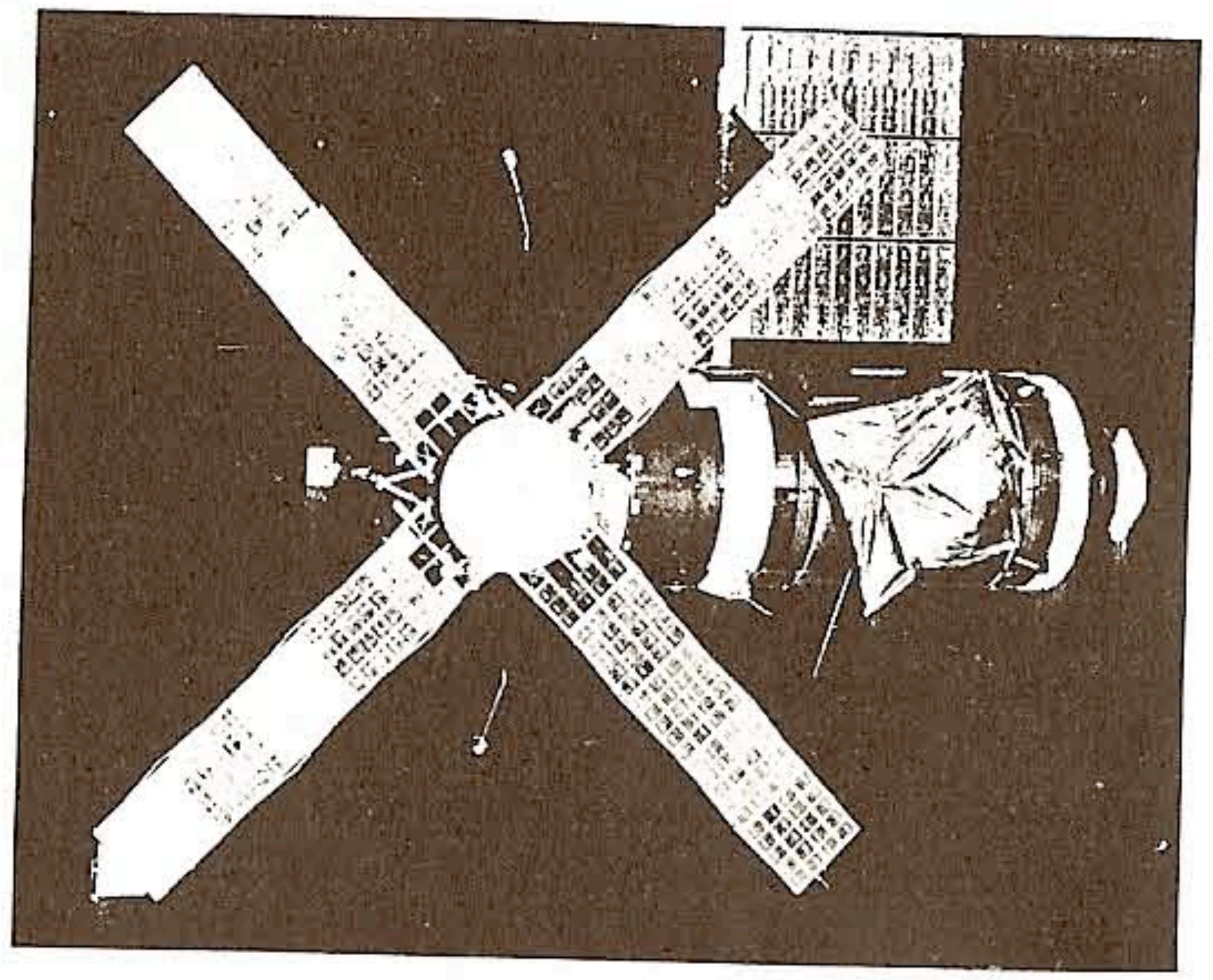


Figure 3-4. Parasol deployed over Skylab Saturn Workshop.

Charles Conrad and Joseph Kerwin of the first Skylab crew released the jammed solar array panel during an EVA. The missing thermal and meteoroid shield problem was solved when the same crew attached a light-weight fabric parasol thermal screen to protect the Saturn Workshop against overheating. This parasol was designed, built and tested in a matter of

weeks and delivered to orbit in an Apollo command module with the first crew of astronauts to activate Skylab. During the first day of occupying Skylab, they deployed the parasol successfully through the scientific airlock. Following parasol deployent, the interior temperatures dropped from about 54 degrees C to 27 degrees C, making it possible to carry out the planned mission activities.[19] See Figure 3-4 for a view of the first parasol deployed on Skylab. The second Skylab crew deployed a more substantial thermal screen during an EVA, securing it to external attachment points so that the scientific airlock could be freed for its intended purposes.

3.4. CURRENT SPACE STATION PROGRAMS

Both the United States and the Soviet Union have active space station development programs. Both these space station programs may be considered as second generation because of their qualitative advances over Skylab and Salyut. These second generation stations, when fully assembled, will be permanently inhabited by crews on a continuous, rotating basis. These designs are modular, comprised of a multiplicity of elements that can be added, exchanged, relocated or removed by the crews. These stations will operate with a much greater degree of autonomy than earlier stations or current spacecraft, because it will be unrealistic to supervise a crew of six or eight or more continuously from the ground in the same ways that crews of two and three have been directed in the past.[20]

NASA SPACE STATION PROGRAM

NASA space station configuration concepts have evolved through a series of analytical design studies over the past five years, in an effort to develop a baseline approach that meets mission requirements and is also affordable within ever-tightening budgets. Each of these research study phases has contributed to a more sophisticated understanding of space station structure and configuration. In the following overview of design development progress, the overall configuration is regarded as a structural system which may be optimized to benefit from lightweight structure research. This research is reviewed in the following section, "Research in Lightweight Structures."

PRE-PHASE A SPACE STATION STUDIES

The current NASA space station program got underway in 1982 with two parallel studies that sought to "bound the problem" of a second generation manned space station, These two studies were the Manned Space Platform by McDonnell Douglas for NASA-Marshall Space Flight Center and the Space Operations Center by Boeing for NASA-Johnson Space Center. Although the initial assembly phases of these concepts were quite different, the fully assembled configuration of both were remarkably similar rectangulated formations of modules joined by special tunnel connectors or "berthing modules." The few differences in terms of lightweight structures were that the MSFC Manned Space Platform deployed its solar arrays from a heavy structural power system module,[21] and the JSC Space Operations Center, deploys its solar arrays from long masts.[22] Also, the MSFC Manned Space Platform included a small box truss frame to provide a construction base for assembling satellites, as shown in Figure 3-5. Note that the attachment of this truss to the module and tunnel connection pattern is somewhat unclear. This lack of clarity resulted from the overall problem of not having a multi-purpose structural system to hold the whole configuration together. The JSC Space Operations Center had one down-pointing truss beam for a construction base or scientific payloads. The designers of this configuration recognized its floppy nature and proposed a system of automated damping actuators to control or "tune" its harmonic modes. However, such a dynamic control system would have been extremely expensive and complex. These "full-up" space station concepts are shown in Figures 3-5 and 3-6 respectively.

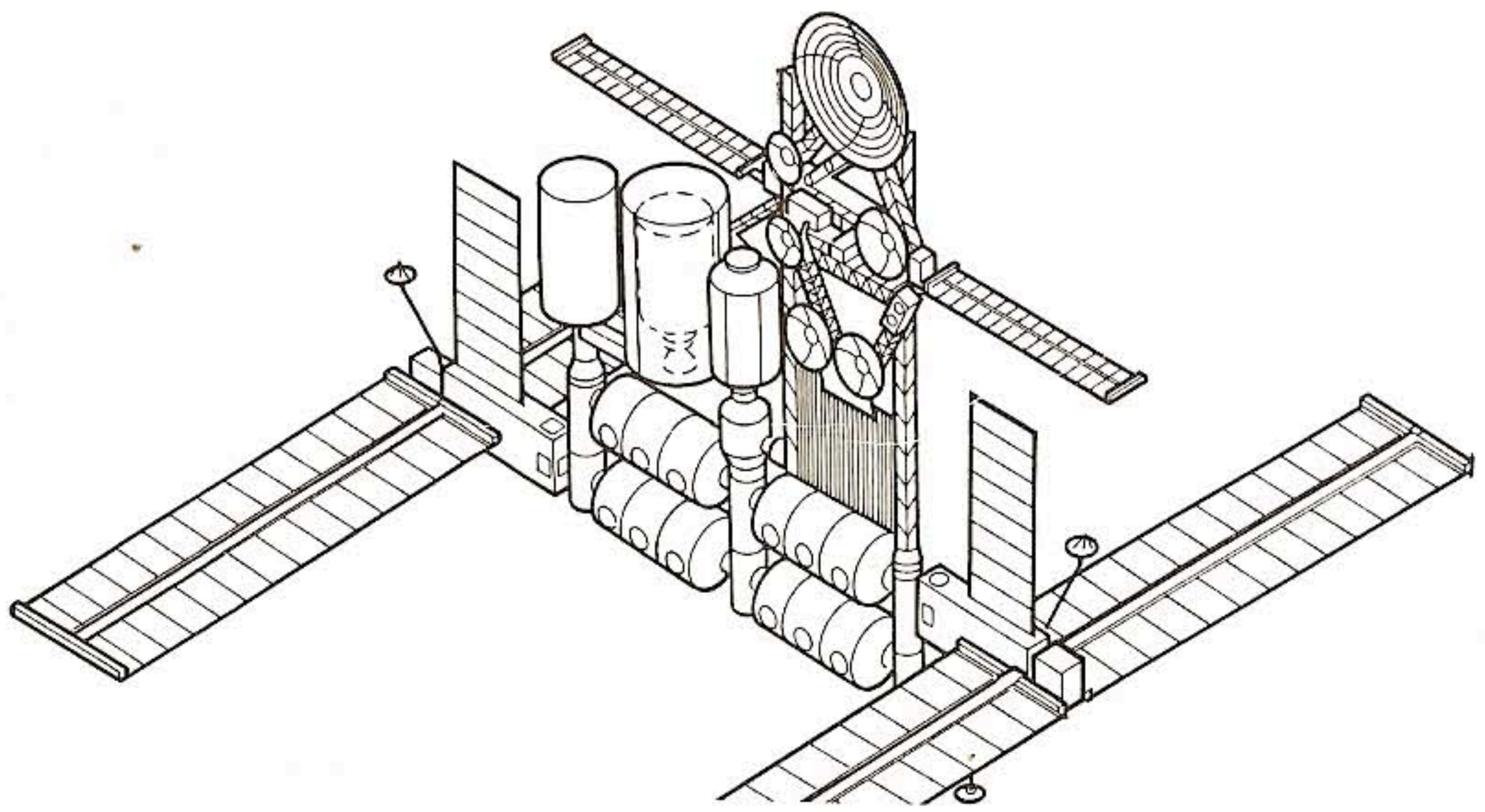


Figure 3-5. MSFC Manned Space Platform.

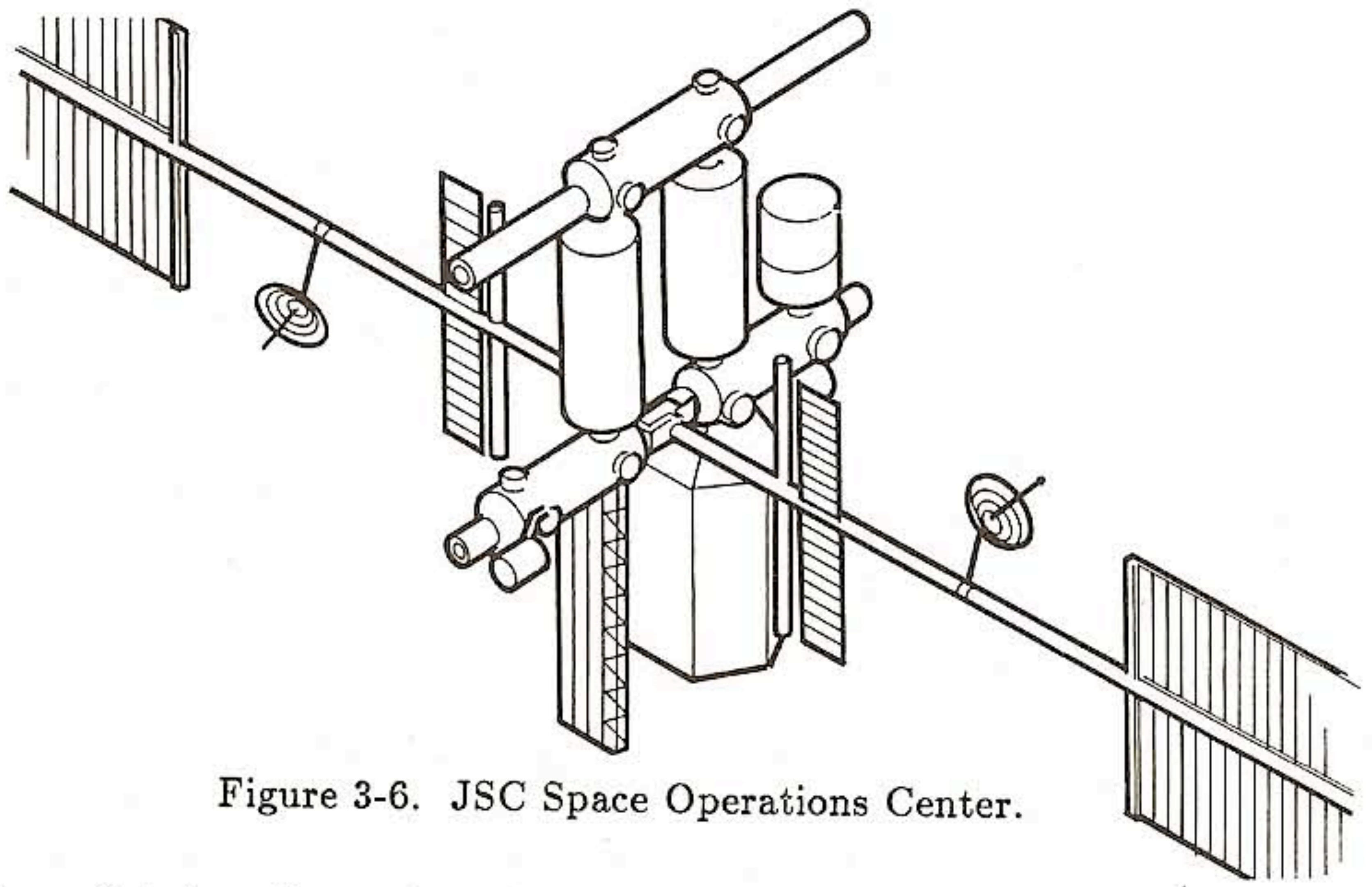


Figure 3-6. JSC Space Operations Center.

These two rectangulated configurations shared a set of common problems: large, floppy solar array support structures, non-self-rigidizing module to module connections, difficulties in the assembly and disassembly process and a lack of rigid strong-back to support scientific instruments. The structural loading problem was particularly acute because the module to module connections were carrying the large moments and torques generated by the large, floppy solar arrays. This placed significant stress on the intermodule connections, which were compelled to act as completely rigid joints to resist bending moments and wracking. In a classical exposition of orthogonal thinking, Sherman Schrock of Martin Marietta expresses this rectangular bias:

> The structural stability is dependent on the docking port stiffness. . . . the stiffness achievable is directly related to the diameter of the docking system and the diameter must be limited . . .[23] [by the circumference of the surface on which it is mounted].

As a solution to these problems associated with rectangulated structures, the author proposed a triangular-tetrahedral concept for a space station which was first presented during March of 1983 at the Space Station Technology Workshop in Williamsburg, Va. This Tri-Tet

approach proposed to eliminate the rigid joint problem by replacing the rigid-jointed rectangular frame with a self-rigidizing triangular pin jointed frame, in which the berthing connectors would not need to resist bending moments by themselves. Instead, the entire megatruss cell would act as a unit structurally. The spherical connection nodes with a specially designed berthing connection mechanism solved the difficulties of assembling and disassembling the structure as well. Although the Tri-Tet concept included one "berthing beam" in lieu of a module for mounting external scientific payloads, the available area of this beam would not be sufficient for all the instrument packages that are part of the space station mission requirements profile which was developed in 1985. A patent application was filed in March of 1984 for the Triangular-Tetrahedral space station concept.[24] The Tri-Tet concept is illustrated in Figure 3-7.

During the pre-Phase A period and throughout Phase A as well, several large truss structures were advocated within NASA as a solution for some of these configuration problems. Two representative large truss concepts of this period are illustrated in Figures 3-8 the "Delta" configuration and in Figure 3-9 the "Big-T" configuration.[25]

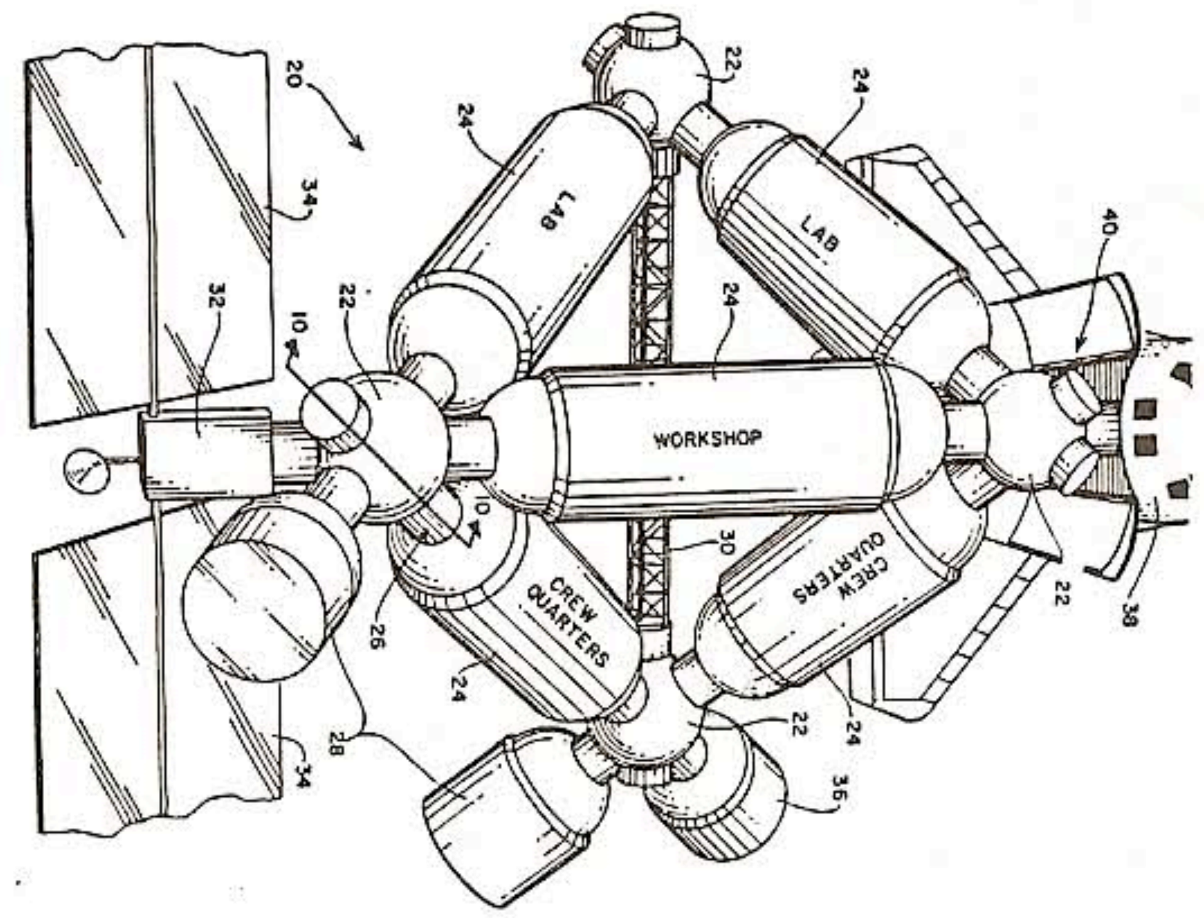


Figure 3-7. Triangular-Tetrahedral Space Station Configuration.

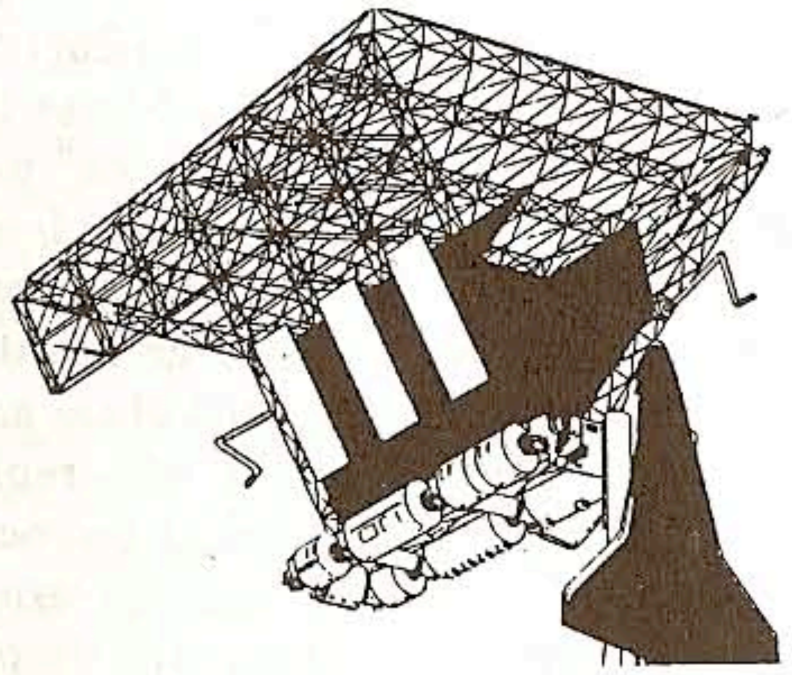


Figure 3-8. Delta Configuration.

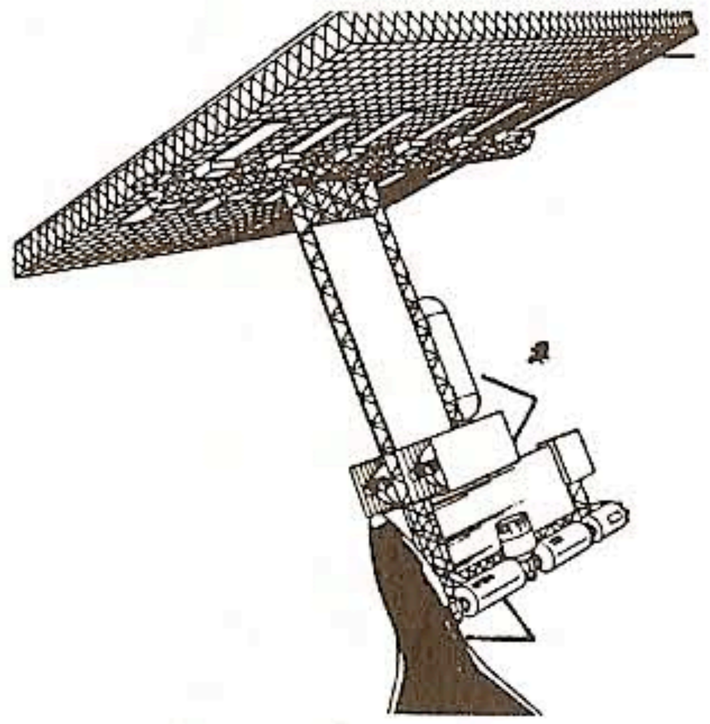


Figure 3-9. "Big-T" Configuration.

PHASE A SPACE STATION CONCEPT DEVELOPMENT

From May of 1983 to May of 1984 a Space Station Concept Development Group (CDG) met at NASA Headquarters in Washington, D. C. The CDG established a baseline configuration which became known as CDG-1. This configuration featured a cruciform arrangement of modules around a central multiple berthing adapter module. A straight box beam type truss supports the solar array from the power module and a second box beam projects from a multiple berthing adapter to provide scientific and commercial payload mounting. Figure 3-10 shows a view of CDG-1.

The CDG-1 modules were all cantilevered off of one or two axial berthing modules so that they could be attached or removed with a minimum degree of complexity. In exchange for this convenience, there was a decline in inherent safety compared to modules which are connected at both ends and thereby have dual remote means of egress. To compensate for this safety decrement, a "safe haven" philosophy was developed according to which each module would stock enough food, water and life support consumables to support crew members trapped inside until they could by rescued by a new orbiter launch, 21 to 28 days of survival time in all. The CDG-1 configuration is an example of how structural configuration choices can influence safety strategies.

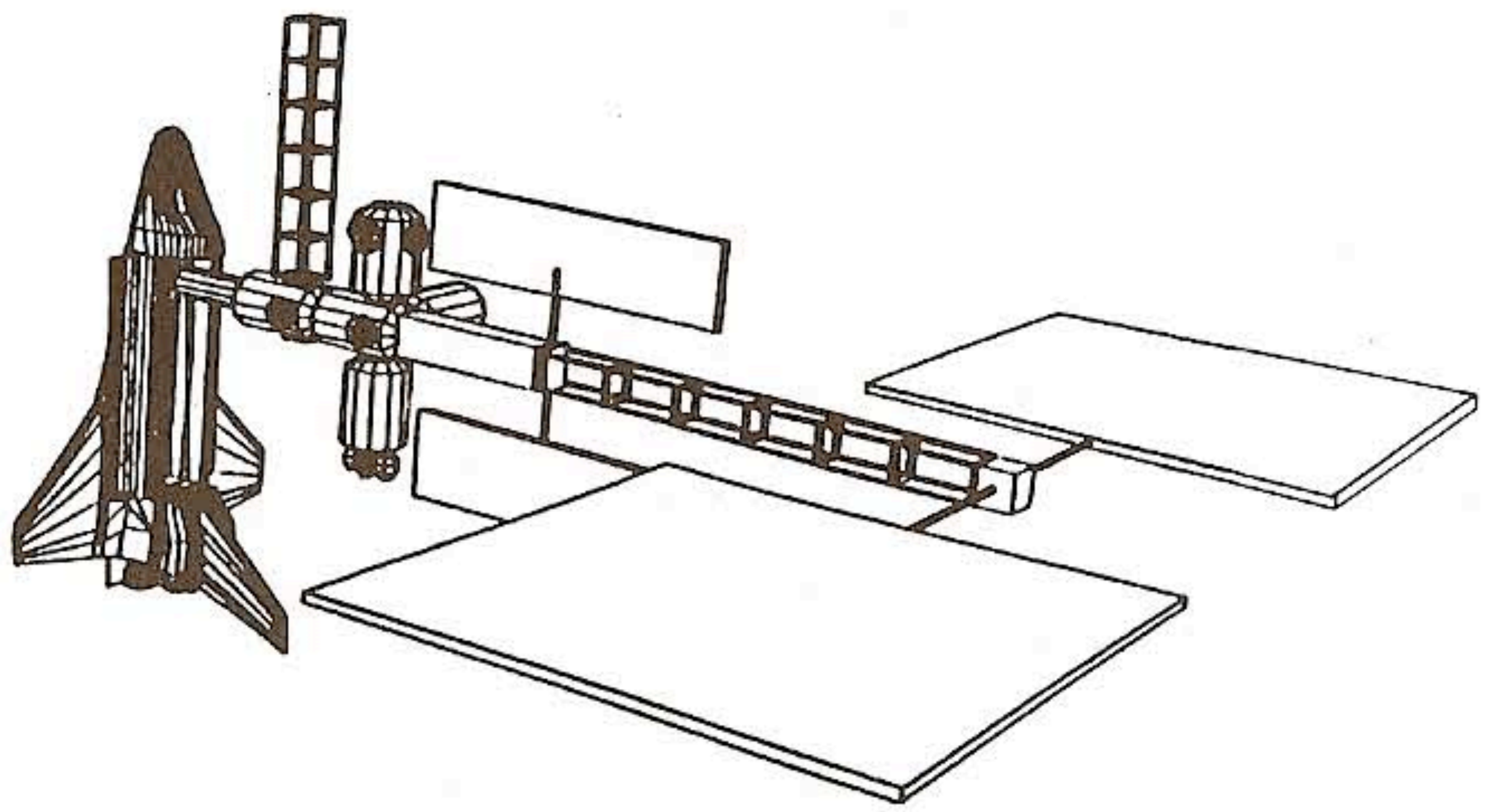


Figure 3-10. CDG-1 Space Station Configuration

PHASE B SPACE STATION DEFINITION STUDY

The NASA space station program is presently in the "Definition Study" Phase B. This phase started with a "skunkworks" that developed a "Reference Configuration" in an effort to match the configuration concept to the actual mission requirements baseline. The Phase B Skunkworks made several significant decisions: to connect the modules in a "racetrack" pattern so that there would be two means of egress from each module, to provide a much larger truss area and to fly the space station in a gravity gradient mode so that if the moment control gyros were turned off, the station would remain in a stable attitude. Most significant of these decisions from the lightweight structures perspective is the greatly increased truss area. Not only does this choice allow much more extensive payload support, but it also replaces the module to module connections as the primary structure carrying the bending moments from the solar arrays.[26] Removing this major structural task from the module pressure vessel shells and mechanisms in favor of a lightweight truss structure solution greatly simplifies the structural analysis, design and fabrication of the modules themselves. The advocates of large lightweight truss structures succeeded. Figure 3-11 shows a schematic view of the original Phase B Reference Configuration truss structure. Note the resemblance to the pre-Phase A "power tower" shown in Figure 2-1. The pressurized modules would be installed inside the bottom "fork" of the truss tower.

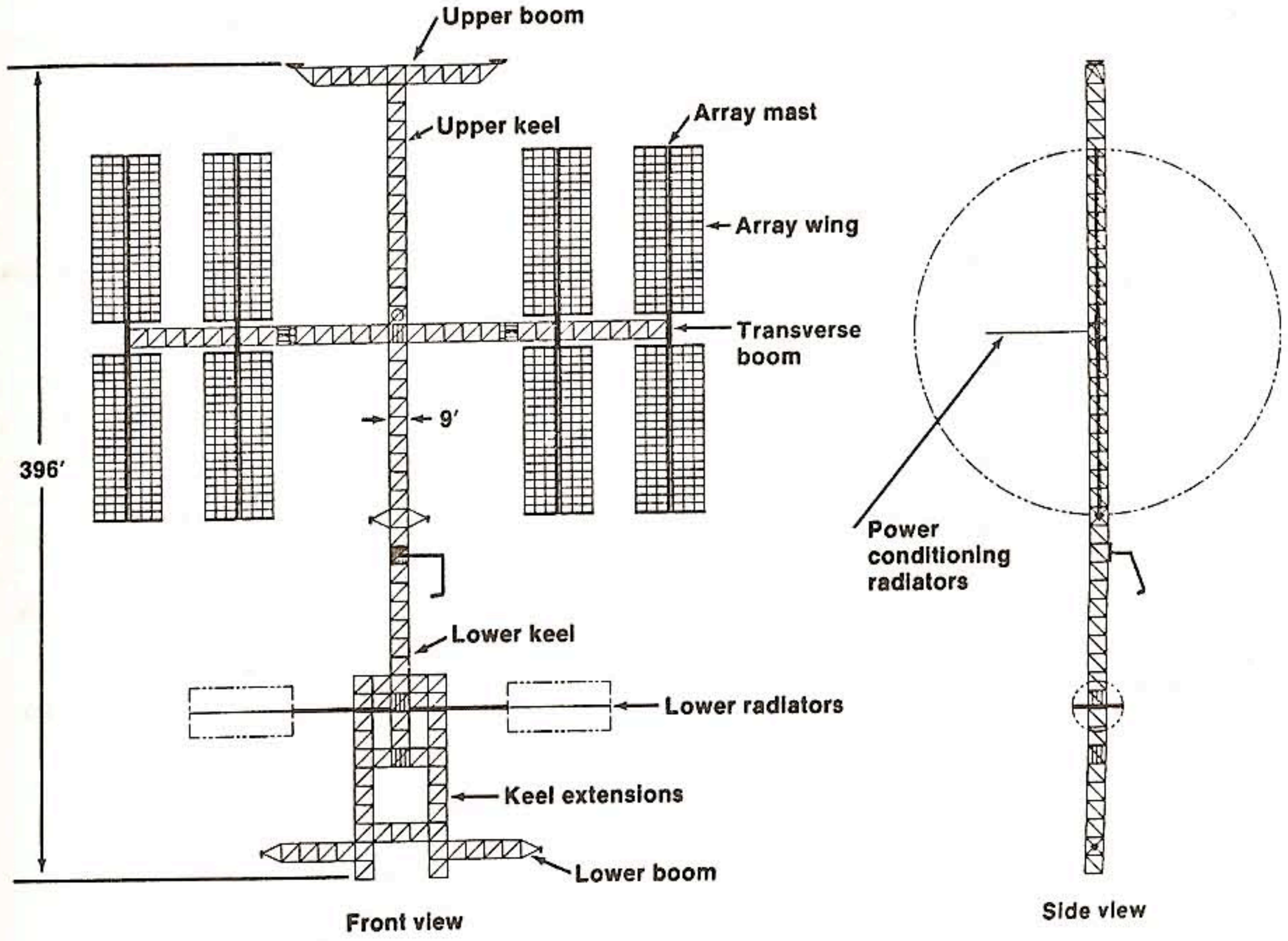


Figure 3-11. Phase B Reference Configuration Truss.

Further analysis of the Reference Configuration led to a further set of refinements in October of 1985, which have become known as the RUR-2 Configuration. The module pattern was changed to incorporate a spherical interconnection node derived from the Triangular-Tetrahedral Space Station Study. This decision finally solved the problem of module to module assembly and disassembly. The RUR-2 Configuration also increased once again the total truss structural area in order to provide a stiffer structure vertically and horizontally between the solar arrays and to provide even more scientific and commercial payload mounting surface. A mobile remote manipulator system arm (MRMS) to be built by the Canadians will run the length and breadth of this 5 meter box truss structure to aid in the assembly of the station and in the servicing of its components. See Figure 3-12 for a schematic of the RUR-2 space station configuration, updated as of February, 1986, also known as the "Dual Keel" configuration.

As a follow-on to the RUR-2 Configuration decisions, not only the Canadian MRMS but the European Space Agency and Japanese laboratory modules were added to the configuration, creating a truely international space station. Both the ESA and Japanese modules would be connected directly into the module connection pattern which is mounted on the major transverse section of the truss structure. See Figure 3-13 for a detailed concept of the international module connection pattern. The American modules are shaded and the international components are labelled. This configuration continues to be refined in many details. This overall configuration can grow through the addition of more modules, solar arrays or truss structure. The present launch target date for the NASA/International space station is 1994.

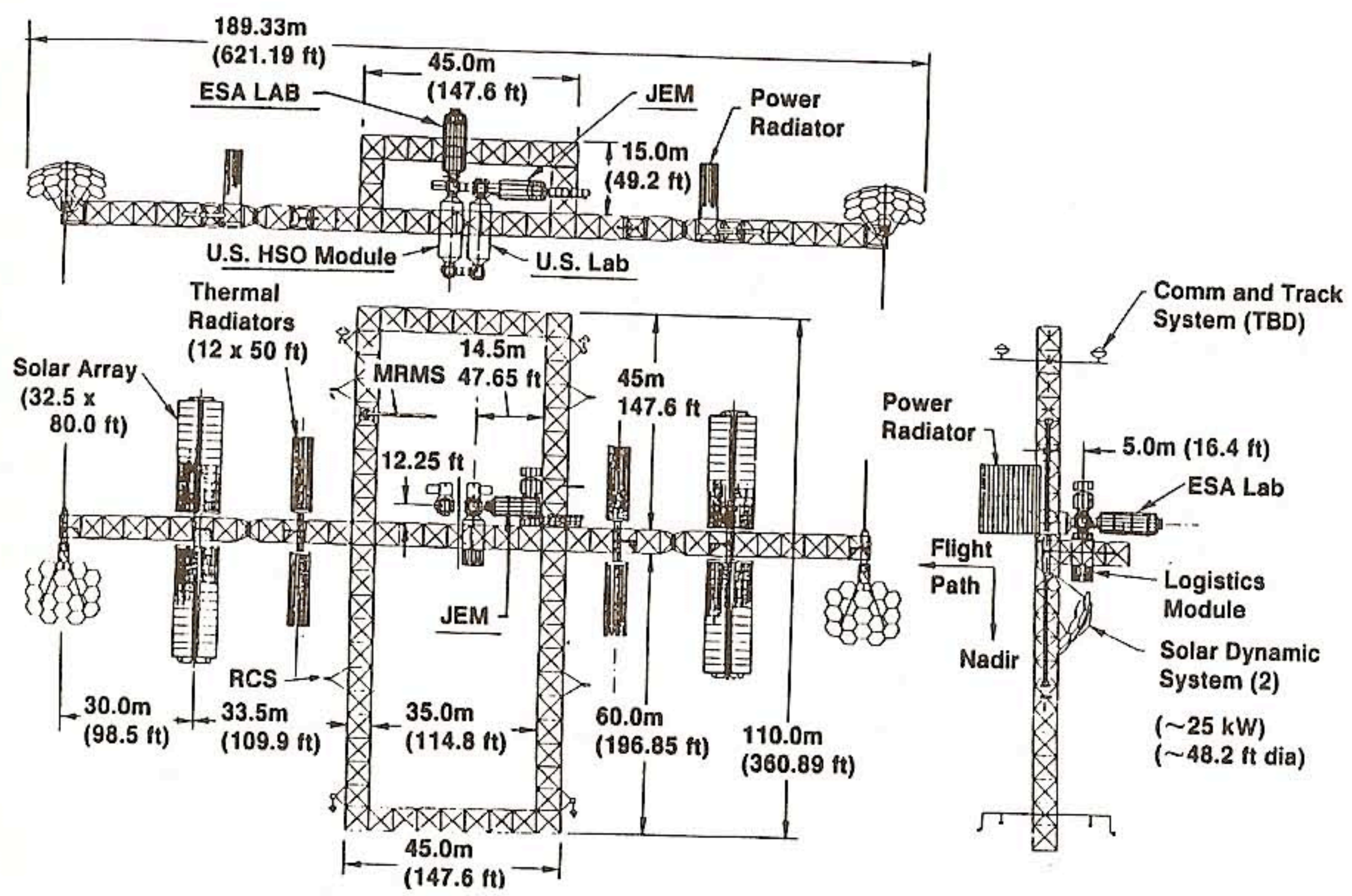


Figure 3-12. Dual Keel space station configuration.

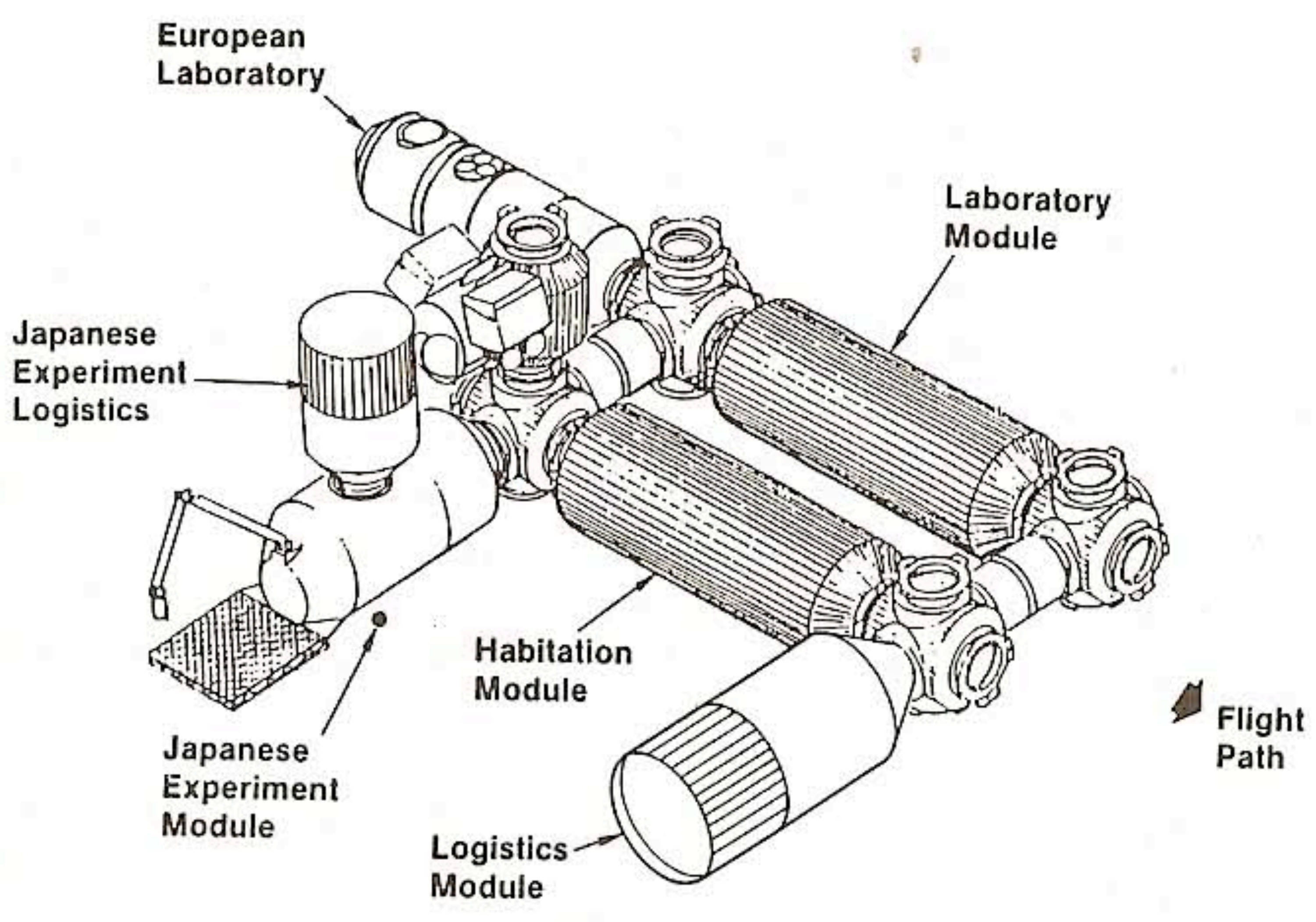
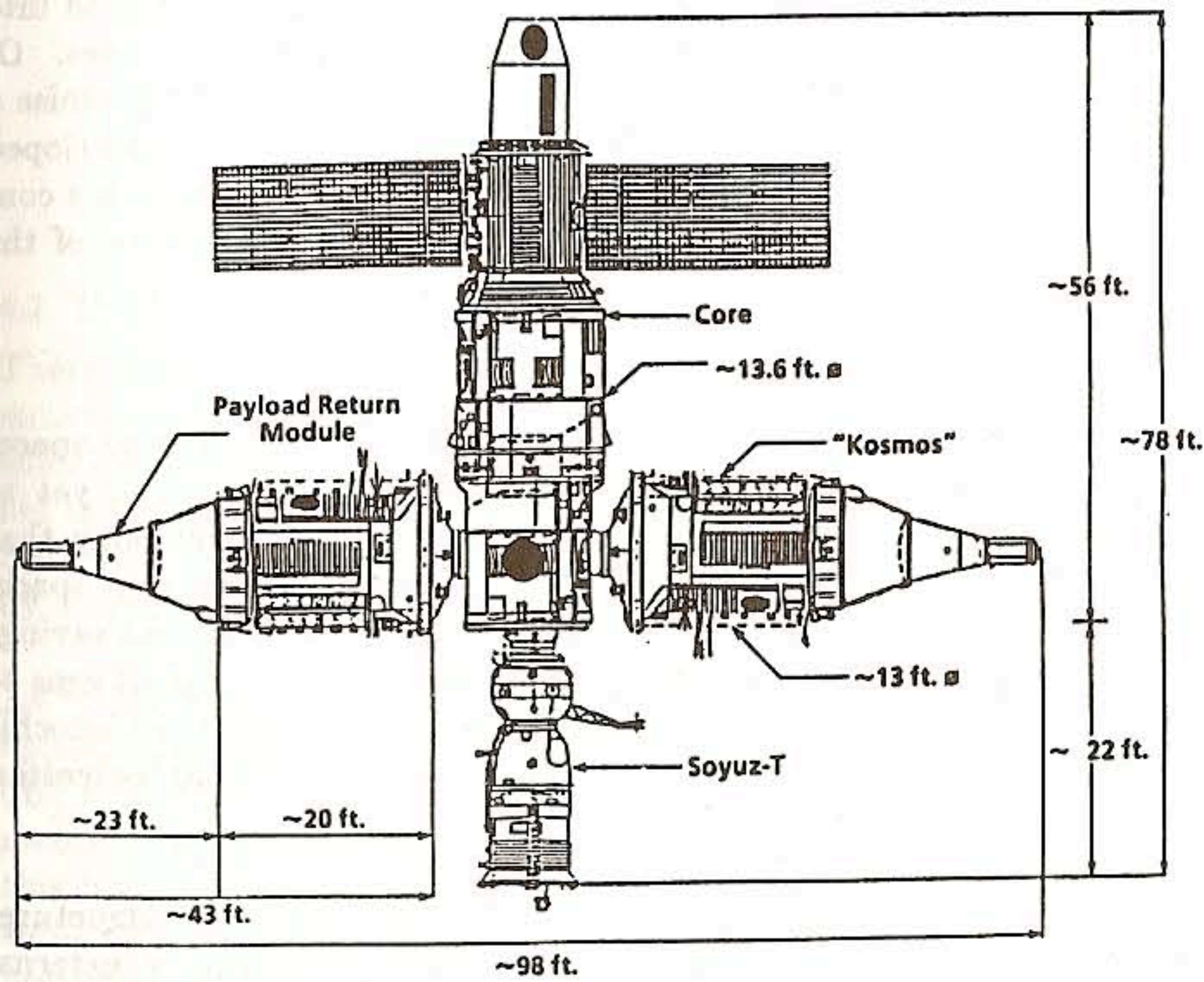


Figure 3-13. International module connection pattern.

SOVIET MIR SPACE STATION

Earlier this year, the Soviets launched the core of their "Mir" space station. Mir means "Peace" or "World" in Russian. This new orbital facility is expected to be comprised of a core element and up to 4 Kosmos series workshop modules, plus 1 or 2 Soyuz-T and/or 1 Progress robot resupply vessel. A detailed view of the MIR complex is shown in Figure 3-14. When fully assembled, Mir will be a modular structure to which it is possible to add, interchange or remove modules. Each of the Kosmos modules will probably be a different type of laboratory which may be a temporary tenant of the Mir core.

One interesting and as yet unanswered question about Mir is the oscillatory characteristics of the multiple Kosmos modules to the Mir core connecting ports. Illustrations available at this time are not definitive, but it appears that the berthing port size is not very large and that the connecting mechanisms and structures may not be very robust. The inference is to speculate about what degree of isolation from vibration the Soviets will achieve in their cantilevered Kosmos materials processing laboratories. However, the Soviets have succeeded with their "mass production" approach to space station development to the extent that they now, for the first time, have two operational stations in orbit at the same time, Salyut 7 and Mir.



ESTIMATED FULL-UP CHARACTERISTICS

Modules:	7 - 1 Core (6 docking ports) - 4 Kosmos - 1 or 2 Soyuz-T Crew Transport/Escape Vehicles, - and/or 1 Progress Resupply Vehicle
Power:	23 kw +
Weight:	235,000 lbs.
Length:	78 ft.
Width:	98 ft.
Crew:	3-6
Launches:	7
Pressurized Volume:	~510 m³
Dedicated Modules:	1. Technological Production & "Shop" 2. Astrophysics 3. Biological Research 4. Medical
Other Additions:	- Private Crew Compartments - Enhanced Communications - Enhanced Automation

Figure 3-14. Soviet Mir space station complex.

COMPARISON OF NASA AND SOVIET SPACE STATIONS

An interesting observation is that "full-up" Mir complex resembles the early NASA "CDG-1" cruciform concept. This resemblance suggests that the Soviet operations and payload accommodations baseline is probably at a level of complexity similar to that of NASA before the

U.S. and international scientific user community began making their mission requirements known. The Soviets have never shown any great interest in large truss structures in space except for their deployable solar arrays. They have always minimized their solar array area by flying in a solar inertial attitude, and so avoid the need to gimbal their solar arrays which must then be supported further out from the space station core. In this respect their solar array is similar to Skylab which also flew solar inertial. Thus the Soviets are taking a much more gradual, incremental approach to their space station program in which they launch an new station approximately once every five years. The technology jump between Salyut 7 and Mir 1, at least in the areas discussed in this paper is not much greater in magnitude than the jump from Salyut 6 to Salyut 7.

In comparison to the incrementalism of the Soviet space station program, the NASA program may be characterized by periodic major technology jumps. The new NASA space station will be vastly more sophisticated than Skylab, in part because of the technology research programs which the next section describes. One of the keys to this research is the way in which NASA has used both Skylab and the shuttle as laboratories for building, servicing and repairing space structures.

4. RESEARCH IN LIGHTWEIGHT STRUCTURES

Ongoing research in lightweight structures for the space station program may be divided into four general areas: composites, inflatables, membranes and large space truss structures. Of these four, large space truss structures are by far the most important. Membranes promise a variety of applications. Composite technology is still in its infancy, with alot of undeveloped potential. Inflatable structures promise some applications, limited however, by the same concerns expressed by Carter and Bogema. It is possible to give a very limited overview of the state of the art as follows:

4.1 COMPOSITES

That composites may be considered to still be in their infancy so far as applications to spacecraft are concerned is supported by the argument that no application has emerged yet to which composites are uniquely suited. Nor is there yet an application or a technology that would be impossible without composites. Rather, composites are employed today in spacecraft as a substitute for metallic structures in "non-critical" applications where weight savings is desired. One possiblity for a composite-unique application is tethers for tieing platforms to the space station by very long (greater than 1 km) high tensile strength cables. MacConochie and Wilson have suggested "pultruded" tensile composite tests for kevlar/polyester, glass/polyester and glass/vinyl ester formulations.[27]

For the space station, the most likely applications of composites are secondary structures inside or outside the pressurized volume such as interior structural stand-offs or external micrometeoroid shields. As was discussed in the first section of this paper dealing with the orbital environment, composites are particularly well suited to external impact shielding. An example of a possible substitution of a light-weight composite structure for an existing metallic one might be the triangle grid floor that was used successfully as a foot restraint system in the Skylab Saturn workshop. One of the few complaints the crews reported about this grid system was that too many triangular holes were made unusable by the supporting structure beneath the grid.[28] Rhodes and Mikulas point out that future "large area structures" may need to be designed on the basis of stiffness rather than strength. They propose a composite lattice triangle grid for general use in large structures.[29] If a Skylab-type triangle grid

structure could be constructed out of a stiffer material (of equal or lower weight) than the original aluminum grid, fewer structural supports might be needed, allowing more efficient use of the foot restraint floor area. Local fiber crushing may be a concern in this application as the surface hardness of the composite lattice might not bear up against the aluminum triangle shoe bottoms unless the triangle shoe bottoms were also changed to a composite of surface hardness approximately equal to that of the floor grid. See Figure 4-1 for a sketch of a triangle grid composite lattice panel.

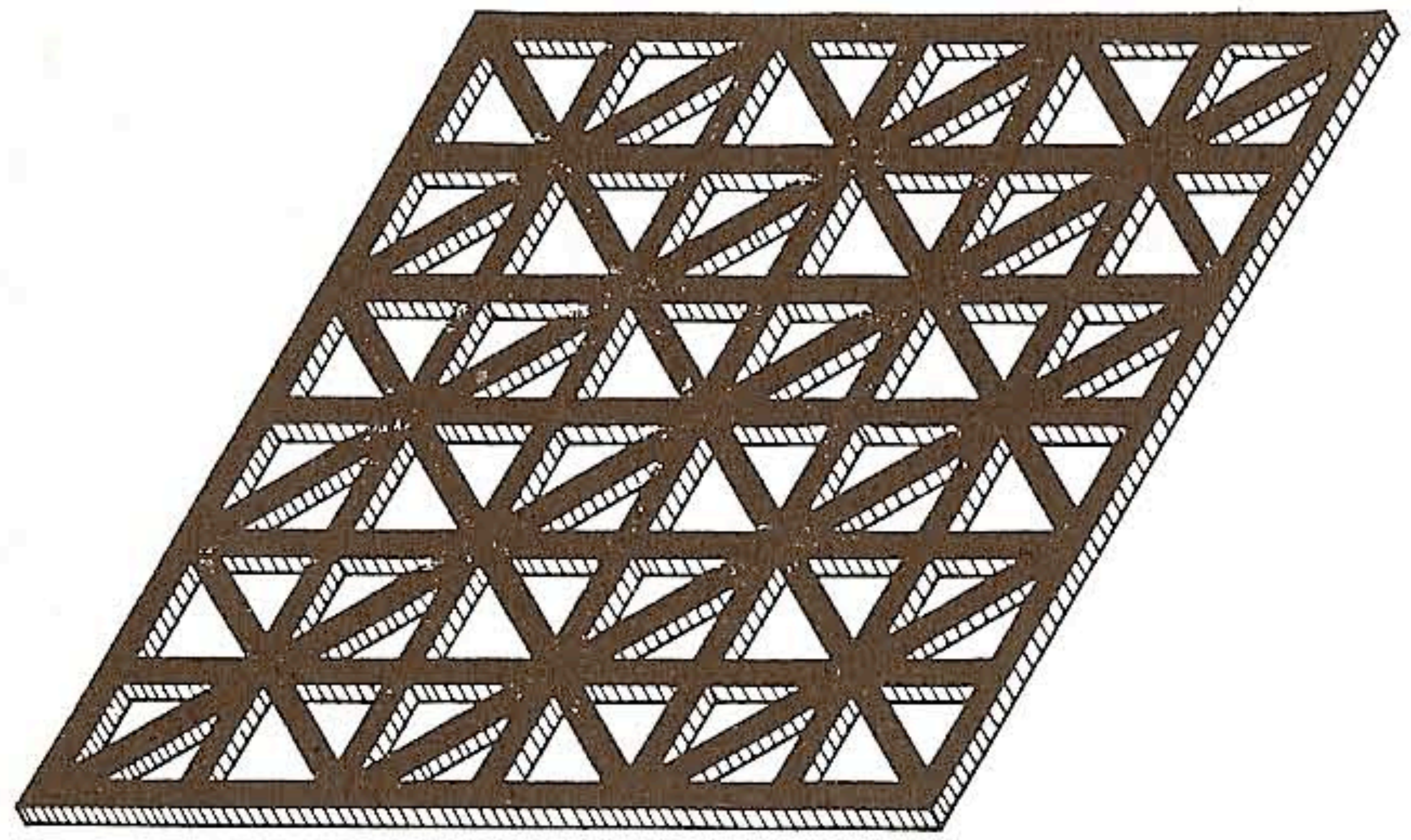


Figure 4-1. Triangle grid composite lattice panel.

4.2 INFLATABLES

There have been several successful if limited applications of lightweight rubber inflatable structures in the space shuttle program for tunnel connectors. The tunnel that connects the shuttle middeck airlock to the European Space Agency (ESA) Spacelab and the docking tunnel that will be used to berth the shuttle to a manned space station are both made of rubber. See Figure 4-2 for a schematic of the space shuttle to space station docking tunnel, proposed by Rockwell International Corp.

As recently as 1984, Frederick J. Stimler of Goodyear Aerospace Corp proposed a variety of applications for "non-metallic space structures," including an unpressurized "inflatable/ rigidized" space hangar, stowable acoustical barrier, extendable docking tunnel,"deployable" manned escape systems - escape capsules, and even an inflatable habitat shell. In the case of this last idea, the habitat shell, he proposes a laminate comprised (from the inside to the outside) of: an aluminum foil flame barrier, a seven ply rubber structural pressure bladder, a polyurethane foam meteoroid shield one inch thick and outer thermal coatings that would also resist free molecular oxygen erosion.[30] The structural pressure bladder would be made of Nomex unidirectional cloth coated with Viton B-50 elastomer, a product which Goodyear claims to have qualified to the strict requirements of the Shuttle Orbiter cabin and Spacelab Module. Stimler claims that this ensemble would be lighter in weight that a conventional aluminum pressure vessel. However, it would be difficult to argue that such a complex structural cross section is either more reliable or less expensive than a single or double wall metallic shell.

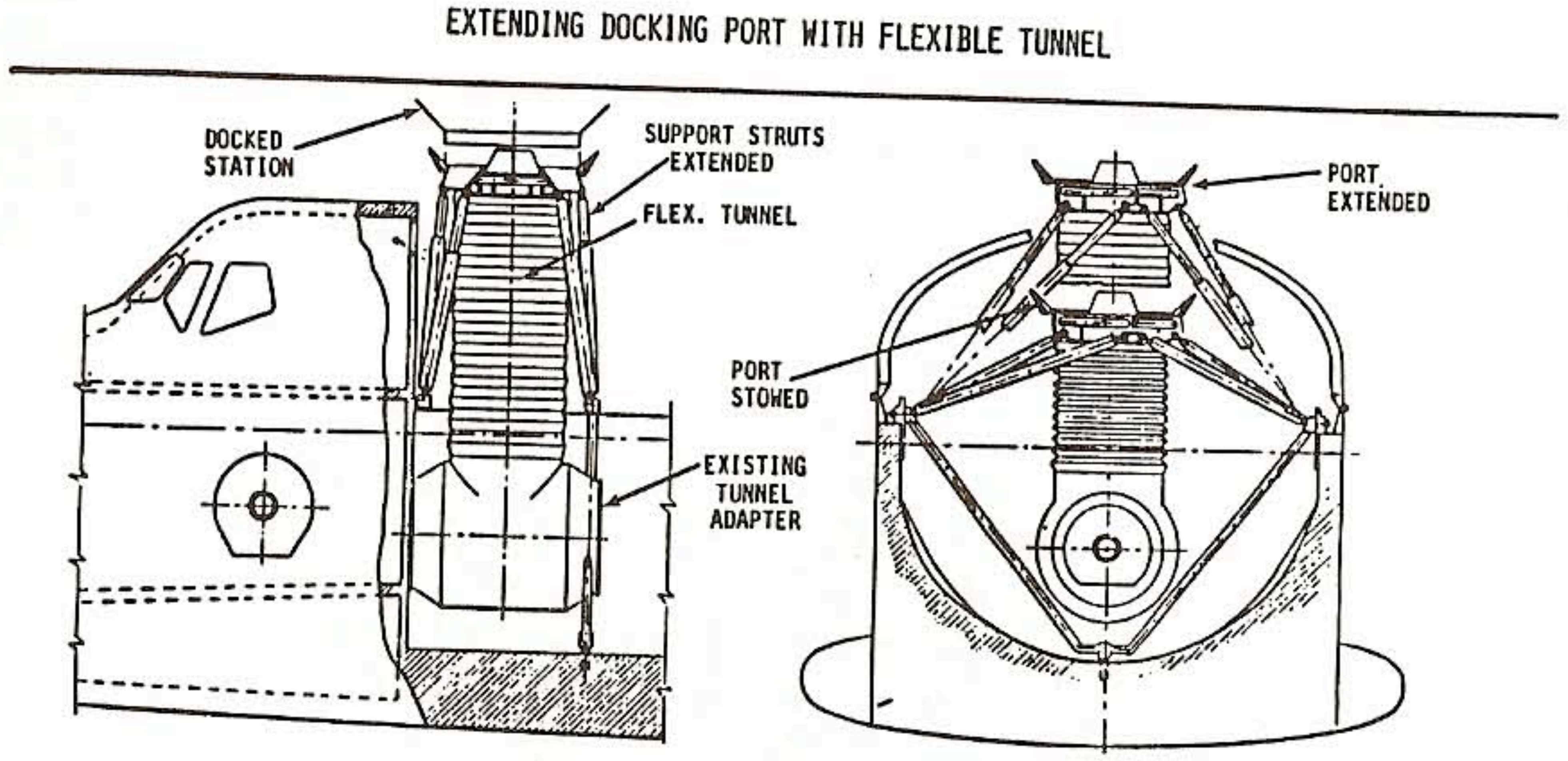


Figure 4-2. Rockwell concept for Shuttle docking tunnel in Orbiter cargo bay.

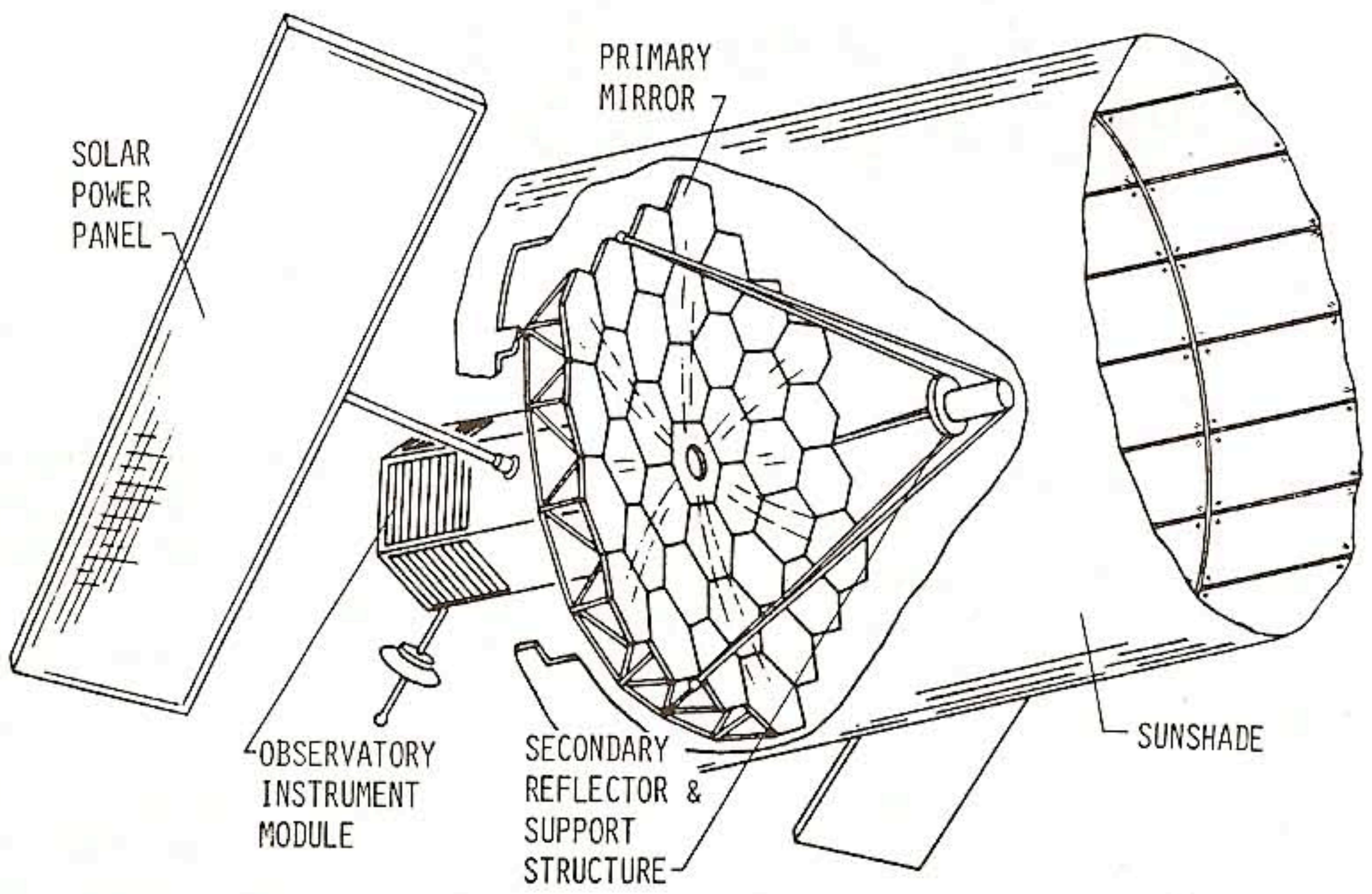


Figure 4-3. LDR mirror with tension membrane sunshade.

4.3 MEMBRANES

Membrane structures include fabrics, foils and thin films which are treated together in the same class of lightweight structures because their applications are similar in some key respects. Thin films and foils are used widely as insulating and reflecting materials in many spacecraft, both manned and unmanned, and as part of thermal and meteor protection outer garment of the current space shuttle extravehicular mobility unit [EMU] space suit. The gold kapton foils with which many spacecraft are protected have become a common component of design, but rarely are they thought of as "lightweight structures" in their own right.

Perhaps one of the most innovative and challanging applications for membranes is as an antenna surface, particularly for the primary reflecting mirror of an antenna-like large, deployable reflecting (LDR) telescope. The non-distortion requirements of such a mirror demand an accuracy to within microns across a 20 to 30 meter diameter. In addition to incredible precision for structural alignment and adjustment by automated actuators, the thin film or thin film coated surface of a mirror will need to handle thermal stresses within these parameters.

A less demanding application of foils, thin films or thin film coated fabric would be the sunshade that will protect the LDR mirror from thermal and light fluxes. An example of such a fabric or thin film sunshade is shown in Figure 4-3. How this type of very large membrane structure would be assembled or deployed is an open question. Early estimates of the EVA labor time required to construct LDR from a space station facility range from 200 to 300 EVA man-hours. Additional internal crew time for operating remote manipulators, testing and planning is more difficult to estimate.

4.3 LARGE SPACE STRUCTURES

Through the space station configuration development process, it has become clear that the NASA space station will require a system of large space frame or space truss structures to perform the major skeletal task of holding the elements of the station together and to resist the large bending moments and torques within the dynamic system. Michael Card, Chief of the Structural Dynamics Division at Langley Research Center summarizes three major construction approaches for these large truss structures as follows:

(1) Erection of efficiently packaged components taken from the shuttle cargo bay.

(2) Deployment of ground-assembled structure.

(3) Fabrication of major structural elements from "raw" materials (shaping and joining flat stock).[31]

NASA has proceeded to research many of these topics, conducting numerous simulation experiments and several flight experiments. Computer modelling analysis, particularly finite element modelling and the Nastrans software, which was developed by NASA have been particularly vital to the lightweight structures technology developent effort.

To summarize very briefly the results of this technology research; joint, packaging and assembly procedure design are critical to the success of large space truss structures for the space station. Most critical of all for large structures involving human construction efforts, the human performance characteristics are key to their feasibility. Because erectable structures are the simplest to analyse, design, manufacture and build on the ground, they have received the most attention to date.

ERECTABLE STRUCTURES

Erectable structures refer specifically to the piece by piece assembly of truss structures, typically comprised of strut and joint elements, which when fully assembled are fully self-rigidizing. Erection may be accomplished either manually by space-suited astronauts during EVA or by automated assemblers, controlled from the space shuttle or other manned space craft. Extensive testing of erectable truss structures has been undertaken in recent years in Water Emmersion Test Facilities (WETF) to simulate these construction activities in the imitation zero-gravity of neutral buoyancy. These WETF simulation experiments have explored a variety of approaches to manually erecting large space structures, and have yielded some valuable insights about what is safe and reliable. For example, there have been proposals to save weight for the internal diagonals of the truss structure to be made of kevlar tensile ties.[32] However, experiments with prototype joint and strut erectable structures have led to some illuminating lessons, summarized elegantly by Jack Stokes of NASA Marshall Space Flight Center:

> First and foremost, the connector should be completely safe for crew operation. A design goal should be that no stored energy shall exist in any of the components prior to, during, or following the mating of components. If stored energy components do exist, the energy level should be kept to a minimum[33]

These conclusions from experiments with full scale prototype structures suggest that tension stiffened structures such as tensegrity structures may not be acceptable for erectable trusses.

As early as 1981, WETF experiments at Marshall Space Flight Center demonstrated the feasability of EVA astronauts manually assembling large trusses in simulated zero-gravity.[34] There are three WETFs in the United States, all of which are in demand for space mission simulations of diverse kinds, located at Johnson Space Center in Houston, Marshall Space Flight Center in Huntsville, Alabama and at McDonnell-Douglas Astronautics Corp. in Huntington Beach, CA. Not only are these facilities used experimentally to design the hardware and construction procedures but also to train the astronauts who will carry them out in space. These simulation experiments prepared the astronaut crews to undertake a flight experiment during which large space stucture prototypes were assembled and disassembled on orbit.

During December of 1985, two astronauts, Jerry L. Ross and Sherwood C. Spring experimented with two prototype truss structures from the orbiter Atlantis, on Mission 61-B. They erected and dismantled the Langley "ACCESS" tower twice and the MIT/Marshall "EASE" pyramid eight times over the course of two EVAS, totalling 12 hours.[35] The ACCESS tower is a truss/beam of about 1m triangular cross-section. In this flight experiment, it was assembled to a length of about 12m. The EASE "pyramid" is actually a single tetrahedron about 4m on each edge. See Figures 4-4 and 4-5 for the ACCESS and EASE flight experiments respectively.

These flight tests provide verification that astronauts can assemble the primary truss structures of the space station on orbit and contributed to the design decision to select a 5 meter erectable truss as the baseline structural system. In addition to the space station structure, large truss structures will support a variety of co-orbiting platform, tethered and free-flying satellite applications. See Figure 4-6 for a concept of a large erected/assembled tetrahedral truss platform.

Future large truss structure assembly operations may be automated to relieve the astronauts of some or most of the strenuous and repetitive tasks. Possible automation devices include shuttle and space station amounted assembling machines. A more advanced possibility is on-orbit fabrication of the strut and joint elements which are then automatically assembled at the point of manufacture.

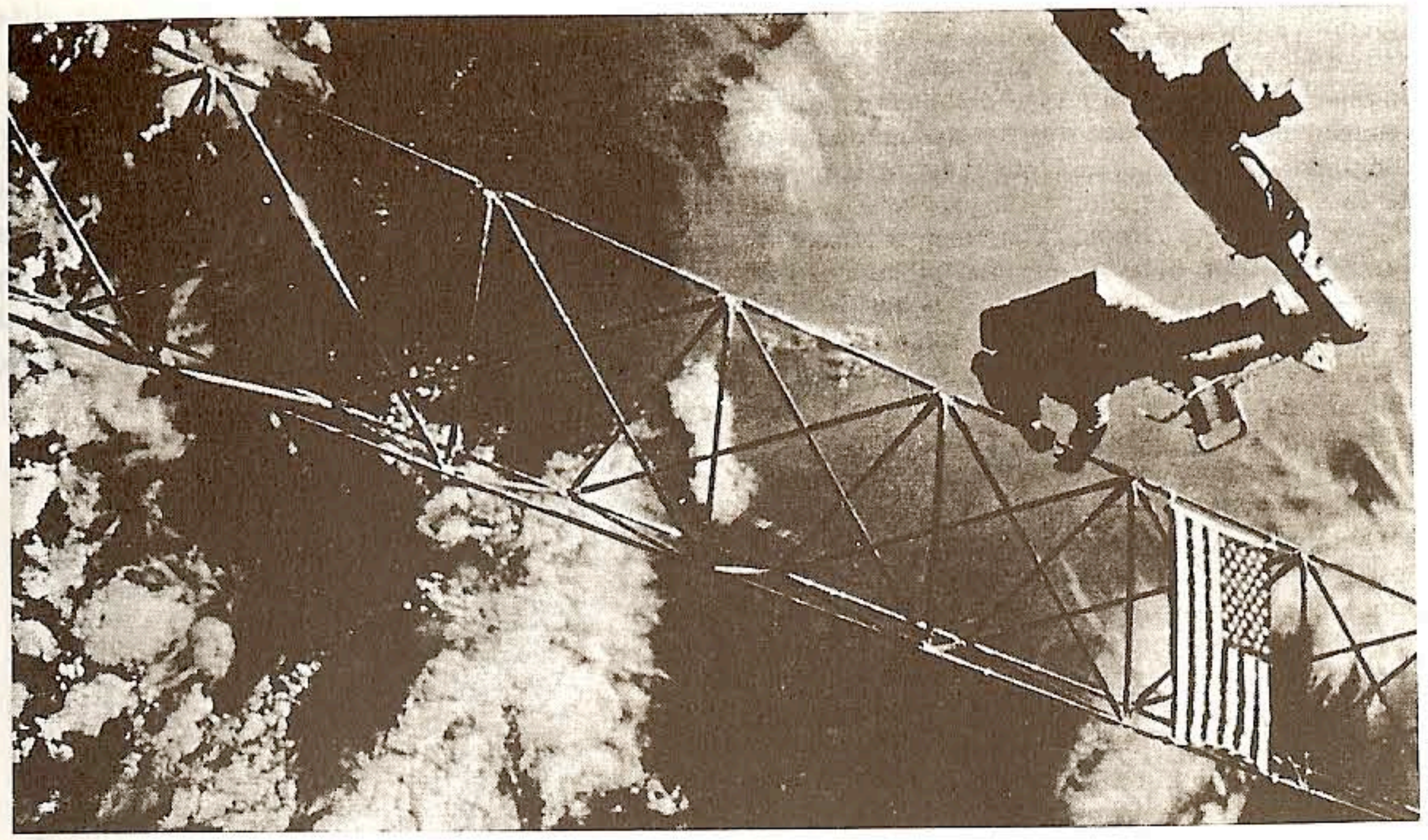


Figure 4-4. ACCESS truss flight experiment.

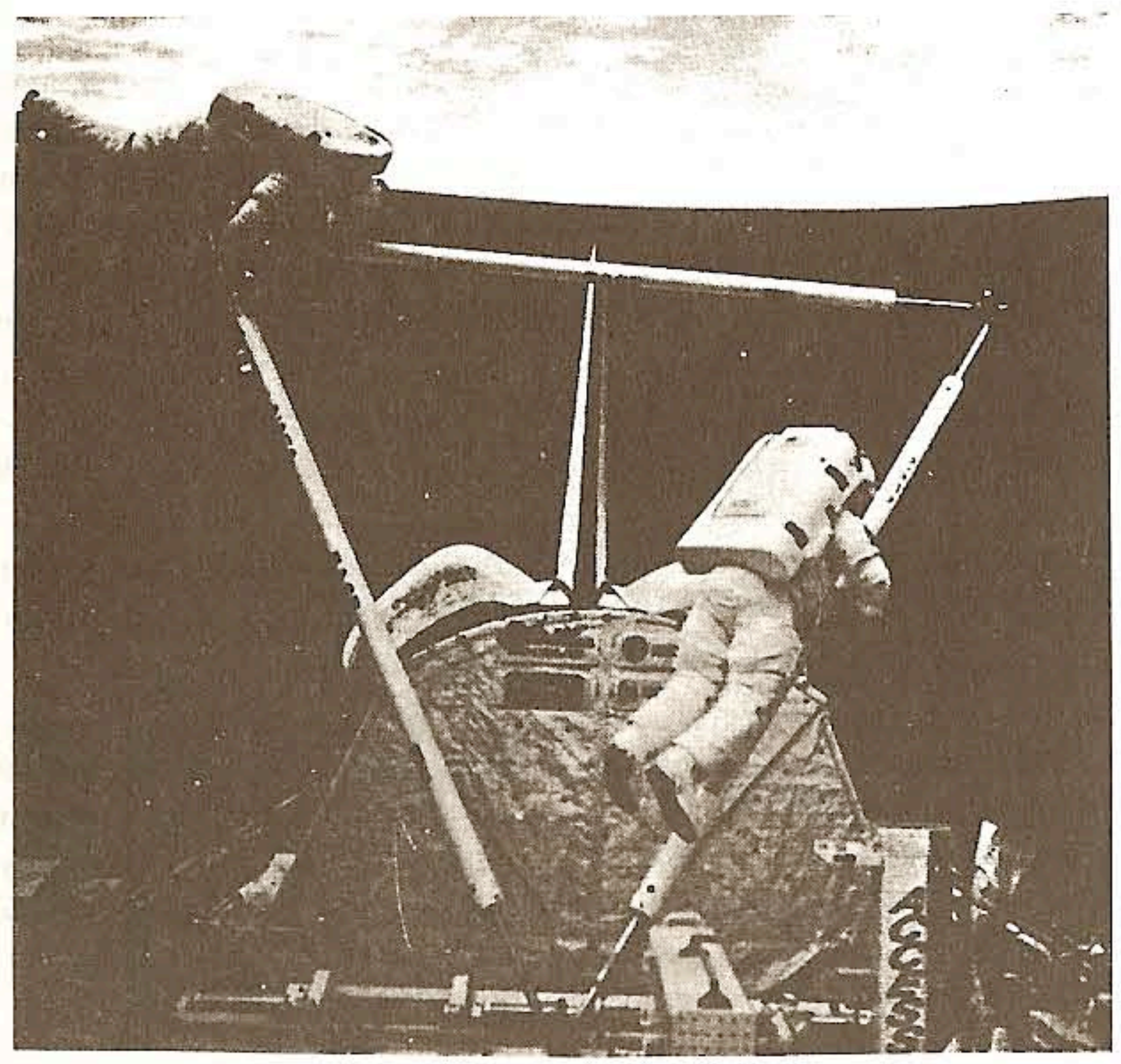


Figure 4-5. EASE truss flight experiment in orbiter cargo bay.

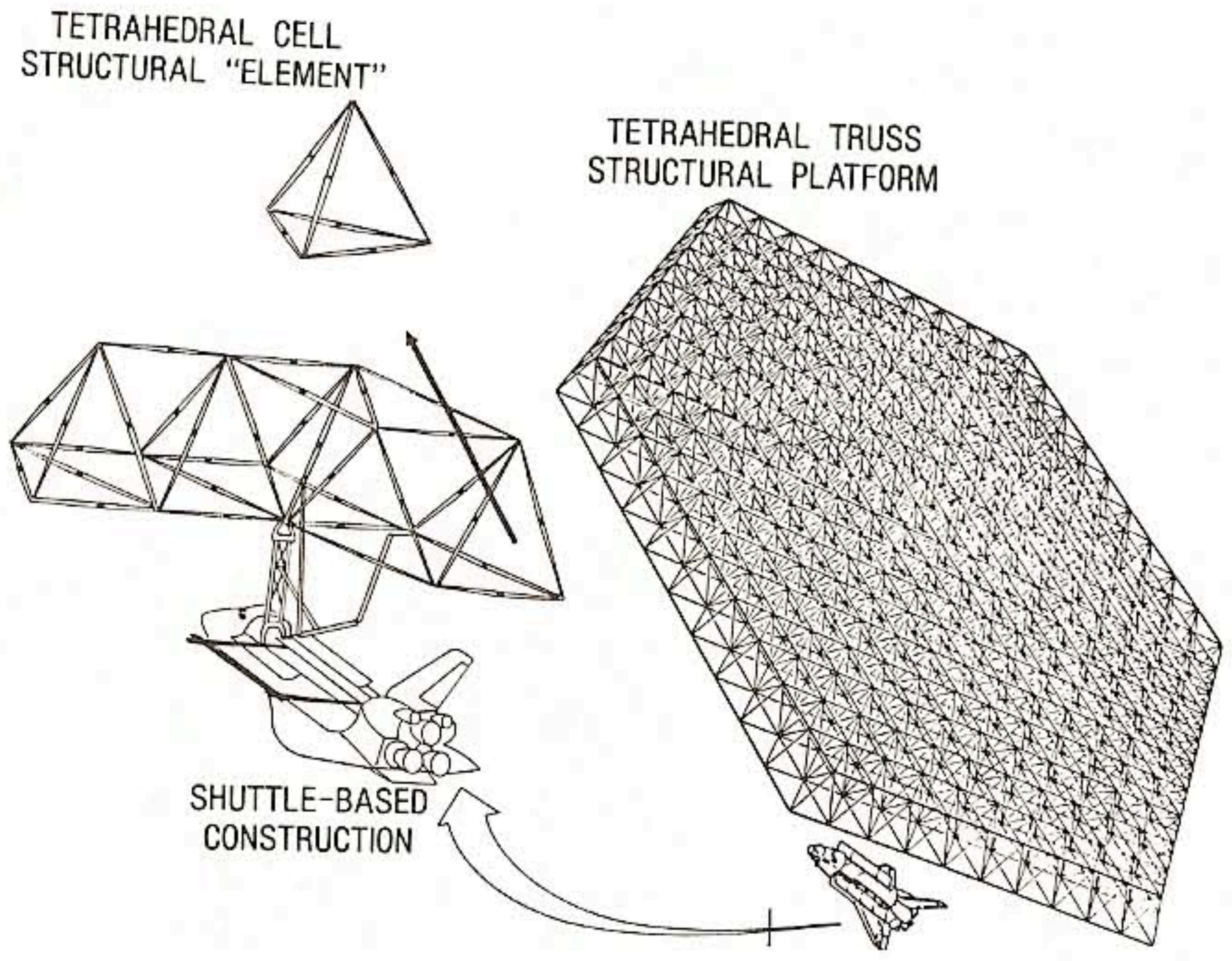


Figure 4-6. Large hybrid erected/assembled tetrahedral platform.

DEPLOYABLE STRUCTURES

Deployable structures refer to structures that are completely assembled and packaged on the ground prior to flight and are then unfolded and locked into a rigidized position. In contrast to erectable structures, however, it may be possible or even necessary to incorporate tension members into deployable structures. To date, deployable masts, beams and trusses have seen some of the most extensive applications in satellite and solar array systems. Common examples of deployable structures in use on spacecraft today are the Astromast on the Voyager planetary probes and the Seasat Extendable Support Structure (ESS). ESS structural members for future applications may be made of "VHM graphite/epoxy" as a substitution for earlier metallic members.[36] See Figure 4-7 for the sequence of ESS deployment.

Because of the complexity of deployable structures, and the fact that generally there is only one chance to deploy correctly, the cost structure is different from many other spacecraft structures. Hedgepeth, Mikulas and MacNeal, describe this situation:

> The first generation of space structural systems will almost certainly be produced in very limited numbers. This means that the costs of development cannot be spread over a large production quantity. Consequently, *the largest cost of a space structural system will continue to be the cost of design, analysis, test and all the systems engineering and tons of paperwork*[1] necessary to give adequate assurance that the system will perform as intended. The next largest cost will be launch and space erection. The smallest, by far, will be the manufacturing costs of materials, hardware, fabrication, assembly and inspection.[37]

This observation reflects the often contradictory relationship between cost of an analysis and the reliability of the analysis. The simpler a structure is to analyse, the more reliable and predictable it is likely to be and the higher the confidence in the analysis itself. For

[1] Authors' emphasis.

deployable structures, the major costs are in analysis and testing on the ground. For simpler, erectable structures the major costs are in the use of the space shuttle and expensive EVA labor time. For initial construction of the space station, deployment or partial deployment of truss structures may be the most economical approach. However, once the space station is completed and becomes a permanent orbital construction facility, the cost of orbital assembly of erectable structures may drop dramatically. Automated assembly techniques would play a crucial role in this cost reduction. Wherever automated systems are introduced, the human performance question changes from direct manual control or labor to system monitoring and remote control. See Figure 4-8 for a concept of a deployed/assembled cellular large truss platform.

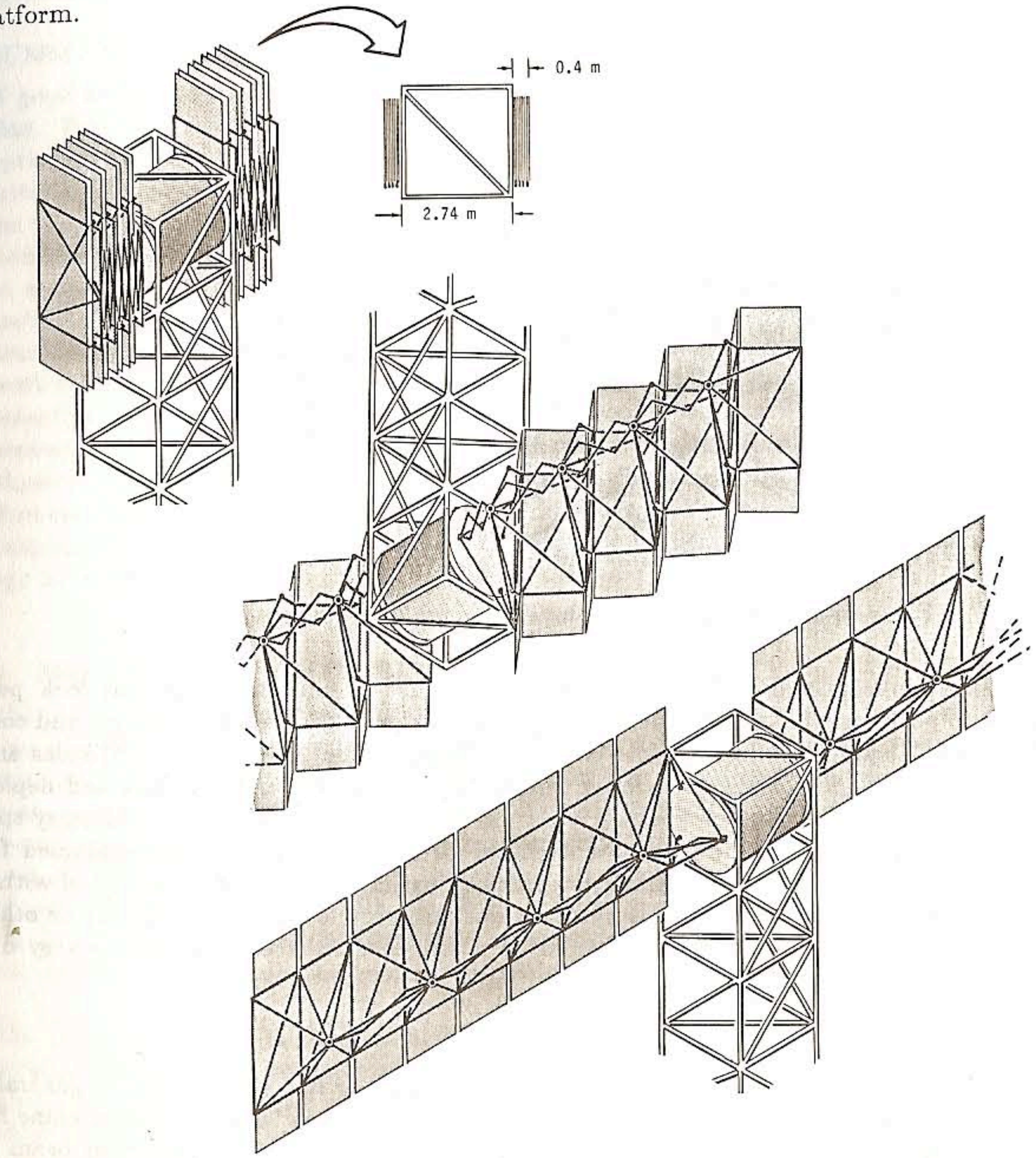


Figure 4-7. ESS deployment sequence from space station truss mounting.

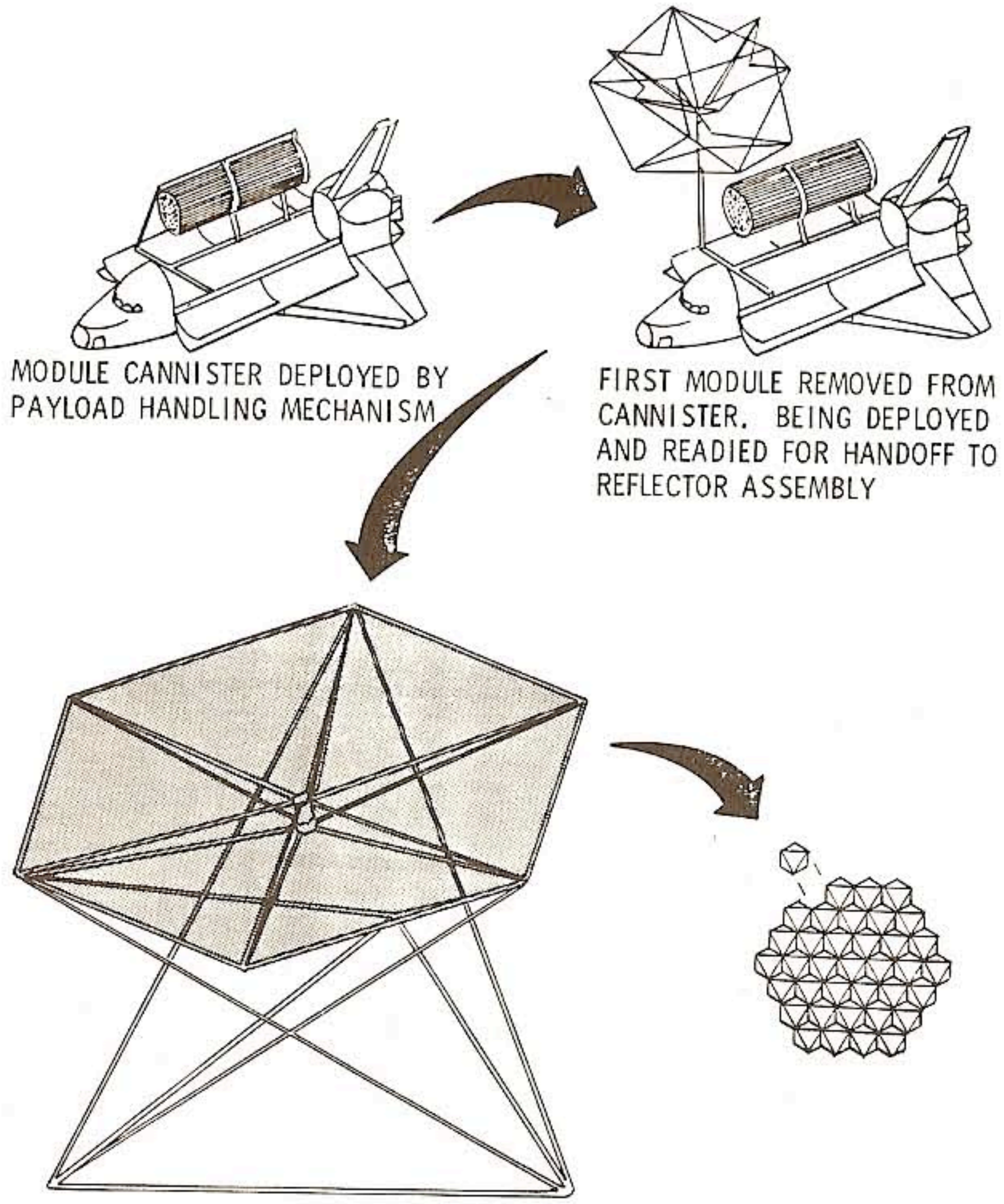


Figure 4-8. Large hybrid deployed/assembled cellular platform.

A fascinating application of a deployable truss structure is one that does not lock permanently into position after a one-time only deployment, but rather remains flexible and controllable. This "Deployable Controllable Geometry Truss Beam" which Martin Mikulas and Marvin Rhodes of NASA-Langley Research center have developed, can manuver and deploy in a serpentine manner to align or position the truss beam tip. Such a beam could carry special remote manipulators or end effectors, cameras or special tools when programmed for robotic operations. As a flexible berthing beam, carrying an extensible rubber tunnel within its geodesic envelope, this truss could serve as a docking port for the space shuttle or other manned spacecraft.[38] This application would be a unique case of combining two very different lightweight structure technologies.

FABRICATED STRUCTURES

Fabricated structures are those in which are made from raw or flat stock material, generally by a highly automated machine. Grumman Aerospace Corporation built such a machine for the Marshall Space Flight Center. This "beam builder" spits out a 1 meter deep beam of 4mm thick aluminum cold-formed angle sections. The beam weighs 1.275 kg/m and can take an axial load of 573 kg. With one loading of rolls of sheet aluminum for the longerons, and magazines of preformed cross braces, the machine can turn out approximately 300m of beam.[39] While this type of highly automated fabrication and assembly process may be necessary at some point in the future, in the near term there appear to be several

disadvantages to the fabrication approach, not the least of which is its high level of complexity and problematic reliability and maintainability. Note that the "raw" materials are not all truely raw, and the cross braces are provided to the machine pre-formed and then are riveted or tack-welded into place. Joe Goodwin of Grumman conceived this method for very large platform structures to support solar power satellite arrays with platform lengths on the order of 1000m. By the time NASA is ready to undertake the construction of space truss structures of the scale Goodwin envisions, the state of the art in automation and robotics will have advanced by several orders of magnitude and the fabrication approach may look more promising.

SUMMARY OF LIGHTWEIGHT STRUCTURES RESEARCH

A good deal of research remains to be done in all areas of lightweight structures for space station. Probably the main research challange in the foreseeable future will be to determine the optimum designs and methods for assembling large space truss structures on orbit. A major criteria for evaluation and selection of truss designs will be the time and complexity required for the construction effort, particularly the demands on the astronauts. Shuttle orbiter mission times are limited to about ten days and the current shuttle EMU space suits are limited to about 22 hours operating time before they need servicing of the life support systems on the ground. Thus technology advances are needed in the EVA technology area as well. The astronauts who have conducted these flight experiments believe that with the appropriate work stations, foot restraints, remote manipulator system assistence and systems support, the assembly of permanent large truss structures from the shuttle orbiter is feasible.[40] At present, the limiting factors on EVA, beside the suit and life support system assembly are physical workloads, fatigue and wear and tear on the space suited astronauts' gloved hands. Because labor time for a spacesuited astronaut during EVA is very expensive, with estimates ranging from 50,000 to 200,000 dollars per hour, the human factor becomes critical in technology assessment.

5. ZERO GRAVITY VERSUS ARTIFICIAL GRAVITY

The debate between artificial gravity and zero gravity begun by von Braun and Clarke continues to this day. Until now, all space craft have been built as zero-gravity environments, however, the artificial gravity approach has not been ruled out and remains the favorite of many conceptual thinkers. For lunar and planetary bases, the question is moot because space crews will simply have to live with whatever gravitational fields they find on other celestial bodies. From another perspective, lunar and planetary bases will enjoy gravity without any of the problems associated with creating artificial gravity. But for future generation space stations, space colonies, interplanetary explorations and other long duration space missions the artificial gravity question remains unresolved.

The arguments given in favor of artificial gravity are primarily biomedical: to prevent bone demineralization and to maintain muscle tone, particularly in the cardiovascular system. Also, there is a belief that gravity provides an element of psychological comfort and convenience, that objects will stay where they are put, without the need for special restrains or enclosures. One new argument for artificial gravity is that of spatial perception and cognition within the space station, that in a so-called zero-gravity environment, the astronauts have experienced some trouble with up-down orientation, thus if a clear gravity cue can be provided, this problem could be eliminated.

There are several objections to artificial gravity which are independant of the advantages claimed for zero gravity. The movie 2001, based on the book of the same title by Arthur C. Clarke, portrays an artificial gravity generating torus type space station. The shuttle craft approaches the center axle of the space station and rotates about its center of mass in concert with the torus wheel. This approach could only work if the axis of the docking port passes through the center of mass of the shuttle craft. However, for the present space shuttle, the center of mass "envelope" is near the tail (shuttle main engines) approximately 12 meters aft of the docking tunnel.[41] Thus, any angular acceleration applied to the shuttle will tend to make it rotate about its tail, not about its docking tunnel.

But even if a shuttle craft were designed so that its docking tunnel aligned with its center of mass, the problems of proximity operations around the space station would be very complex. Already, the workload for two crew members in the space shuttle is very close to the tolerable limit for reliability and safety. To add an element of differentially moving coordinate systems could complicate the proximity operations scenario exponentially.

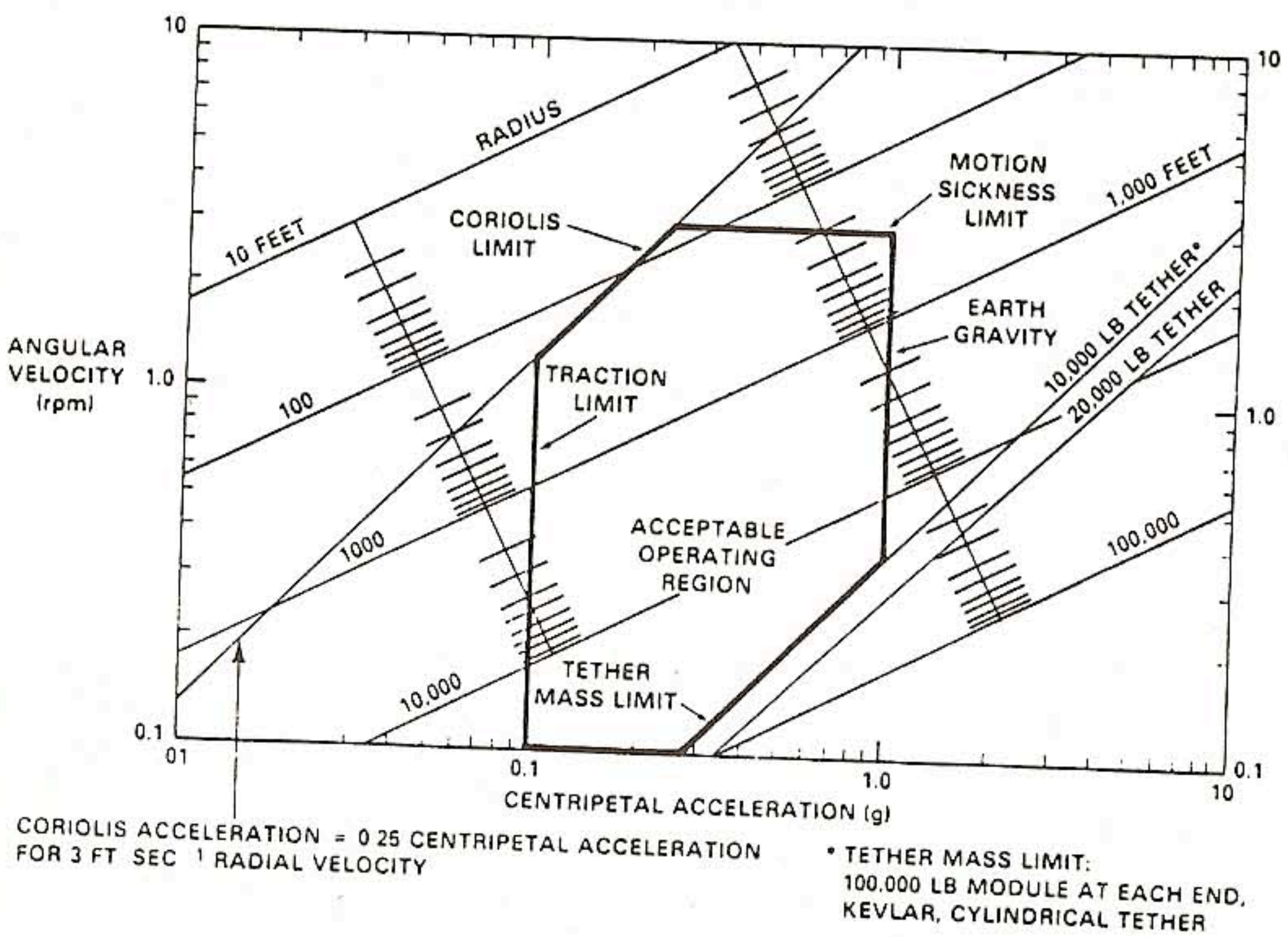


Figure 5-1. Artificial Gravity Parameters.

The arguments in favor of zero-gravity are primarily scientific and commercial. Virtually all scientific users want to fly their experiments or instruments in zero-gravity and they want the best isolation from gravity and vibration that they can achieve. Some materials processing payloads require 1 X 10^{-6}g isolation from vibration. Some astronomical instruments may require even greater steadiness. Since structure-borne vibrations in the space station may be produced by crewmembers moving around and pushing off the walls and floors, some of these commercial and scientific payloads may require accommodation on unmanned corbiting platforms or freeflyers. Although there has been some experience with spatial disorientation in zero gravity, there is some evidence that clear visual cues for a local vertical, can compensate for the lack of a physical gravity cue. However the spatial orientation problem for human perceptual and cognitive needs is proving to be far more complex that local vertical cues,

particularly as concerns the reconciling of internal local or global vertical with the external orbital coordinate systems.[42]

It is not possible in this paper to ajudicate the debate between artificial gravity and zero gravity space station advocates For the forseeable future, space stations will probably continue to be zero-gravity affairs. It may be possible to develop a station with seperate zero-gravity and artificial gravity sections. However, significant advances will be needed in numerous technical disciplines to overcome the vibrational, infrastructural, operational and perceptual/cognitive problems of such a design. One of the most promising possibilities for artificial gravity space stations is the use of tethers which could reduce the mass of radial structure by an order of magnitude compared to rigid compressive structures. Bryant Cramer, a medical doctor and mechanical engineer who is Chief of the Human Productivity Branch at NASA HQ, has prepared an excellent summary of the interactions of the coriolis effect limit, the tractor limit, the tether mass limit and the motion sickness limit to create an artificial earth-like gravity effect. Cramer indicates that for a 6,060m (20,000 foot) diameter space station rotating at 0.3 rpm to generate 1.0g of centripetal acceleration, the cylindrical kevlar tether would weigh about 4,550kg (10,000 pounds). Cramer's graph of artificial gravity parameters is reproduced as Figure 5-1.

6. FUTURE SPACE SETTLEMENTS?

Over the past 15 years, scientists and engineers have made numerous proposals for very large space colonies or space settlements, often in the form of free-floating habitats. Some of these proposals avocate designs for populations of as many as 10,000 people. The Lagrangian point L-5 is a favorite construction site for these structures, where the earth's and the moon's gravity neutralize each other, and an object placed there would theoretically remain fixed, without need for reboost propulsion.[43]

However, just as the torus concept is driven by a single conceit of physics that artificial gravity can be produced by centrifugal motion, so is the entire L-5 concept driven by a conceit of orbital mechanics. However, as the preceding discussion suggests, these large settlements are highly problematic with or without artificial gravity, L-5 or other such paradigms.

In addition to the problems already discussed is the question of replacing consumable resources; propellants, leakage from life support systems, replacement of materials and parts that require manufacturing to complex even for a civilization of 10,000 skilled professionals, and the supply of materials for space based manufacturing. Even the best artificial closed ecological life support system will encounter a scarcity among those materials or items that too expensive to recycle or manufacture in small quantities just for itself.

One approach to the resupply problem are the numerous proposals from Gerard K. O'Neill of Princeton University to build an electo-magnetic "mass driver" or rail gun on the surface of the moon which would hurl lunar ores and other materials into low lunar orbit where they could be collected for use on a space colony.[44] O'Neill et. al.'s understanding about operational requirements for handling remotely controlled or collected payloads on orbit is called into question by statements such as the following:

> The manipulation of buckets and payloads has been studied only to the extent necessary to ascertain that no fundamental problems arise, and that the repetition rate of 10 launches/sec is a conservative choice.[45]

By "fundamental problems," O'Neill refers to the physical mechanics of a superconducting, linear system of 500g or greater. He offers no discussion of systems safety, reliability, quality assurance on the lunar surface or on orbit.

The prime alternative to free-floating space colonies is to build lunar and planetary bases. Locating the bases near the resources will greatly reduce the materials supply problem that confounds the space colony advocates. The material resources needed for space-based manufacturing are already on the moon, Mars and the asteroids. Lunar and planetary rocks and soils will provide Micro-gravity materials processing could be conducted on small platforms in low lunar or low Mars orbit, where it would be relatively accessible to both surface bases and trans- orbital vehicles for the return of "exports" to earth. And lunar and planetary rocks and soil will provide excellent shielding from meteoroids and radiation. Why transport them all the way out to L-5 when we can use them right where they are?

NASA and other space exploration agencies must give serious attention and analysis to the economic issues of transport and location. LEO, GEO and L-5 have no natural resources except for angular acceleration, microgravity and vacuum. Propulsion resupply will be a continuing demand of space settlements in any of these locations, even at L-5 where the station will balance on a knife edge of stability between the two "gravity wells" of the earth and the moon.

For the forseeable future, space stations will probably be relatively small orbital depots that will serve as transportation and servicing nodes on a larger network of orbital and trans-orbital transportation systems. Former NASA Administrator James Beggs has described the space station as "the next logical step," and it should be regarded in this context as just a step, not an end in itself.

The moon and Mars are very promising sites for future space settlements, especially Mars which has a thin atmosphere and water ice in its soil. For these settlements, whole new technologies for automated underground tunnelling, construction and sealing tunnels to create pressure vessels will be required. Nadar Khalili of the Southern California Institute of Architecture (SCI-ARC) is developing techniques for creating ceramic interiors by glazing and firing clay soil structural interiors at very high temperatures.

The role of lightweight structures on lunar and planetary bases will probably focus on parasols, temporary or contingency enclosures and possibly wind screens on Mars. For lightweight structures, space stations and other space vehicles will continue to present the best opportunities for innovative applications and design solutions.

7. REFERENCES

[1] General Reference for space station safety issues: *Space Station Crew Safety Alternatives Study - Final Report,* (Rockwell International, Downey, California) June, 1985.

Volume I - Final Summary Report, Robert L. Peercy, Jr., Robert F. Raasch, and Lisa A. Rockoff, NASA CR-3854.

Volume II - Threat Development, R. F. Raasch, R. L. Peercy, Jr., and L. A. Rockoff, NASA CR-3855.

Volume III - Safety Impact of Human Factors, L. A. Rockoff, R. F. Raasch, and R. L. Peercy, Jr., NASA CR-3856.

Volume IV - Apprendices, Peercy, Raasch and Rockoff, NASA CR-3857.

Volume V - Space Station Safety Plan, G. H. Mead, R. L. Peercy, Jr., and R. F.

Raasch, NASA CR - 3858.

Technical Co-Monitors for this Contract Report were Robert Witcofski of NASA-Langley Research Center and Marc M. Cohen of NASA-Ames Research Center.

[2] Romere, Paul O., *On-Orbit Free Molecular Flow Aerodynamic Characteristics of a Proposed Space Operations Center Configuration,* NASA TM 58243, (Johnson Space Center, Houston, TX) March, 1982.

[3] Leger, L.J., Visentine, J. T. and Kuminecz, J. F.: *Low Earth Orbit Atomic Oxygen Effects on Surfaces,* AIAA-84-0548, AIAA 22nd Aerospace Sciences Meeting, January 9 - 12, 1984, Reno, Nevada.

[4] Susko, Michael, *A Review of Micrometeoroid Flux Measurements and Models for Low Orbital Altitudes of the Space Station,* NASA TM-86466 (Marshall Space Flight Center, Huntsville, AL) September, 1984.

[5] Levinson, David A. and T. R. Kane, *Docking of a Spacecraft with an Unrestrained Orbiting Structure,* AIAA-82-1423, presented at the AIAA/AAS Astrodynamics Conference, August 9-11, 1982, San Diego, CA.

[6] Dorsey, John T. and Harold G. Bush, *Dynamic Characteristics a of a Space Station Solar Wing Array,* NASA TM 85780, (Langley Research Center, Hampton, VA) June, 1984.

[7] Rader, W. P., J. Baratano, H. Bandgren, R. Erwin, *Noise in Space,* (Acoustical Society of America, 89th Meeting, Austin, TX.) April 7-11, 1975. Page 20.

[8] Vaicaitis, Rimas, *Vibrations and Structureborne Noise in Space Station,* NASA CR-176291, NASA Grant NAG-1-541 (Columbia University Department of Civil Engineering and Engineering Mechanics, New York, NY) Progress Report for the Period Jan 1, 1985 - June 30, 1985.

[9] *Space Settlements: A Design Study* edited by Richard D. Johnson and Charles Holbrow, authored by the 1975 Summer Faculty Fellowship Program in Engineering Systems Design at Ames Research Center, NASA SP-413 (Scientific and Technical Information Office, Washington, D.C.) 1977.

[10] Hale, Edward Everett, *The Brick Moon,* Atlantic Monthly, vol. XXIV, Oct., Nov., Dec. 1869.

[11] Logsdon, John M. and George Butler, "Space Station and Space Platform Concepts: A Historical Review," in *Space Stations and Space Platforms- Concepts, Design, Infrastructure and Uses,* edited by Ivan Bekey and Daniel Herman, Progress in Astronautics and Aeronautics, Volume 99 (American Institute of Aeronautics and Astronautics, Inc., New York, NY) 1985. pp. 203-204.

[12] Logsdon, John M., *Space Stations: A Policy History, Final Report,* NASA CR-167801, (George Washington University, Washington, DC) 1983. p. I-1.

[13] Logsdon and Butler, Op. Cit., p. 205.

[14] von Braun, Werner, *Crossing the Last Frontier,* Colliers Magazine, March 22, 1952. page 29.

[15] Carter, J. W. and B. L. Bogema, "Inflatable Manned Orbital Vehicles," *Proceedings of the Manned Space Stations Symposium,* Los Angeles, CA., April 20-22, 1960 (sponsored by the Institute of Aeronautical Sciences, New York, NY) 1960. page 193.

[16] Arthur C. Clarke, *Islands in the Sky,* (John C. Winston Co., London) 1952.

[17] *SALYUT: Soviet Steps Toward Peranent Human Presence in Space - A Technical Memorandum,* OTA-TM-STI-14, U. S. Congress (Office of Technology Assessment, Washington, D.C.) December, 1983. page 30.

[18] Skylab Program Office, *MSFC Skylab Mission Report - Saturn Workshop,* NASA TM X-64814 (Marshall Space Flight Center, Huntsville, AL) October, 1974. pages 7-13 - 7-29.

[19] Ibid., pages 3-14 - 3-15.

[20] Cohen, Marc M., *Human Factors in Space Station Architecture I: Space Station Program Implications for Human Factors Research,* NASA TM-86702 (Ames Research Center, Moffett Field, CA) 1985.

[21] *Evolutionary Space Platform Concept Study, Vol. 2 - Technical Report,* "Part B - Manned Space Platform Concepts, Fritz Runge, study manager, NASA CR-170829 (McDonnell Douglas Astronautics Company, Huntington Beach, CA) May 1982. page 133.

[22] Space Operations Center System Analysis, Final Report, Volume 3, "Book 1 of 2, SOC System Definition Study, Rev. A," Gordon Woodcock, study manager, NASA JSC Contract NAS9-16151 (Boeing Aerospace Co., Seattle, Washington) January, 1982. page 405.

[23] *Space Station Needs, Attributes and Architectural Options Study - Final Report, Volume 4,* "Mission Implementation Concepts," Sherman Schrock, program manager, NASA HQ Contract NASW-3686 (Martin Marietta Aerospace, Denver, CO) April, 1983. page 4-13.

[24] Cohen, Marc M. *Space Station Architecture, Module, Berthing Hub, Shell Assembly, Berthing Mechanism and Utility Connection Channel, NASA Case ARC-11505-1, No. 588,036, March, 1984.*

[25] *Conceptual Design and Evaluation of Selected Space Station Concepts Executive Summary, JSC-19521 (NASA-Johnson Space Center, Houston, TX) December, 1983.*

[26] Systems Engineering and Integration, Space Station Program Office, *Space Station Reference Configuration Description,* JSC-19989 (NASA-Johnson Space Center, Houston, TX) August, 1984.

[27] MacConochie, Ian O. and Maywood L. Wilson, "Pultrusion Process for Fabrication of Tethers," *Applications of Tethers in Space, Vol. 2,* compiled by Alfred C. Cron, NASA CP-2365, Proceedings of the Applications of Tethers in Space Workshop, June 15-17, Williamsburg, VA (NASA Scientific and Technical Information Branch, Washington, D. C.) 1985. page 5-222.

[28] Dalton, Maynard, *Skylab Experience Bulletin No.9,* "Foot Restraint Systems," JSC-09543 (NASA-Johnson Space Center, Houston, TX) December, 1974. page 15.

[29] Rhodes, Marvin D. and Martin M. Mikulas, Jr. *Composite Lattice Structure,* NASA TM X-72771, (NASA-Langley Research Center, Hampton, VA) September, 1975.

[30] Frederick J. Stimler, *System Definition Study of Deployable, Non-Metallic Space Structures,* NASA CR-171090 (Goodyear Aerospace Corporation, Akron, Ohio) June, 1984. pages 35-43.

[31] Card, Michael F. and William J. Boyer, *Large Space Structures - Fantasies and Facts,* AIAA-80-0879-CP, 21st Structures, Structural Dynamics and Materials Conference, May 12-14, 1980.

[32] Nansen, Ralph H. and Harold Di Ramio, "Structures for Solar Power Satellites," *Aeronautics and Astronautics,* October, 1978. page 58.

[33] Stokes, Jack, "Comparative Evaluation of Operability of Large Space Structure Connectors," *15th Aerospace Mechanisms Symposium,* NASA CP-2181, (NASA-Marshall Space Flight Center, Huntsville, AL) May 14-15, 1981. page 365.

[34] Bement, Laurence J., Howard G. Bush, Walter L. Heard, Jr. and Jack W. Stokes, Jr., *EVA Assembly of a Large Space Structure Element,* NASA TP-1872 (NASA-Langley Research Center, Hampton, VA) June, 1981.

[35] Covault, Craig, "EVA Assembly Demonstrates Space Station Building Concept" Aviation Week and Space Technology, December 16, 1985.

[36] Mehran, Mobrem, *High-Performance Deployable Structures for the Support of High-Concentration Ration Solar Array Modules,* Final Report AAC-TN-1142 prepared by Astro Aerospace Corp., Carpinteria, CA for NASA-Marshall Space Flight Center under contract No. NAS8-36043, Accession No. N86-16413, October, 1985. pages 19-26.

[37] Hedgepeth, John M., Martin M. Mikulas, Jr. and Richard H. MacNeal, "Practical Design of Low-Cost Large Space Structures," *Aeronautics and Astronautics, October,* 1978. page 30.

[38] Rhodes, Marvin D. and Martin M. Mikulas, Jr., *Deployable Controllable Geometry Truss Beam,* NASA-TM 86366, (NASA-Langley Research Center, Hampton, VA) June, 1985.

[39] Goodwin, Charles J., "Space Platforms for Building Large Space Structures," *Astronautics and Aeronautics,* October, 1978. pages 44-47.

[40] "Astronauts Believe Lengthy EVA Building Sessions Are Feasible" *Aviation Week and Space Technology,* December 16, 1985. pages 21-22.

[41] Walding, J. G., *Attitude and Pointing Flight Procedures Handbook,* JSC-10511 (NASA Johnson Space Center, Houston TX) January 1982. pp. 1-12 - 1-15.

[42] Cohen, Marc M., "An Overview of Architectural Research," *Space Station Human Factors Research Review, Volume 3,* Space Station Habitability and Function: Architectural Research, edited by Marc M. Cohen and Alice Eichold, (Ames Research Center, Moffett Field, CA) December 5, 1985. pp. 74-88.

[43] Cramer, D. Bryant, "Physiological Considerations of Artificial Gravity," compiled by Alfred C. Cron, NASA CP-2364, *Proceedings of the Applications of Tethers in Space Workshop,* June 15-17, 1983, Williamsburg, VA (NASA Scientific and Technical Information Branch, Washington, D. C.) 1985. page 3-101.

[43] Johnson and Holbrow, Op. Cit. page 60.

[44] *Space Resources and Space Settlements,* edited by John Billingham and William Gilbreath, NASA SP-428, technical papers from the 1977 Summer Study at NASA Ames Research Center, Moffett Field, CA (NASA Headquarters Scientific and Technical Information Branch, Washington, D. C.) 1979. pages 87-158

[45] Ibid., page 141.