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A WIDELY ADAPTABLE HABITAT CONSTRUCTION SYSTEM UTILIZING SPACE RESOURCES

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ABSTRACT

This study suggests that the cost of providing accommodations for various manned activities in space may be reduced by the extensive use of resources that are commonly found throughout the solar system. Several concepts are proposed for converting these resources into simple products with many uses.

Concrete is already being considered as a possible moonbase material. Manufacturing equipment should be as small and simple as possible, which leads to the idea of molding it into miniature modules that can be produced and assembled in large numbers to create any conceivable shape. Automated equipment could build up complex structures by laying down layer after layer in a process resembling stereolithography. These tiny concrete blocks handle compression loads and provide a barrier to harmful radiation. They are joined by a web of tension members that could be made of wire or fiber-reinforced plastic. The finished structure becomes air-tight with the addition of a flexible liner.

Wire can be made from the iron nodules found in lunar soil. In addition to its structural role, a relatively simple apparatus can bend and weld it into countless products like chairs and shelving that would otherwise need to be supplied from Earth. Wire woven into a loose blanket could be an effective micrometeoroid shield, tiny wire compression beams could be assembled into larger beams which in turn form larger beams to create very large space-frame structures.

A technology developed with lunar materials could be applied to the moons of Mars or the asteroids. To illustrate its usefulness several designs for free-flying habitats are presented. They begin with a minimal self-contained living unit called the Cubicle. It may be multiplied into clusters called Condos. These are shown in a rotating tether configuration that provides a substitute for gravity. The miniature block proposal is compared with an alternate design based on larger triangular components and a tetrahedral geometry.

The overall concept may be expanded to envision city-sized self-sufficient environments where humans could comfortably live their entire lives. One such proposal is the Hive. It is configured around a unique sunlight collection system that could provide all its energy needs and that could be scaled up to compensate for the reduced solar intensity at greater distances from the sun. Its outer perimeter consists of a cylindrical section mated to two conical end walls that taper inwards toward a small aperture at the center of rotation. Light collected by two huge mirrors of unusual design enters the aperture and is redirected to the inside of the cylinder. The conical end walls are shielded from direct sunlight and are designed to radiate heat into space. They are lined with air ducts that passively recirculate the atmosphere while extracting moisture by condensation. Although there is no immediate demand for spacecraft on this scale, their consideration can influence even the earliest stages of the development process.

1. INTRODUCTION

Raw materials are plentiful in space. The development of practical processes for their conversion into building materials would facilitate the transition from expendable spacecraft to an era of permanent manned bases.

Lunar regolith will provide the first opportunity. Any future mission to the moon is likely to test processes for the extraction of water, hydrogen and useful minerals, notably iron from its pervasive soil. Lunar concrete has a great potential significance, and not just for its usefulness to moonbase architects. Lunar concrete products delivered to LEO might someday compete favorably with materials supplied by Earth. What's more, a technology that is perfected on the moon could be appropriate anywhere a similar regolith is present, including Mars, the Martian moons and possibly the asteroids.

This paper envisions a generic construction system designed to adapt to the resources and conditions available at any of these locations. It suggests that habitat components can be simplified down to identical small symmetrical blocks that join together to produce a structure of any desired shape.

The diminutive size of the parts should have a positive effect on the size of the fabrication equipment as well. This is a great advantage in developmental cost savings as well as deployment. Adding duplicate units would boost the rate of production to any desired level without the all-or-nothing gamble that is inherent in a single large factory.

As the construction is refined, it should require less active control. At some point artificial intelligence may assume management functions. Eventually such systems could be sent ahead of a manned expedition, preparing component parts or even a largely completed habitat for the arrival of a crew. A mission may begin with a single unit, to be replaced if a failure occurs or reinforced with additional units if success seems likely. The mission planner has the option of trading an extended time frame for constrained costs and reduced risk factors.

Wire is an important building product. It can be used in combination with the concrete or as a structural material in its own right. Between these two materials, a habitat could be constructed almost entirely from space resources

Several habitat configurations are provided to illustrate the range of possibilities. Cubicles are modular living units that could serve a small crew on the lunar surface or in open space. Hives are very large self-sufficient systems designed for a population of thousands. They would be home to a new kind of human society free of dependence on a planetary surface.

2. BUILDING BEADS

Conventional construction systems produce specific shapes that are dictated by the design of the components, If those components are symmetrical and capable of connecting to each other in three dimensions the shape that results can be varied indefinitely incorporating curved or faceted surfaces. The complexity of the product is limited only by the size chosen for the pieces

Building beads are compression blocks one cubic inch or less in size. A web of tension wires or high-strength fibers pass through or between the beads and the resulting composite structure exhibits both properties. The beads must be small enough to make practical partitions but suitable for multiplication into structural hull sections or beams of any required depth.

Although "lunarcrete" inspired the concept, beads might be produced from a variety of materials, including ceramics, an aggregate material that could be sintered or bonded with an organic resin, powder metallurgy, cast iron or aluminum or even from cut and machined rock. This flexibility means that only the bead production process needs to change to fit the resources available. The assembly equipment and all the support systems that go with a particular bead design remain the same.

The examples illustrated all possess the familiar x/y/z symmetry. A number of other interesting geometries are shown along with a partial survey of space-filling shapes.

Cube based systems are easy to visualize. Large curved or diagonal surfaces will exhibit stair-steps rather than a smooth surface. Complex interlocked shapes and unmoldable undercuts may be executed as a series of parallel sections. Stereolithography uses this principle. Automated assembly robots could build each successive layer directed by a CAD system and an invisible grid.

Cubes do produce smooth surfaces along their major axes but this can be a disadvantage structurally. Without any physical interlocking they are vulnerable to shear forces. In Figure 2a, threaded fasteners between the blocks prevent slippage along these planes. The second example (fig.2b) relies on dimples to resist shear and welded wire nails through the blocks to tension the assembly.

The third example (fig.2c) introduces a shape called the smoothed cube . Each bead has six circular faces centered on the three axes, with a diameter half the overall width. A matrix of smoothed cubes joined at these faces will create a negative space that is identical to the filled space. If that negative space is also occupied by connected beads, the result is two interlocked but independent networks with each set blocking the cleavage planes of the other.

There are several ways to reinforce smoothed cubes. Metal thumbtack shapes can be inserted into holes in each face and resistance welded in the center. The springy dome of the tack-head is flattened by pressure, and an additional preload may occur as the metal cools and shrinks. The tack heads may be adhesive bonded, projection welded or mechanically fastened to each other

If a very high strength product is required, an alternate system may be preferred (fig.2d). It uses small pads of a putty-like sheet molding compound composed of aramid, carbon or glass fibers in a resin binder. The compound is squeezed between the rows as each new bead is inserted. A chemical reaction must be induced before the resin will harden and bond to the beads.. It might be caused by a catalyst sprayed on the surface of the parts or triggered by radiation. Ultraviolet-cured resins are available. Microwaves might serve the same function in space. The structure could also be divided into smaller sub-assemblies and cured in a heated chamber similar to the inflatable factory shown in the section on reinforced concrete blocks.The result should be a strong omnidirectional honeycomb with excellent strength in both tension and compression. Several other geometric shapes can be joined in this manner including the rhombic dodecahedron and the truncated octahedron

3. CUBICLES

Cubicles are modular living/working units designed to stand alone or to be joined indefinitely into complexes called condos. Each cubicle has its own life support system. If building-beads and wire are used in the hull and most of the internal furnishings, they would represent a mass far greater than any likely load of people, supplies and equipment.

In the example, beads are used to create two 20' diameter cylindrical pressure vessels which intersect each other forming a single main deck roughly 32' (10m) wide and 44' long, this last number suggested by the length of the shuttle cargo bay. Two equipment pallets fit into the valleys between the cylinders. They contain the essential systems and are sized to fold and be transported in the shuttle.

Cubicles depend on an external source of power - probably solar or nuclear and located at the hub in the case of the spinning system shown. Since missions several years long are possible, a plant growth system is integral. The Soviet Bios program [1] achieved a stable closed ecological loop and maintained it for six months with no negative health effects on the three crew members. They grew 77.5% of their own food and recycled all of their air and water. Academician Gitelson suggested at a Planetary Society presentation in May of 1992 that 30 sq.meters/person could completely support one person. Gas exchange alone could be accomplished with 10 to 15 square meters. Using this data, a single cubicle could support 4 people and recycle the air of 8 to 10. This extra capacity fits a transportation scenario in which transient crew would bring dehydrated meat and other products to spice up the basic grain and vegetables grown on board. It is likely that the "Tubular Membrane Plant-Growth Unit" [2] and other sophisticated hydrophonic systems may provide even greater yields.

The design places the plants over the heads of the crew. This configuration takes advantage of the ceiling arch with a system to rotate the plants towards the center as they grow. Space-wasting aisles are eliminated, and the light that escapes the area provides the ambient illumination in the living areas. Sleeping chambers have their own sealable cylinders which contain an independent air supply. Since humans spend 1/3 of their lives asleep, the total radiation exposure is averaged down by providing extra shielding. Some shelter would be needed in any case as protection from solar storms.

Cubicles may be used in pairs at opposite ends of a rotating tether system. Partial or full artificial gravity can be generated in this way. If we take 2 RPM to be the maximum rate of rotation which can be generally tolerated, simulated full gravity would require a tether with a 733' radius. The pairs of cubicles on opposite sides of the circle are nearly a mile apart measured along the curve. To travel between them, a ferry system is more logical than passing through the hub. The ferries simply shorten their tethers and their momentum produces a higher angular velocity. Lengthening the tethers then allows them to rendezvous with another location on the rim.

Low gravity facilities would be attached to the hub and reached by elevator. A frictionless, possibly superconducting magnetic bearing[3] could join the stationary component to the revolving cubicles. The part of the original spacecraft with cubicle production equipment is free to move on to the next site, leaving its dock free for supply ships.

4. WIRE

The production of metal products in space is also being considered. Iron is particularly accessible since it may be found in nodules in the lunar regolith and extracted by sifting through magnets [4]. Materials processing experiments on the Space Station could lead to practical refining and handling systems. Metals may be cast, foamed or turned into a powder and sintered, but one uniquely useful form is wire. Potential applications go far beyond its role in a bead system, and it's fairly easy to produce. Renaissance craftsmen made a high quality music wire with mostly wooden tools from an alloy of iron and phosphorus.

The challenge of wire production can be deferred until the production problems of concrete are solved, but once we add this capability a wide range of space-products become feasible. To begin with, we can furnish the apartment. Wire shelving and storage systems are commonplace. A wire space frame with a thin plastic sheet on top makes a fine table. Inflated plastic bladders can pad a wire chair or a bed. Wire is such an adaptable material that astronauts can design and construct new devices on the spot, either bending and welding the wire by hand or designing with a CAD system and letting a robot arm do the work.

Woven wire mats can function as micrometeoroid shields. The multilevel welded mesh would be designed to deflect, shatter and trap the high-velocity energetic particles that might seriously damage a concrete based structure.

Many of the structures we might create from wire call for it to resist compression loads. A long wire under load will simply deflect to the side and collapse but if its shortened enough it's capacity begins to approach the limits of the material. This is the principle of the beam just scaled down to fit the gauge of the wire. If a long boom is needed, it can be built from tiny pieces, with an approach that was suggested by the property of fractals that causes them to re-create the same shapes again and again at progressively larger scales.

The illustration shows how a three-inch wire beam can be the basis for a thousand-foot span in three fractal-like stages. This beam in turn may be a component in a huge spaceframe structure for the vast sunlight-concentrating mirrors required to build a hive. The rigid octahedron shown could be part of a tensegrity structure. The three beams have one straight edge which is the primary load path. This allows them to pass in the center without interference.

5. REINFORCED CONCRETE BLOCKS

Concrete and wire can be combined into more conventional molded modular shapes. They can form building components with properties far beyond familiar bricks and cinder-blocks. Ferro-cement boats come closest to creating the type of hull a spacecraft would need. The Bible of the industry [5] suggests an optimum thickness of 7/8 inch and states that a square foot will weigh 13 lbs. Concrete hardens and gains strength through hydration. The water used is largely recoverable. Boat hulls can be cured with steam to 90% of their full strength in 6 days, followed by drying for an additional month. The recommended practice is to use 6 mesh hardware cloth and 3/16 inch rod as reinforcement. T.D. Lin studied concrete space structures for the Portland Cement Association [6]. He pointed out that concrete reinforced with 4% by weight of iron fibers has nearly twice the flexural strength of the plain product. A commercial plastic fiber is also used for this purpose [7]. Fibers in the slurry might be a lightweight alternative to wire reinforcment, especially valuable if the wire must be brought from Earth.

The illustration shows a two-chambered inflated factory based on a design proposed by Lawrence Livermore laboratory. Blocks are molded in an automated machine assisted by a teleoperated robot arm which moves the blocks through a series of curing and drying chambers around the periphery. Finished blocks are assembled into wall sections in the lower chamber which also functions as an air lock. A bow-string tension wire system is suggested to rigidify the multiple block panels and a series of edge connectors would join these compound triangles into the finished form. An inner tube makes the finished cubicle air-tight. If the blocks shown in the illustration are a meter long on each edge, each of the cubicle segments shown would be able to support one person.

Rectangles dominate block systems on Earth largely because gravity makes them stackable. In a zero-G environment a shape like the triangle may be more useful. The equilateral triangle is the most versatile. Martyn Cundy gave the name deltahedron to any polyhedron composed of equilateral triangles. There are 8 convex forms, including the tetrahedron, octahedron and icosahedron. The other five are shown in the inset box.

The size of the blocks can be adjusted to fit other criteria. Four blocks make a new triangle twice as large, nine are needed to triple the size, etc. Blocks in the center may be omitted to create passages or windows. The facility can grow by adding a tetrahedron at a time while still in service.

6. HIVES

The key design goal of hives is self-sufficiency. A closed-loop ecology can be maintained but a minimum energy input is needed. This is roughly 2 kW/person/day in the form of light that must be provided for photosynthesis. Concentrated sunlight may be brought inside the hull with far greater efficiency than any system of conversion to electricity and back again.

In this design, large curved mirrors create two cones of light focused on a central aperture in the revolving hull. Within the aperture, a second conical mirror re-directs the light to illuminate the inside of the cylinder. This area is devoted to agriculture. Plants fuel the entire biosphere by converting this sunlight to chemical energy.

The mirrors are large enough to behave like solar sails, so a self-aligning system has merit. A parabolic bowl would be unstable. Instead the flat mirror segments are divided into a series of parallel angled rows and arranged in hyperbolic shape. The center of light pressure moves behind the axis of rotation and service accessibility is improved. The orientation of a hive with its axis of rotation perpendicular to the plane of its orbit around the sun means that the mirrors must complete just one revolution every orbital year. The alignment problems that plague ground-based solar systems do not exist for a hive.

The shaded patches show the frontal area of the mirrors as seen from the sun. In most cases this area must be greater than the area of the illuminated crops inside the hive. The size of the mirrors can be adjusted to compensate for increased distance. A hive at the edge of the asteroid belt (2.5 AU) would need 6.25 times the area of a hive near the Earth. Sunlight in space is twice as intense as the filtered light that reaches Earth's surface, but the losses involved in collecting it may neutralize this advantage. A minimum of two reflections are required. Even an optimistic 90% reflectivity means that nearly 20% is lost in transit.

Air is the working fluid of the hive. Gas exchange between plant and animal, water recirculation and the elimination of waste heat all come about through the medium of the atmosphere. Furthermore the system is passive, a product of the configuration rather than using pumps and fans.

The conical end walls are never lit directly by the sun. They radiate heat into space. Passages line the inside surface carrying air from the low-G upper areas to the higher gravity at the base of each cone. As the air inside loses heat it grows denser and sinks, pulling in fresh air at the top. The longer this path, the colder the air will become, so a state of winter could be created at will for the perennials growing near the outlets. Condensation provides a constant supply of distilled water to the dwellings that line the wall.

The hive design is dictated by the energy system and the need to minimize the obstruction of incoming and redistributed light. The inhabitants live over the ground level in a series of concentric rings suspended below the conical end walls. Architecture is supported by cables from the overhanging wall above rather than columns from the ground below.

Only a small part of the spherical volume is required to house more people than the ecosystem can possibly support. Just ten evenly spaced levels would exceed the surface area of the farms below by half. At 30 sq.m/person, a 1500 ft. diameter hive could support 12,000 people. Improvements in crop yield and techniques for converting inedible biomass into food could double the population density, and artificially lit greenhouses are possible as well.

Hive hulls may be designed as rigid shells constructed from billions of beads or with a series of nested rings derived from another block design. Supplementary tension bands carry the principal loads in either case. NASA has recommended 4.5 tons/sq. m of material for radiation shielding. This is far more material than required by the structure so chambers filled with rubble and a thick layer of soil will be needed to reduce the health risk to terrestrial levels.

A hive is a massive undertaking. It may seem like a fantasy now, but if the exploration of space follows the course of most other waves of human expansion, we will someday need a city in space, and economics will be sufficient to demand its construction.

7. CONCLUSIONS

Space resources could provide nearly all of the mass in the structure of a space habitat. A widely adaptable system would be attractive for the savings in development costs and the potential reuse of the equipment. The building-bead system requires smaller equipment, insures against total mission failure from a single breakdown, makes possible virtually any shape, wall thickness or degree of complexity and will work with a wide range of materials. If a larger block is desired, equilateral triangles may be the most versatile shape.

Wire produced in space may be used to reinforce a bead or block system and is suited for several other key roles:

1) large open structures using fractal style replication
2) An infinite range of more conventional product/furnishings
3) allows astronauts to respond to unanticipated needs by improvising and fabricating at the site.

Cubicles offer an entry-level product for either beads or blocks, are useful for missions in or out of a gravity field or in rotating systems to simulate gravity, and can provide food and gas exchange for the modest crew sizes needed in the near future.

Hives provide for all of the life-support and energy needs of their occupants.with comfort and safety emulating Earth, and could be built anywhere in the solar system within the practical limits of the light amplification system.

The author is indebted to Jerome Pearson, who offered technical criticism and suggestions throughout the evolution of this concept, along with guidance in its presentation.

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[3] Misovec, K; Johnson, B; Downer, J; Eisenhaure, D; Hockney, R; Marshall Space Flight Center; Heteropolar magnetic suspension. NASA Tech Briefs, June 1990:75 MFS-26096

[4] Lewis, J.S; Lewis, R.A; Space Resources, breaking the bonds of Earth. Columbia University Press; 1987:262

[5] Bingham, B; Ferro-cement design, techniques and application. Cornell Maritime Press 1984

[6] Lewis, R S; Space in the 21st century. Columbia University Press, 1990

[7] Fibermesh; Fibermesh company, 4019 Industry Dr. Chattanooga, TN 37416

[8] Wells, D; Penguin dictionary of curious and interesting geometry. Penguin Books 1991

2. BUILDING BEADS

Fig.2a Mechanical Fasteners used to create tension paths between the beads

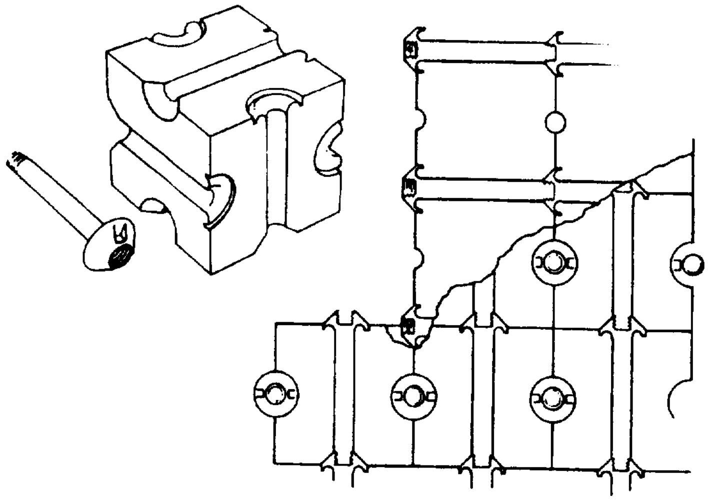


Fig.2b Resistance welded wire nails passing through the blocks

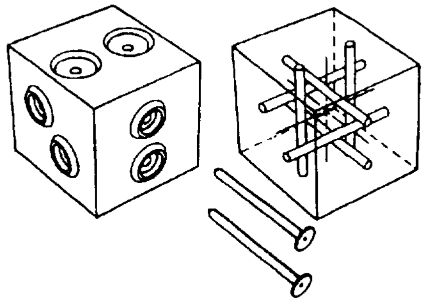
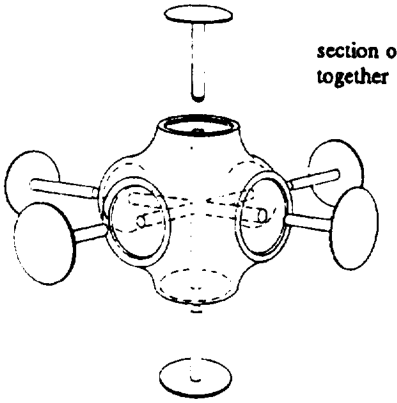


Fig.2c Smoothed cube with a metal skeleton formed by resistance welding six thumbtack shapes together in the center - the skeleton could also be cast-in-place



section of an assembly showing the tack heads bonded together with adhesive or projection spot-welded

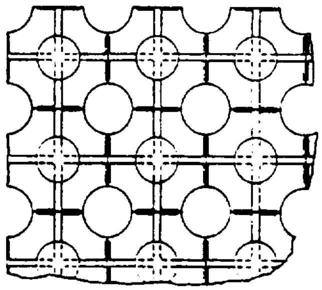
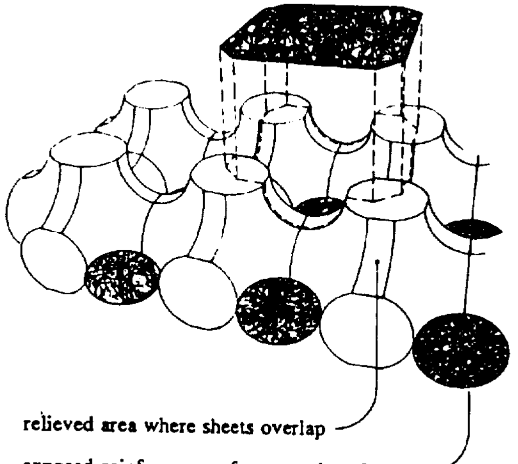
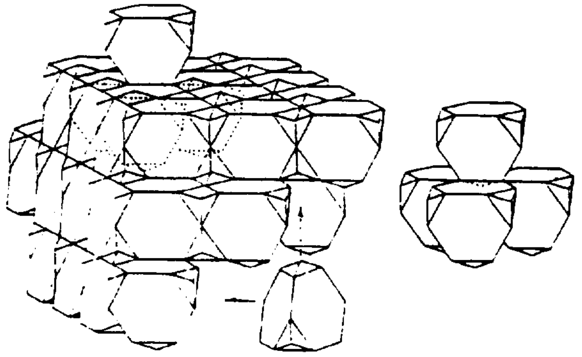


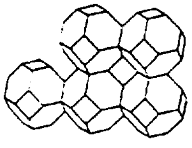
Fig.2d uncured resin and fiber sheet will be forced into the matrix by the next bead



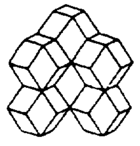
Some other possible space-filling geometries 8



Tetrahedron with beveled edges - since the faces are not perpendicular, the design process is made more difficult.



Truncated octahedron



Rhombic Dodecahedron

3. CUBICLES

Fig.3a two cubicles joined to form a condo

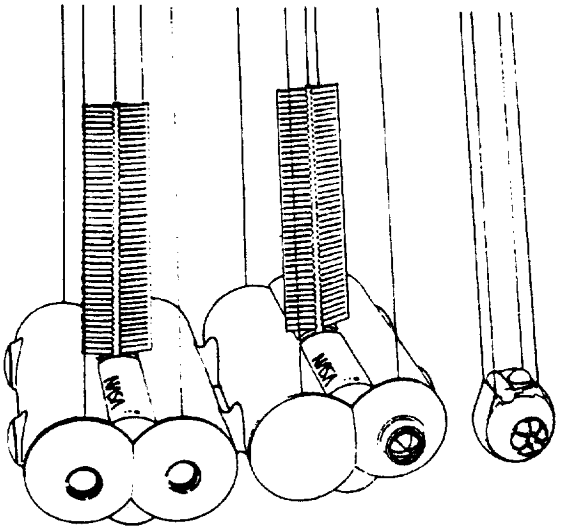


Fig.3b plan view with a ferry pod at the airlock

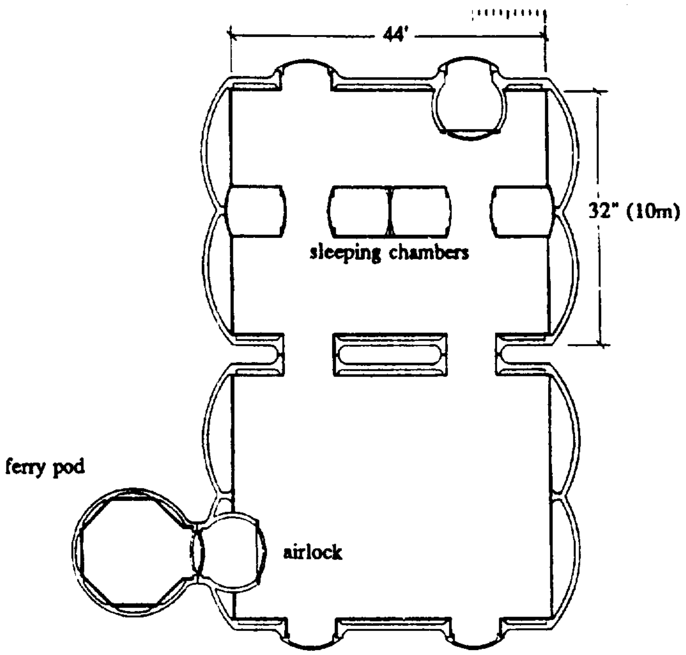
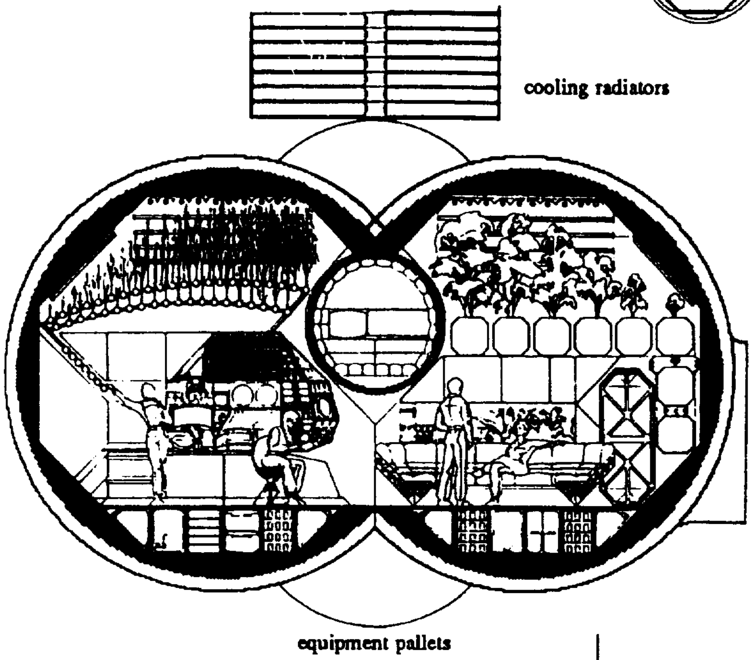


Fig.3c section of a typical cubicle



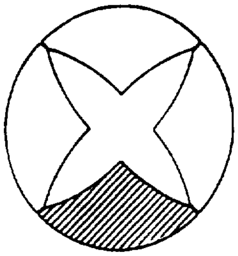


Fig.3d equipment pallets arranged to fit the shuttle bay

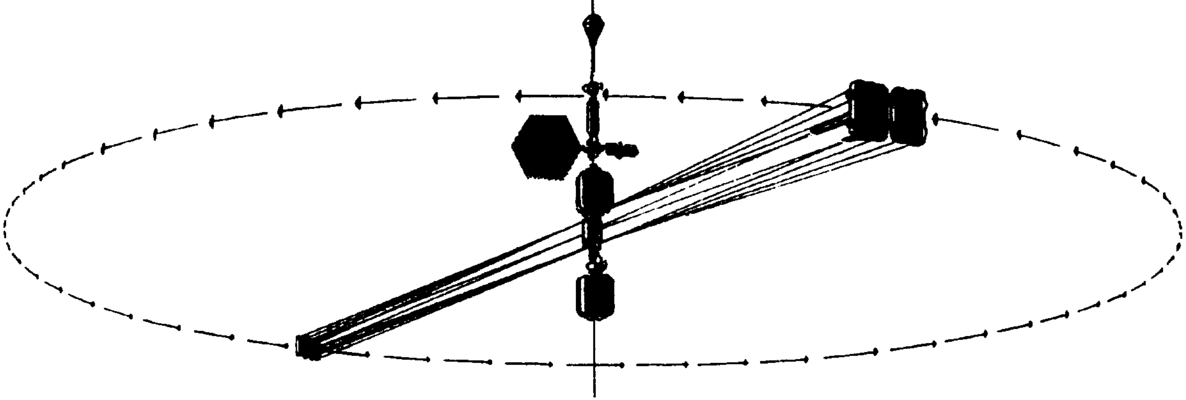
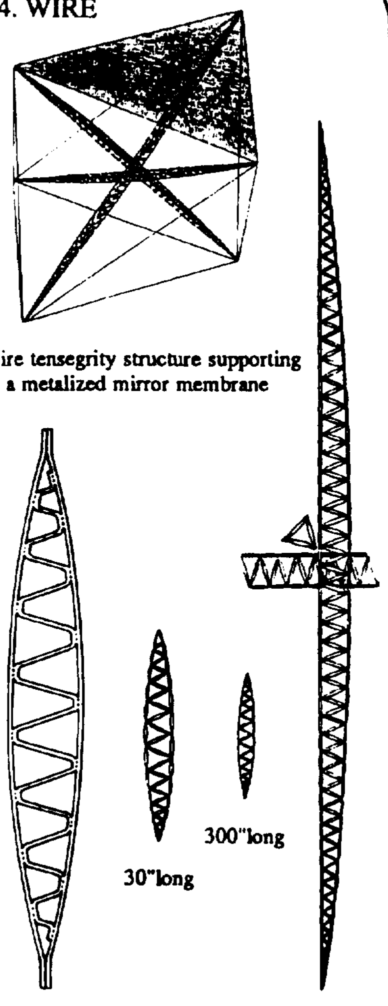


Fig.3e two condos rotating around a central hub complex

4. WIRE



wire tensegrity structure supporting a metalized mirror membrane

5. REINFORCED CONCRETE BLOCKS

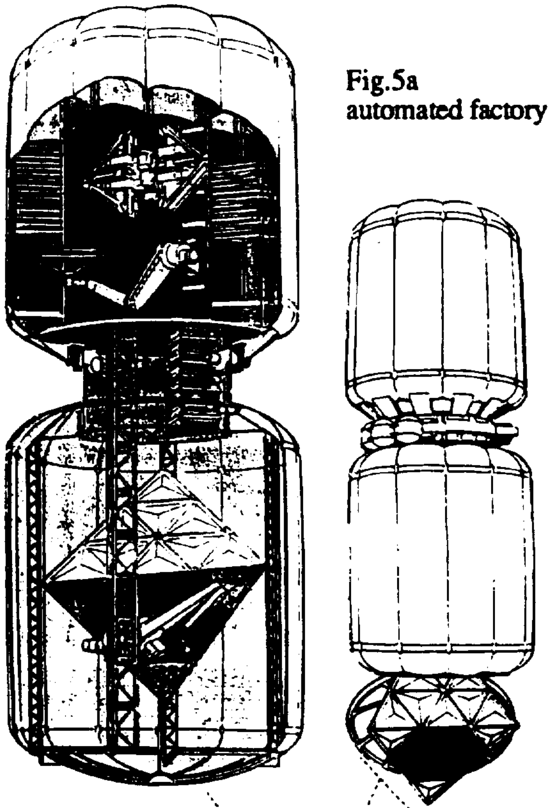


Fig.5a automated factory pods

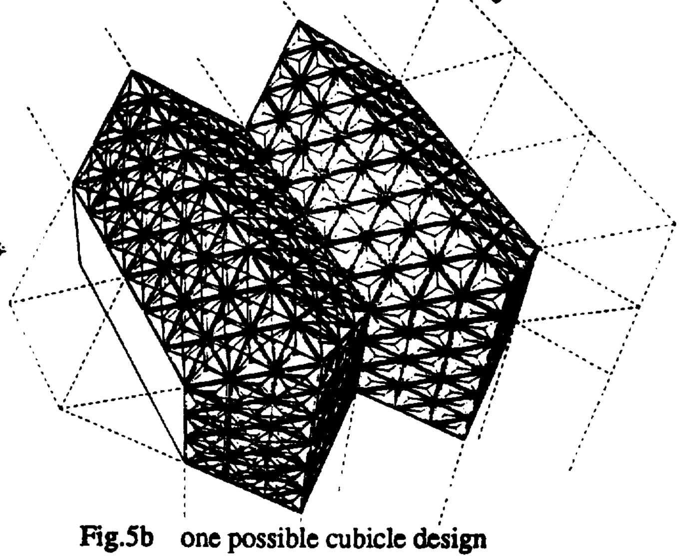


Fig.5b one possible cubicle design

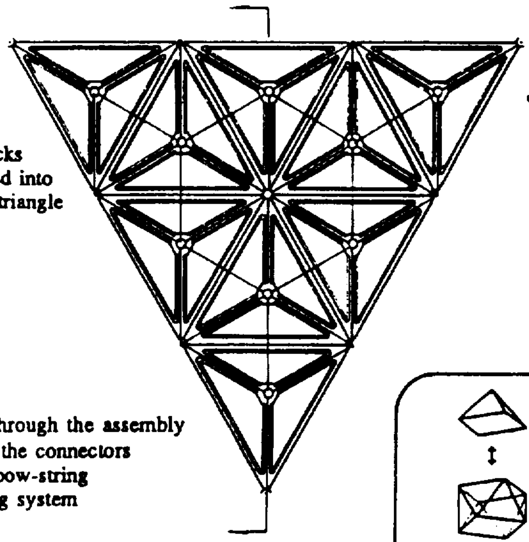
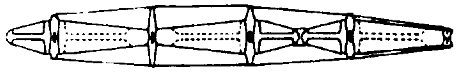
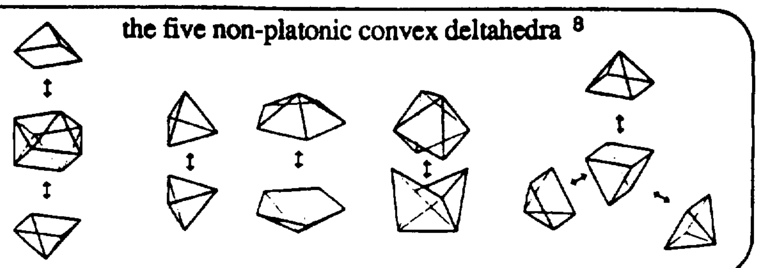


Fig.5c nine blocks assembled into a larger triangle

Fig.5d section through the assembly showing the connectors and the bow-string tensioning system





the five non-platonic convex deltahedra [8]

6. HIVES

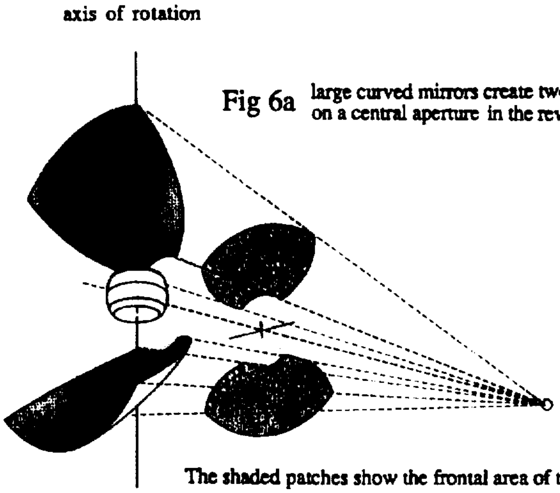
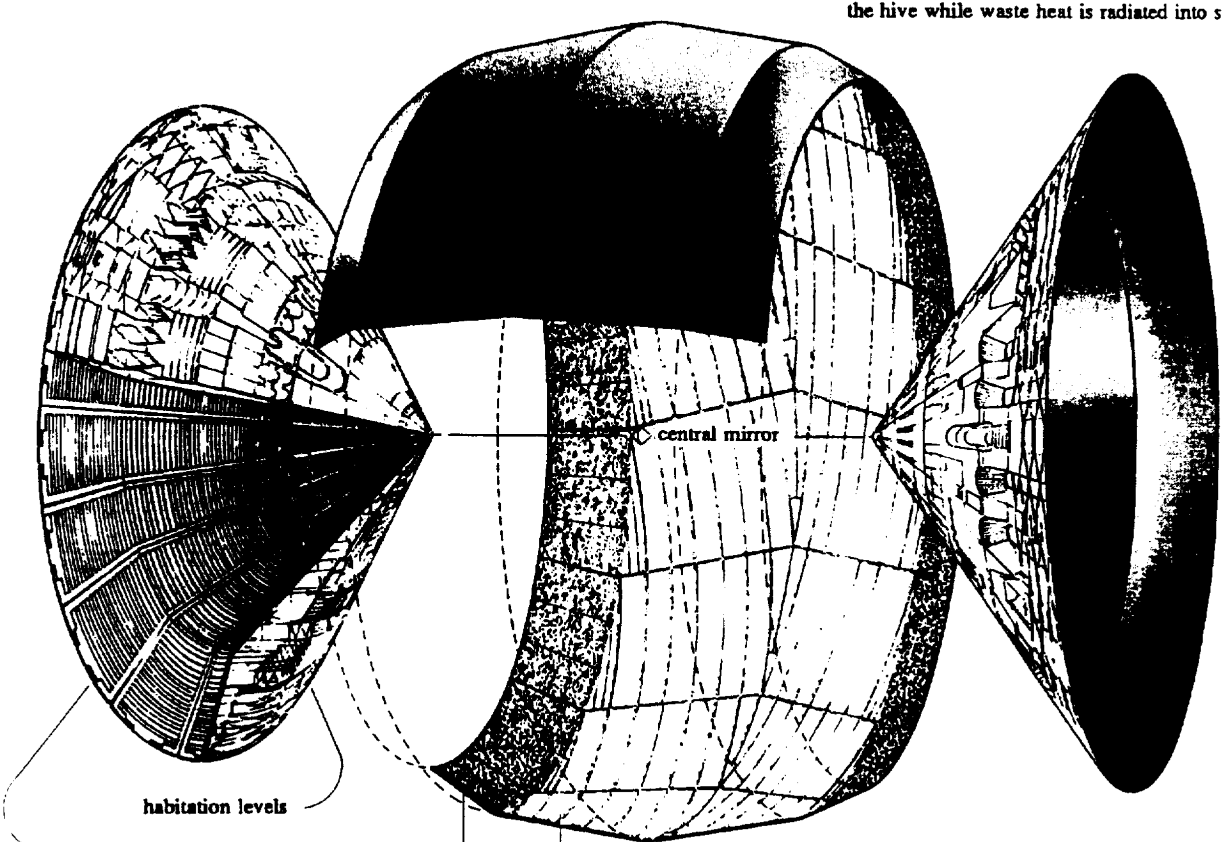


Fig 6a large curved mirrors create two cones of light focused on a central aperture in the revolving hull.

The shaded patches show the frontal area of the mirrors as seen from the sun.

Fig.6b exploded view of a hive with portions removed



conical ends permit concentrated light to enter the hive while waste heat is radiated into space

habitation levels

complex air passages line the inside of the cones

food production

orchards and wood products occupy a zone where seasonal temperatures can be created