Chapter V

STRUCTURE, FORM, AND MEANING IN MICROGRAVITY ~ THE INTEGRAL SPACE HABITATION

FIRST PUBLISHED IN THE INTERNATIONAL JOURNAL OF SPACE STRUCTURES, VOL. 5 NO.2,
UNIVERSITY OF SURREY, UNITED KINGDOM, 1990 (PREPARED IN RESPONSE TO THE EDITOR'S INVITATION).

ABSTRACT

There will likely be an intensive colonisation movement into Space within the foreseeable future. Presuming eventual adaptation to microgravity, the structural, habitable, and meaningful environment of Space Architecture will be fundamentally redefined. The primary shift in spatial conception will be from two-dimensional decentralised horizontal schema with singular up-down vertical axis, to three-dimensional centralised polyaxial schema with in-out the primary existential axis.

Mega-structures are proposed, to provide ample habitable space in Space. Their structure is provided by means of centralised tensile lattices stressed by pneumatic enclosures. These are envisaged to be large-scale, of about 13 kilometre in diameter each, with Primary Tensile Lattice ties of 1 km length. The geometry of the tensile lattice is given by the author's centralised polyaxial zonahedral expansions. Secondary tensile assemblages are then stressed by means of the primary tensile lattice, with tertiary and subordinate assemblages as desired. This permits a "soft" non-rigid architecture to be developed.

Principles of Traditional Architecture are relevant to Space Habitation studies, and indicate Space Habitation theory should seek to integrate metaphysical, psychic, and physical human needs appropriate to dwelling in microgravity. Ideally the Space Habitation should integrate structure, form and meaning.

This paper encapsulates ideas presented in the author's book, The Integral Space Habitation ~ Towards an Architecture of Space.

FROM A HISTORICAL PERSPECTIVE, IT IS INEVITABLE that - barring global catastrophe - Humanity will colonise Space. We need only escape Earth's gravitational well, and establish our development efforts from within the microgravity environment.

At the same time, we need to recognise that the Earth is currently in a severe environmental crisis, as a consequence of acute global mismanagement. Healing this planet is the number one priority. One in five people now live in a state of absolute poverty; and the same proportion of people are unhoused.

Unenlightened settlement patterns are causing massive pollution of the environment, and this condition is exacerbated by the ruthless exploitation of resources to fuel greed - including horrendous "Wall of Death" drift-net fishing techniques here in the South-West Pacific.

It is good that we put our house in order before leaving home. But I do not see the incipient colonisation of Space as being in competition or conflict with the necessary healing of the Whole Earth organism. Rather I believe this to be an expansion of consciousness into the Universe, which represents the complementary expression of the simultaneous implosion of human into planetary consciousness, which is now taking place.

Cohen points out that current Space Habitation theory is in need of radical revisioning.[1] The tendency - often unconscious - to import gravity-bound preconceptions into a gravity-free environment needs to be overcome.[2] We need fresh ways of looking at problems of structure and habitation.

In time the recognition of the microgravity environment as desirable and indeed normal will take place. Notwithstanding major problems to be overcome in long-term adaptation of the human organism and other Earth life-forms to microgravity, the astonishing pace of technological development together with the enormous benefits that will follow from this adaptation lead me to proceed on the premise that in the foreseeable future it will occur.

Microgravity fundamentally redefines the structural, habitable and meaningful environment that space architecture aspires to provide. I approach space architecture through certain key configurations of Sacred Geometry, a traditional discipline which integrates human consciousness into natural languages of geometrical space.

> *The primary shift in architectural conception that microgravity redefines is from a predominantly two-dimensional schema of decentralised horizontal plane and singular vertical axis, to a predominantly three-dimensional schema of centralised polyaxial space.*

Associated with this is the recognition of the appropriateness of "soft" (i.e. non-rigid) structure, together with the dematerialisation of form this permits. I therefore propose a centralised tensile architecture stressed by pneumatic enclosure.

One major factor to be identified in Space Habitation studies is the problem of confinement.[3] My approach to space structures raises the exciting potential of *what might it be like if there is more than enough space in Space?*

If confinement is no longer a problem, and ample habitable space is provided, what form might this take?

Most importantly, traditional human settlement patterns are relevant to space habitation studies. Sharon Skolnick draws attention to the need for nurturance, meaning, spiritual sustenance, love, and human touch in regard to space station design.

One place to look for applicable answers is here, with the indigenous cultures of planet Earth,

"because people who can make a human environment from available materials in an economic, ergonomic way, while at the same time keeping their spiritual energies focused through meaningful ritual and reverence, have much to teach the high tech world".[4]

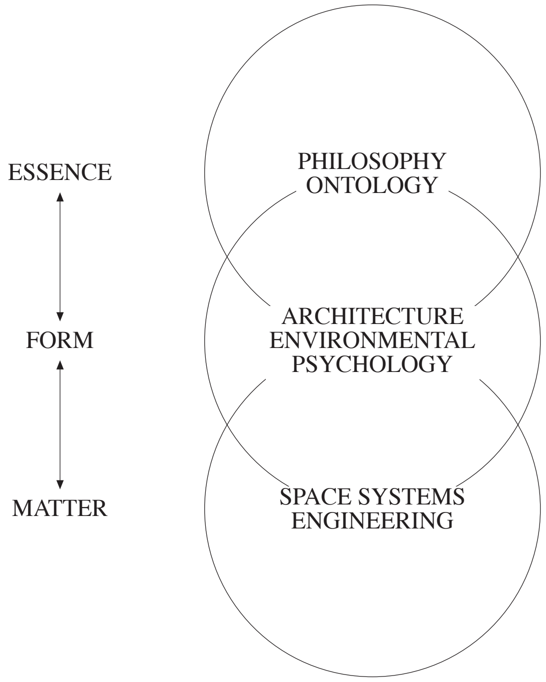

Figure 1: Preliminary Metaphysic model

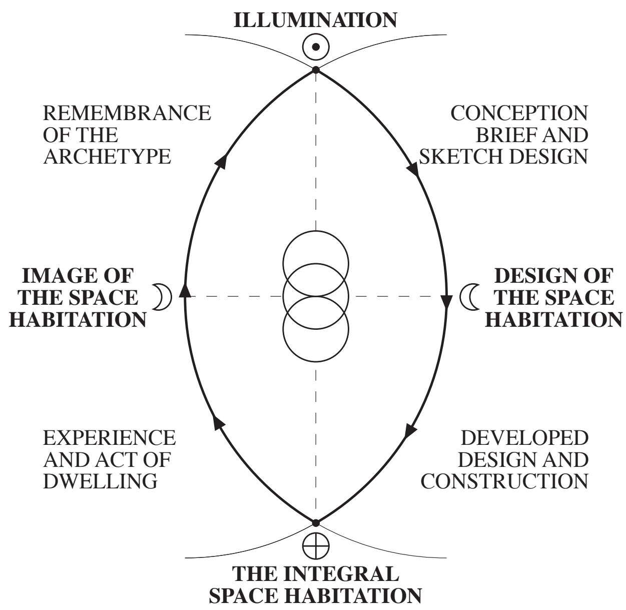

Figure 2: Preliminary Philosophy of Integral Space Habitation

Traditional architecture satisfies a variety of physical, psychic (i.e. of the psyche), and spiritual or metaphysical needs in an *integral* manner.[5] Traditional human settlements are in general ecologically responsible, efficient, rich to inhabit, beautiful to behold, and have the capacity to inspire. The same cannot be said of more recent settlement patterns, which tend to be unstable, banal, ugly, crime-ridden, and pollution and disease producing.

Thus I postulate that we envisage Space Settlements and Habitations with reference to principles of Traditional Architecture, which are found to be of perennial relevance. Fig. 1 makes a preliminary application of these ideas, and Fig. 2 suggests a traditional philosophy of Space Habitation. Assuming a metaphysical perspective enables us firstly to address that which lies beyond the physical. Secondly it permits us to adopt an integral framework within which diverse facets may be situated, and thirdly it allows us to realise a vision of being-in-the-world. Enquiry into metaphysical and ontological aspects of the movement into Space indicate that the focus of this is the act of dwelling, and at the core of this act is the perennial issue of meaning:

< *what does it mean to dwell in Space?* >

Specifically, I propose the Integral Space Habitation as a paradigm that encapsulates what I consider to be important aspects of dwelling in Space.

Once we experience weightlessness (albeit vicariously), the preponderance of gravitationally derived structures of meaning in our Earthbound architectural thinking becomes apparent. Where there is no longer any "up" or "down" - how then can habitable environments be organised? Where it no longer makes sense to have floors on which we walk, with roofs overhead, and walls bounding our horizontal extension; where there is no longer the solid closure of "earth" below and the translucent openness of "sky" above; and where "roads" need no longer be linear two-dimensional surfaces - how then are we to conceive and realise environments that make sense?

I approach the spatial structuring of meaning in architecture through certain key configurations shown in Fig. 3, as taught by Keith Critchlow in the KAIROS School of Sacred Architecture.[6] In the traditional perspective, which these represent, we inhabit a mediating realm between earth and sky.

This schema refers not merely to the physical situation, but symbolically applies more generally to our existential position in the Cosmos. On Earth, we stand and walk on the earthly plane under the Heavens, as in Fig. 4; both we and our buildings mediate these two realms. The earthly realm is that of closure, confinement, the material, the temporal, nature, support, chaos, and so forth.

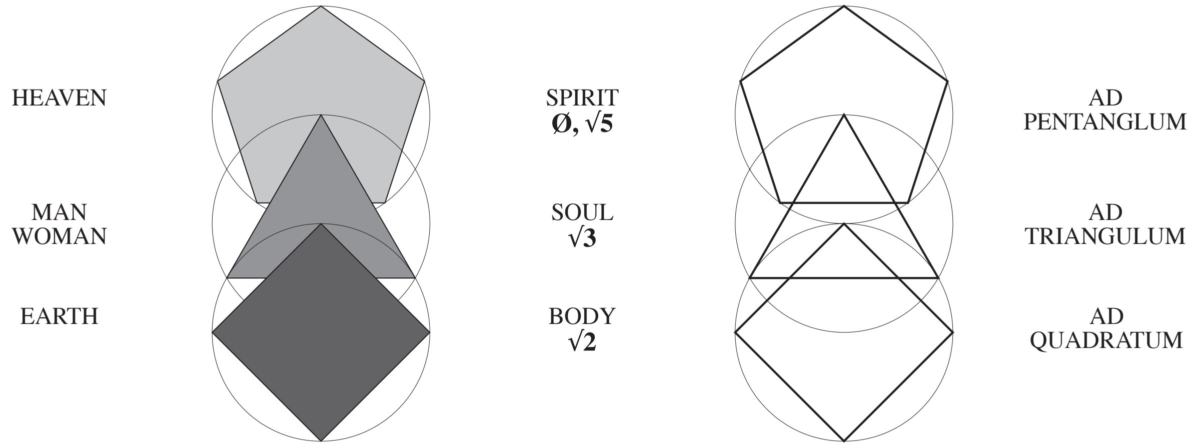

Figure 3: KAIROS Traditional Sacred Geometrical Schema and Proportions

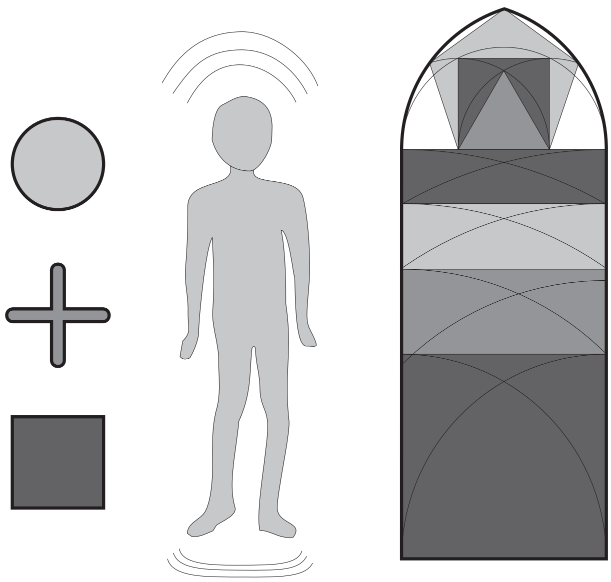

Figure 4: Geometrical Symbolism of Heaven, Man/Woman and Earth in the Arched Portal

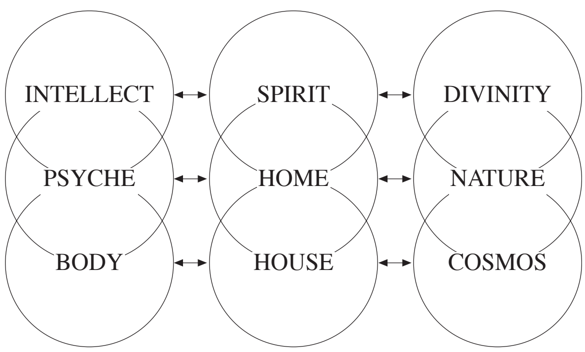

Figure 5: A Traditional Homology

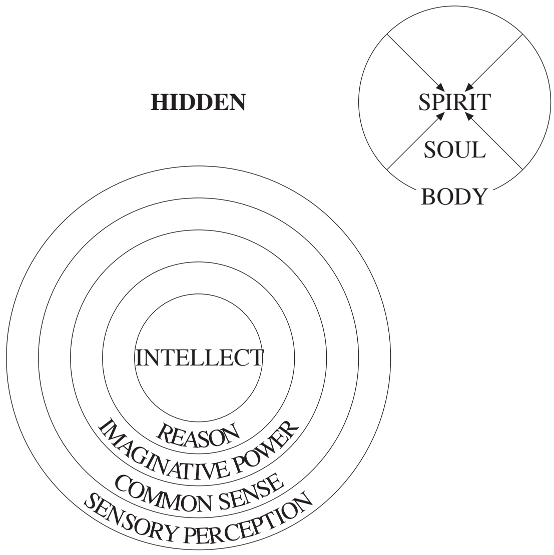

Figure 6: Mediæval PsychoCosmic Model

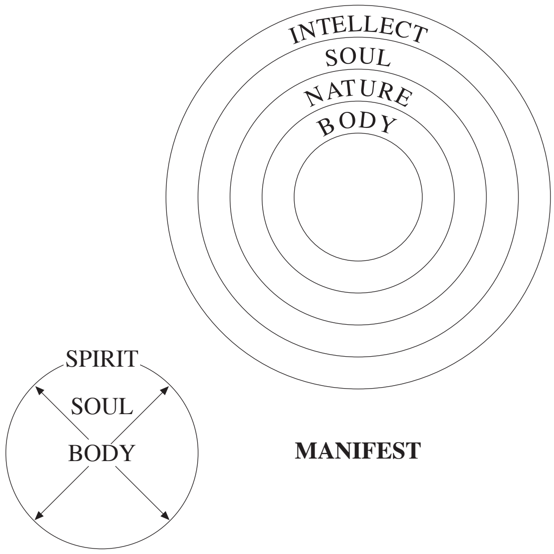

Figure 7: Complementary Mediæval PsychoCosmic Model

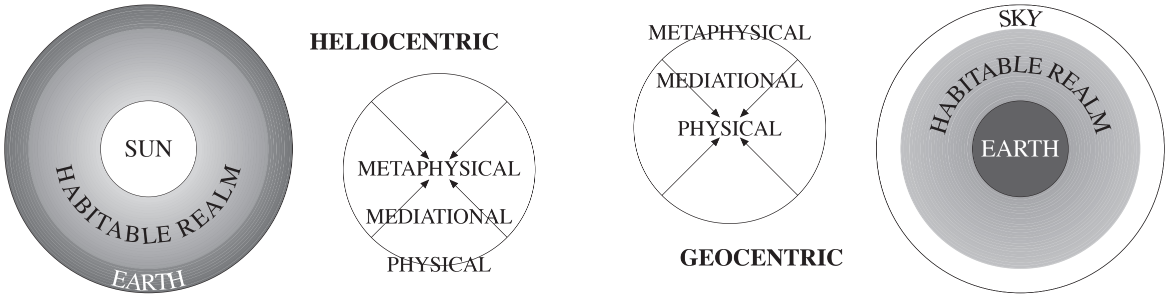

Figure 8: Heliocentric and Geocentric Schema, showing Inbetween Habitable Realm

Figure 9: Heliocentric and Geocentric Forms of Space Habitation

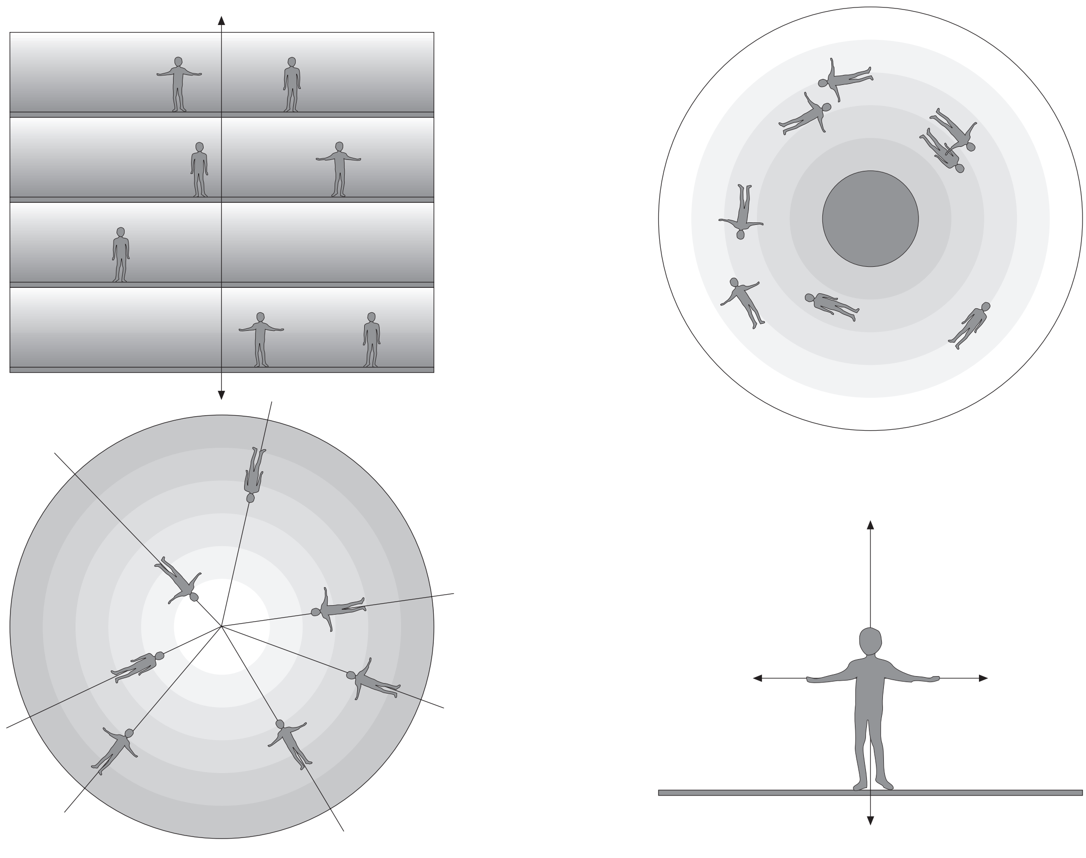

Figure 10: Comparative Orthogonal and Centralised Articulation of Habitable Space

In contrast, the sky realm is that of openness, liberation, the spiritual, the eternal, that which lies beyond nature, essence, order, and so forth. We partake of both, and in an ideal sense the Temple is the architectural means of harmonising both extremes within us, and of healing.[7]

The vertical differentiation is apparent in the homology of Fig. 5, and appropriate to our situation whilst on Earth. The preliminary schema of Figs. 1 and 2 are derived from it and from Fig. 3. But in the microgravity of Space, vertical differentiation is no longer appropriate. Consequently we refer to even more fundamental centralised diagrams advanced by Burckhardt,[8] which date from, at the very least, Mediæval times. These situate firstly the Sky or Sun at the centre and the Earth about, as in the Heliocentric model of Fig. 6; and secondly the Earth at the centre and the Sky without, as in the Geocentric model of Fig. 7. They should be understood in a symbolic sense and not taken literally. In both cases, Man inhabits the inbetween realm.

These schema lead me to suggest that Space Habitations in microgravity should ideally be centralised, as Figs. 8 and 9 show. This accords with the important symbolic qualities of centralised space advanced by Eliade,[9] which suggest that archetypically the centre is the source, sustenance, and goal of Creation. The establishment of the Centre brings order to chaos, and together with the associated boundary demarcating Sacred from profane space, combats *anomie*.

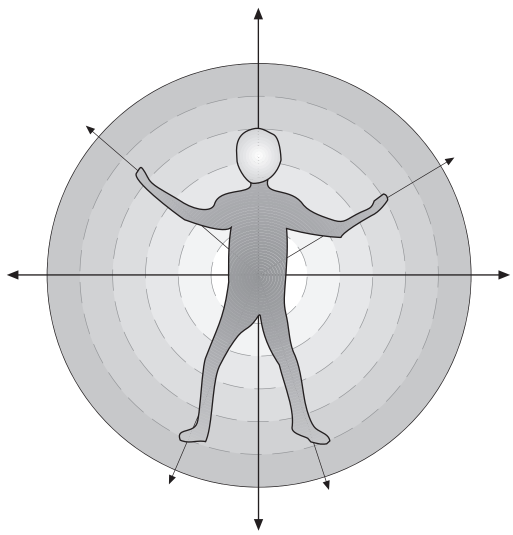

Figure 11: Centralised Man and Woman

Architecturally, these factors suggest that we no longer structure space as slabs of horizontal extension, with floors on which we walk, and vertical walls that confine and structure form. Instead we move from walking, standing and sitting *on* the two-dimensional plane, to freely floating *within* and through three-dimensional voids, as shown in Figs. 10 and 11. We exploit and revel in the freedom of orientation, movement and association that microgravity affords.

There are natural formal constraints to the regular articulation of centralised space. Archetypically, this articulation proceeds firstly radially into concentric spherical shells; and secondly circumferentially in accord with the symmetries of the Platonic polyhedra. Thirdly, the envisaged provision of *"more than enough space in Space"* permits harmonic structuring, so that in an iterative sense we have a centre of centres, and so forth. This accords with Traditional doctrine, where a Centre differentiates into a plurality of centres, each of which has the capacity to represent the Centre.

So I believe it important that we conceptualise habitable space in microgravity as being centralised and truly three-dimensional, and fully exploit the potential richness of architecture this permits.

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In microgravity, the absence of gravity has profound structural implications. Very large structures become feasible. Structural members, and objects, assemblages, and services, no longer have weight but only mass, and do not need to be carried, i.e. supported on horizontal surfaces. Concomitant with this is the freedom in many applications of not requiring rigid structures and structural members. Structure is needed to localise elements, and also to facilitate movement. But this localisation can be flexible; elements need merely be restrained, tethered in place - rather in the way in which tensegrity structures maintain struts in a soft oscillating equilibrium. There remains the need to dampen potentially destructive oscillation.

These factors suggest the appropriateness of establishing our constructional and fitting-out activities from beachheads in microgravity Space. Once these are established, large-scale space structures are built and deployed without needing to withstand the gravitational forces extant on Earth's surface, nor those considerable forces generated by being launched from there into Space.

In general these considerations favour the dematerialisation of structure, and the deployment of a tensile architecture. The structural efficiency and economies of tensile structures are well-known. Further economies obtain in the potential for prefabricated folded structures, which are constructed and delivered in a contracted state, and then deployed *in situ*.

Take for example a living room in microgravity, within a generally habitable environment. Why expend valuable energy providing a rigid floor to support occupants and furniture, and rigid walls and roof, when they are no longer needed? One inhabits instead soft three-dimensional voids, which are defined by enclosing tensile surfaces. Objects are restrained by ties both within the void and upon its various surfaces (including velcro-type fixing). On Earth, the paradigm of Architecture might well be the brick; in Space paradigms might well be the balloon, self-supporting geodesic climbers' tents (such as the highly-refined Bibler I-tent), or a living organ such as the lungs, or a living organism such as the jellyfish. The entire living assemblage is therefore quite flexible; "walls" need only maintain their approximate position, resist impact loadings, provide visual and acoustic privacy, insulation, and so forth. Tensile diaphragms are quite adequate for this. *The entire living unit can in principle be tensile*, providing only that adequate securing is available about the circumference to maintain tension. Preliminary proposals for individual tensile Space Habitations are shown in Figs. 12 and 13.

This suggests a large-scale general habitable environment throughout which the potential for tension securing of elements is provided. It could feasibly be of thirteen kilometre diameter, with individual tensile members of one kilometre length.

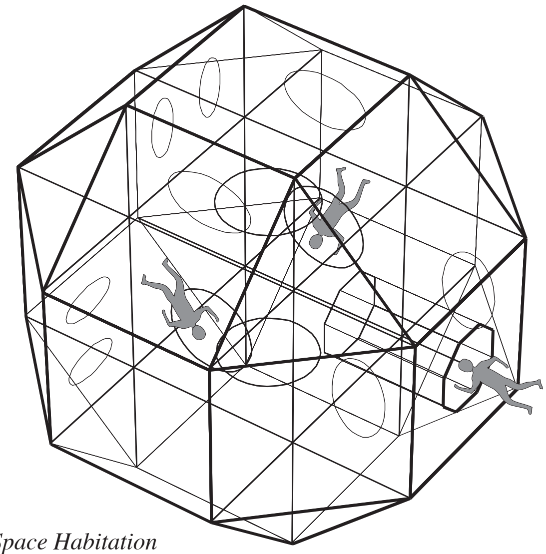


Figure 12: Individual Tensile Space Habitation based on Rhombicuboctahedron

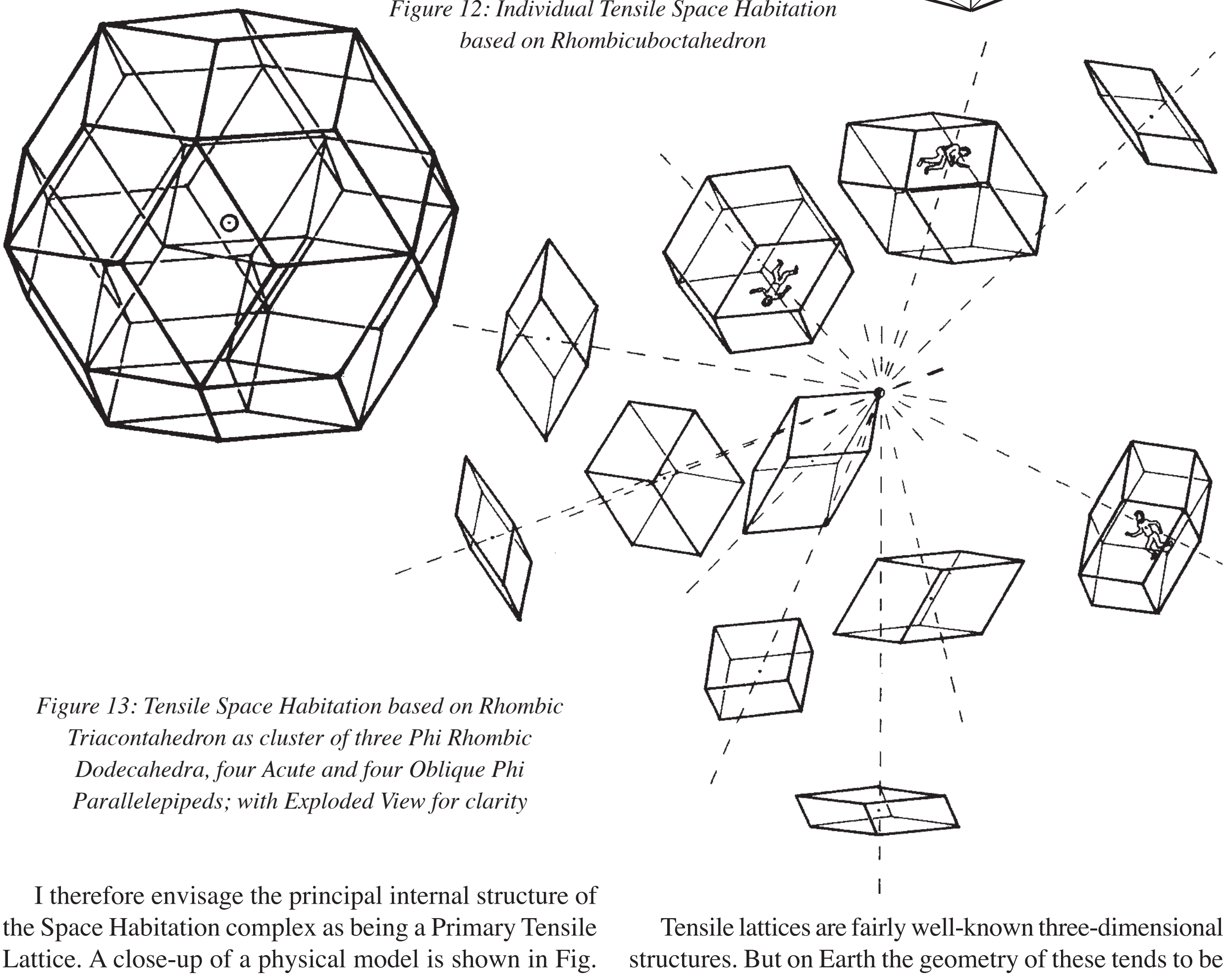


Figure 13: Tensile Space Habitation based on Rhombic Triacontahedron as cluster of three Phi Rhombic Dodecahedra, four Acute and four Oblique Phi Parallelepipeds; with Exploded View for clarity

I therefore envisage the principal internal structure of the Space Habitation complex as being a Primary Tensile Lattice. A close-up of a physical model is shown in Fig. 14. This is a highly efficient structure. Once provided, all points within the habitation complex can in principle be stressed circumferentially in tension and thus held in equilibrium. Secondary tensile assemblages are attached to particular nodes, chords, superficial and spatial arrays of the primary tensile lattice, as shown in close-up in Fig. 15. Tertiary assemblages can be attached to these in turn, and so forth.

It is therefore possible to structure the habitable environment, and provide necessary elements of attachment, restraint, privacy, space formation, etc.

Tensile lattices are fairly well-known three-dimensional structures. But on Earth the geometry of these tends to be either monoaxial centralised (the bicycle wheel), or what I term *decentralised* such as the cubic lattice. Decentralised geometries are characterised by a multitude of centres of symmetry, any one of which is in principle the equivalent (or the complement) of any other. The tetrahedral array of Fig. 16 - with ties from each centre to the respective vertices of component tetrahedra of a virtual octet truss - appears most efficient with a minimum of four ties to each internal node. However, this form is in principle of infinite extent, while actual man-made structures never are.

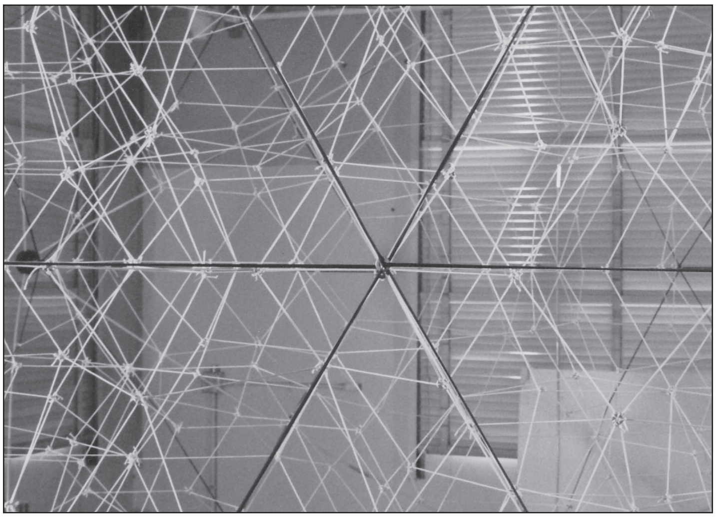


Figure 14 (Top and Right) :
Close-ups of Tensile Lattice showing ties

Figure 15 (Left and Bottom) :
Tensile Lattice Close-ups with Interior Pneumatic Enclosures

But in my doctoral research,[10] I discovered elegant *centralised* three-dimensional geometries. These are inherently finite, exhibiting natural tendencies to closure. I later realised that they are particularly appropriate to centralised tensile lattices, and that such structural forms are well-suited to microgravity applications. In contrast to a decentralised array, a centralised three-dimensional geometry has one unique Centre, and characteristically sub-centres form in rotationally symmetric fashion about that Centre. Regular geometries of this kind are inevitably governed by the polyaxial symmetries of the Platonic polyhedra. Elsewhere I advance a new and important ordering system for these fundamental symmetries.[11]

I develop these centralised geometries by means of zonahedral principles. Zonahedra are polyhedra, each of whose faces are zonagons, as shown in Fig. 17. A zonagon is a polygon with all sides occurring in opposite parallel pairs. So a square or a diamond is a basic zonagon; and a cube or a parallelepiped a basic zonahedron. Baer describes decentralised zonahedral clusters, and also refers to single-skin monoaxial centralised zonahedral domes.[12] I develop the latter in some depth in my doctorate, suggesting their elegant geometry may account for the form and surface decoration of the Islamic dome and *Iwan*. But I believe the centralised polyaxial zonahedral clusters that I have discovered - together with their structural application in microgravity as pneumatically stressed tensile lattices - to be an original discovery. The elegance of the geometry may be appreciated from Table 1.

These centralised polyaxial geometries are developed from seed radials of Platonic and Archimedean polyhedra. Seed radials develop into diamonds by a mating process between adjoining vectors. Sheaths of parallel equal-length members are generated, which form the edges of a centralised cluster of zonahedra. These centralised zonahedral expansions are quite beautiful to contemplate. The expansions culminate in a natural limit which is itself a multi-frequency zonahedron. The circumference of Fig. 18 shows various increments of the staged expansion, whilst the circumference of Fig. 19 shows the cumulative progression. The interiors of Figs. 18 & 19 show the geometry of the tensile lattice model of Figs. 20 & 22.

Tensile lattices require peripheral stressing. Archetypically this is provided in three-dimensions by spherical tensing, with a circumferential array of radial ties, as shown in Fig. 20. Intuitively, it is apparent that (finite) three-dimensional tensile matrices in microgravity will approximate an ideal spherical configuration in their structural integrity. That is, there will be differentiation of the forces radially into concentric spherical layers, and circumferentially in accord with the fundamental Platonic polyhedral polyaxial symmetries. I therefore suggest that centralised polyaxial zonahedral expansions are structurally a more appropriate geometry for tensile lattices than those based on decentralised arrays.

It then makes sense to tense the entire lattice by means of a pneumatic enclosure which is approximately spherical. Fig. 21 depicts a two-dimensional analog of this structural behaviour. The necessary breathable atmosphere functions structurally to maintain the tension of the pneumatic enclosure, which in turn stresses the primary tensile lattice. This in turn stresses secondary, tertiary, and subordinate lattices, and by these means loads

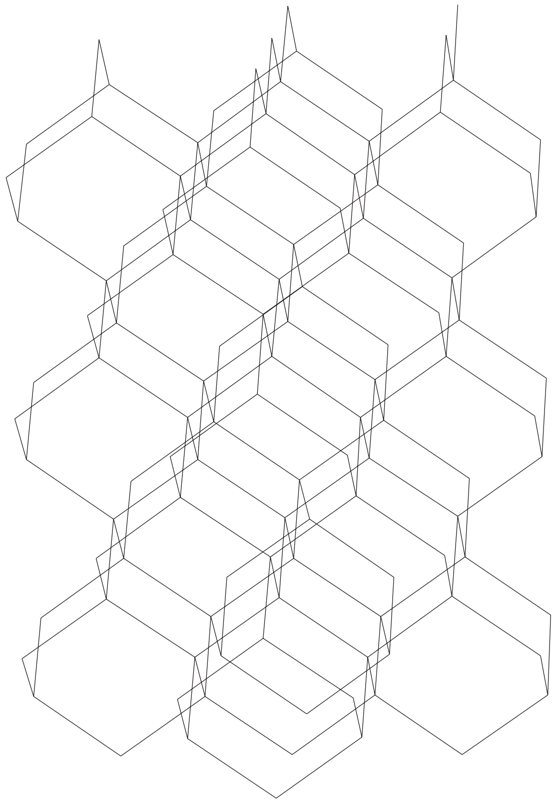
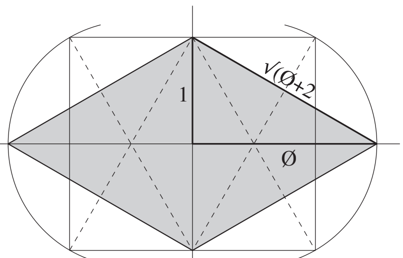
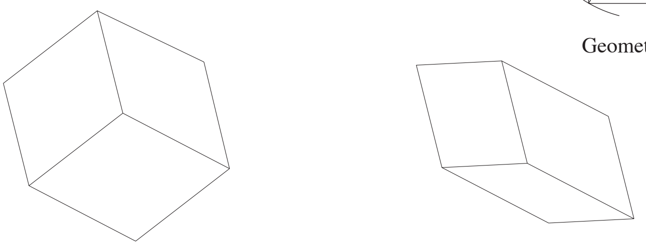


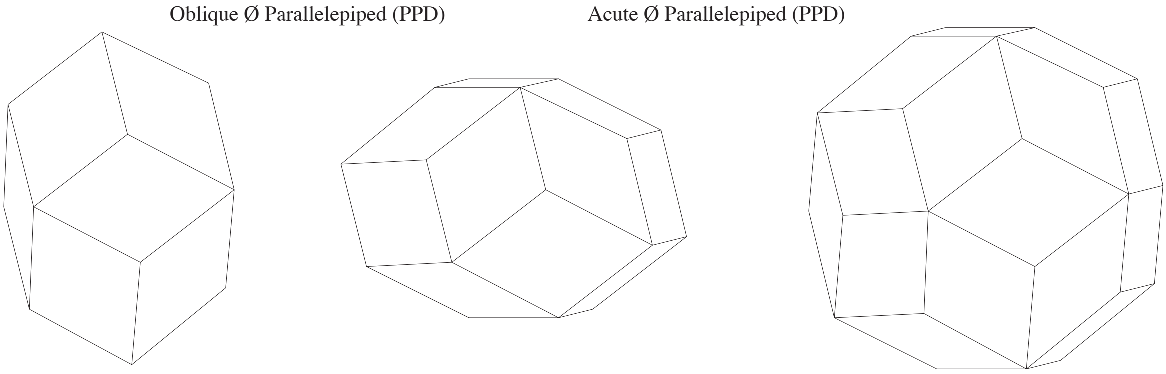
Figure 16: Decentralised Tetrahedral Tensile Lattice



Geometry of the Phi Diamond



Oblique Ø Parallelepiped (PPD) Acute Ø Parallelepiped (PPD)



Ø Rhombic Dodecahedron (RD) Short (5-zone) Rhombic Triacontahedron (RT) Regular (6-zone) Rhombic Triacontahedron (RT)

Figure 17: Geometry of the Phi Diamond (above right), and Zonahedral Elements of the Expansion

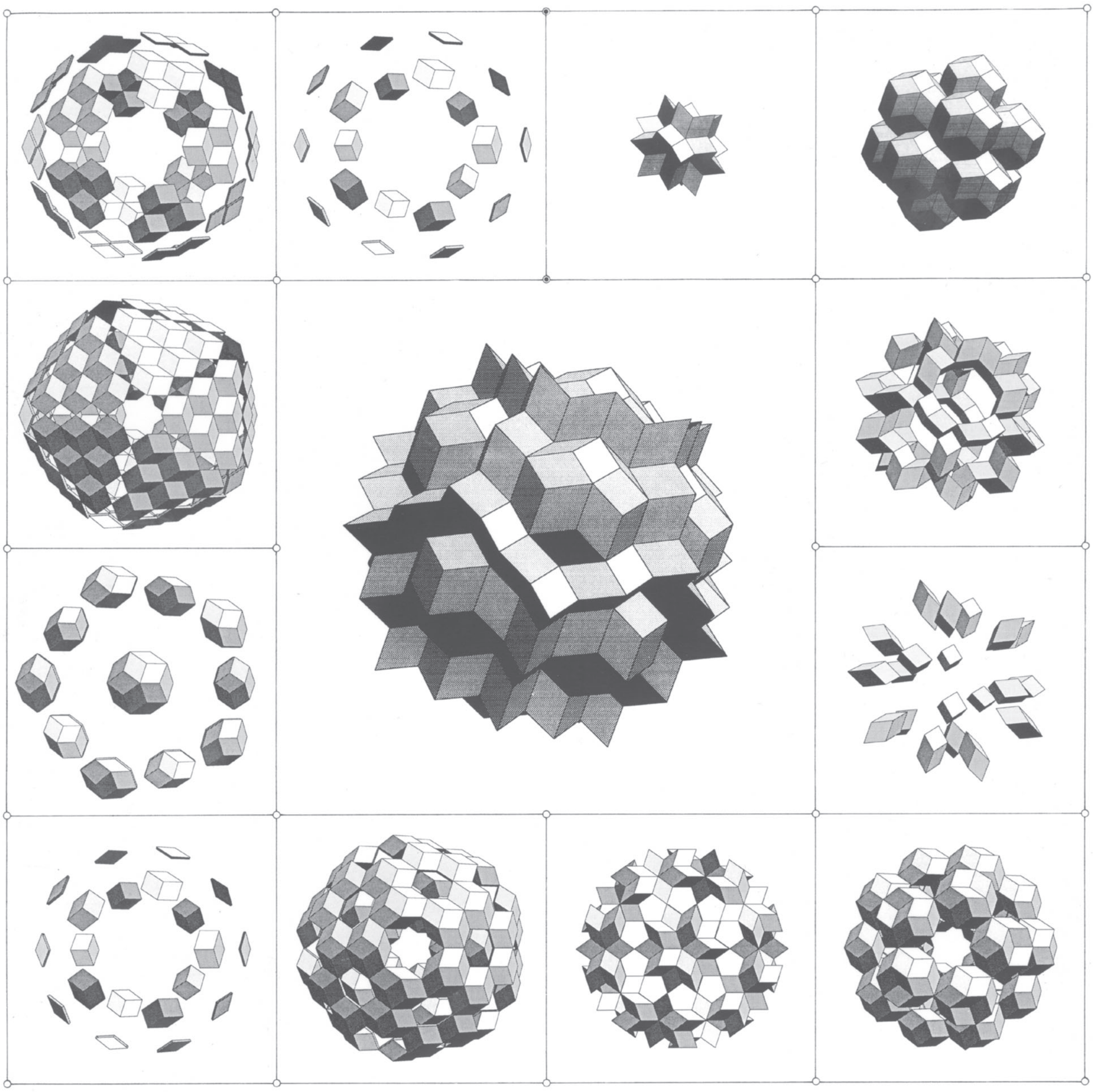


Figure 18: Zonahedral Mandala Expansion of the regular Icosahedron :
Circumference - Incremental Sequence of Stages (with change of orientation);
Interior - Solid Geometry of the Physical Model of Figs. 20 and 22, being Stage Four of the Expansion

within the structure are distributed and equilibrium maintained. Figs. 15 and 22 show secondary pneumatic enclosures within the icosahedral array of regular rhombic triacontahedral voids formed by the Primary Tensile Lattice of Figs. 14 and 20.

As the natural limit of expansion of the primary tensile lattice is itself a zonahedron, this suggests that the pneumatic enclosure may not be a pure sphere, but could be a compound closed surface which is articulated with the corresponding zonahedral (and thus Platonic polyhedral) polyaxial symmetries. It may for example be composed of component portions of spheric surfaces, which meet in circular arcs and points.

I illustrate in Fig. 23 an icosahedral array of interpenetrating spheres tangential to and coincident at the Centre, which form is the spherical inversion of the dodecahedral array of planes extending to infinity. Elsewhere, R. Buckminster Fuller illustrates a spherical rhombic triacontahedron, which exploits the economic fabrication of strip fabric into curved diamonds.

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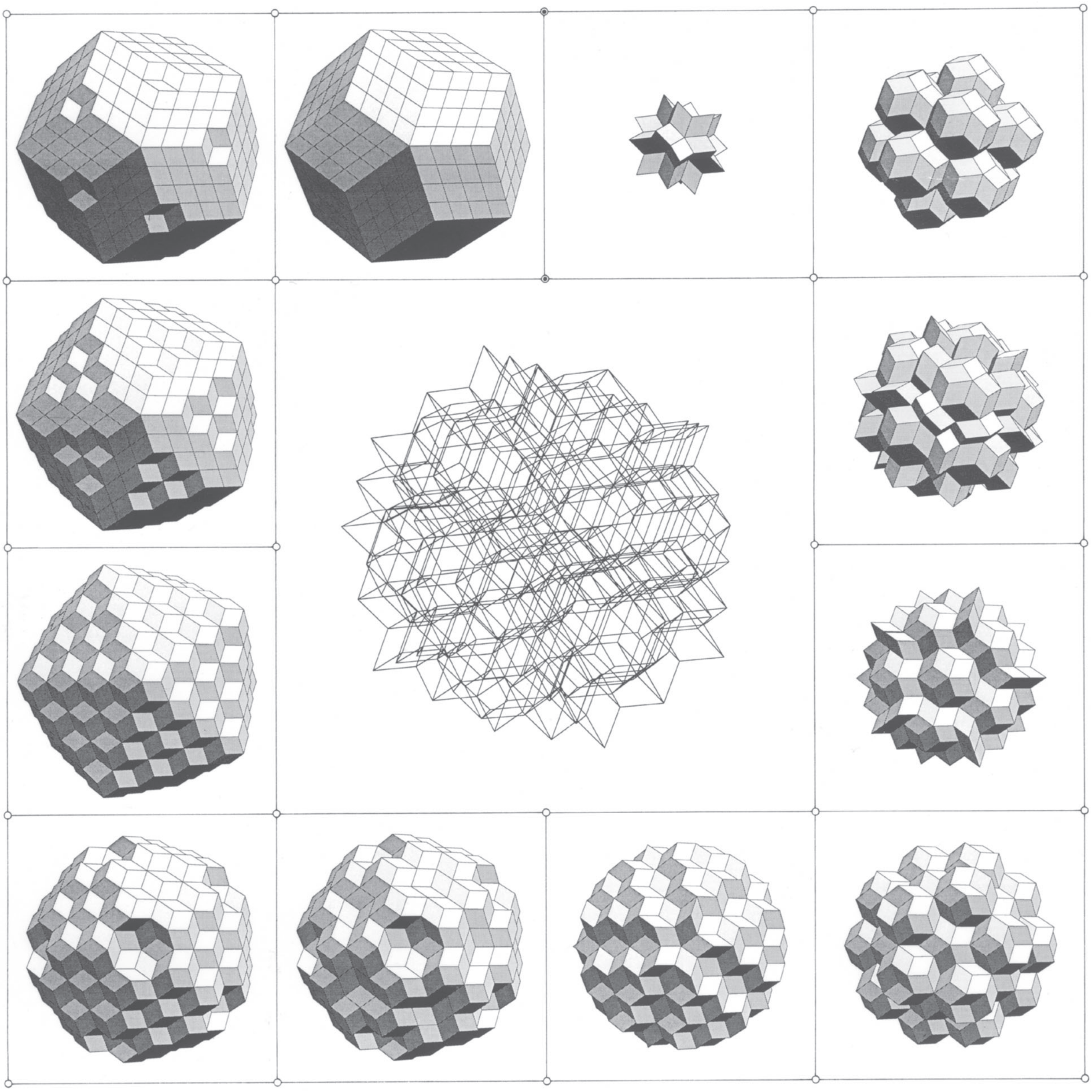

Figure 19: Zonahedral Mandala Expansion of the regular Icosahedron :
Circumference - Cumulative Sequence of Stages (with change of orientation);
Interior - Spatial Geometry of the Physical Model of Figs. 20 and 22, being Stage Four of the Expansion

I therefore propose large-scale pneumatically stressed centralised zonahedral tensile lattices for Space Habitation complexes in microgravity. The schematic proposal of Fig. 24 gives an indication of the integration of structure, form and meaning that is sought. The geometry of the primary tensile lattice of the structure is given by the centralised zonahedral expansions. As component zonahedra are produced, any of these may itself be articulated into a secondary centralised tensile lattice, and this process can be repeated at smaller and smaller levels. Conversely, the entire tensile lattice, itself a zonahedron, may be reconfigured as just one component of a more embracing centralised zonahedral complex.

I have chosen not to consider at this stage external openings for access and egress, or for natural light and external view. These are likely to be small-scale in relation to the mega-structure. Similarly I have not dealt with servicing, nor the necessary external skin, which must of course withstand pressure differential, thermodynamic stress, micrometeorite penetration and docking impact, and provide insulation and radiation protection, as well as perform structurally to tense the primary tensile lattice. But it could in principle be designed as a stressed skin pneumatic enclosure.

I would welcome opportunities for sponsored research to develop these proposals.

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ZONAHEDRA Edge Length √(Ø+2)	Axial Diam. / Transverse	Dihedral A. (2π = 1)	Solid Angles (4π = 1)	Sum Solid A.	Surface Area	Volume
ACUTE PHI PARALLELEPIPED	√3Ø^2 √(Ø+6)	4/20, 6/20	1/20 3/20	1	12Ø	2Ø^2
OBLIQUE PHI PARALLELEPIPED	√3/Ø √(5Ø+6)	8/20, 2/20	7/20 1/20	1	12Ø	2Ø
REGULAR RHOMBIC TRIACONTAHEDRON	2Ø√(Ø+2) 2√3Ø	8/20	5/20 7/20	10	60Ø	20Ø^3
SHORT RHOMBIC TRIACONTAHEDRON	√5√(Ø+2) Ø√(3Ø+7)	8/20, 6/20	5/20, 4/20, 7/20	6	40Ø	10Ø^3
PHI RHOMBIC DODECAHEDRON	2Ø^2 2√(Ø+2)	4/20, 8/20, 6/20	2/20, 3/20, 4/20, 7/20	3	24Ø	4Ø^3

VOLUMETRIC RATIOS	ACUTE PPD.	OBLIQUE PHI PPD.	REGULAR R.T.	SHORT R.T.	PHI R.D.
ACUTE PHI PPD.	1 : 1	1 : Ø	10Ø : 1	5Ø : 1	2Ø : 1
OBLIQUE PHI PPD.	Ø : 1	1 : 1	10Ø^2 : 1	5Ø^2 : 1	2Ø^2 : 1
REGULAR R.T.	1 : 10Ø	1 : 10Ø^2	1 : 1	1 : 2	1 : 5
SHORT R.T.	1 : 5Ø	1 : 5Ø^2	2 : 1	1 : 1	2 : 5
PHI R.D.	1 : 2Ø	1 : 2Ø^2	5 : 1	5 : 2	1 : 1

VOLUMETRIC CORRESPONDENCES	many of these accord with actual decompositions
1 REGULAR R.T. (RHOMBIC TRIACONTAHEDRON)	= 10 OBLIQUE Ø PPDs + 10 ACUTE Ø PPDs = 8 OBLIQUE Ø PPDs + 8 ACUTE Ø PPDs + 1 Ø R.D. = 6 OBLIQUE Ø PPDs + 6 ACUTE Ø PPDs + 2 Ø R.D.s = 4 OBLIQUE Ø PPDs + 4 ACUTE Ø PPDs + 3 Ø R.D.s = 2 OBLIQUE Ø PPDs + 2 ACUTE Ø PPDs + 4 Ø R.D.s = 5Ø R.D.s = 5 OBLIQUE Ø PPDs + 5 ACUTE Ø PPDs + 1 SHORT R.T. = 3 OBLIQUE Ø PPDs + 3 ACUTE Ø PPDs + 1 Ø R.D. + 1 SHORT R.T. = 1 OBLIQUE Ø PPDs + 1 ACUTE Ø PPDs + 2 Ø R.D.s + 1 SHORT R.T. = 2 SHORT R.T.s
1 SHORT R.T.	= 5 OBLIQUE Ø PPDs + 5 ACUTE Ø PPDs = 3 OBLIQUE Ø PPDs + 3 ACUTE Ø PPDs + 1 Ø R.D. = 1 OBLIQUE Ø PPD + 1 ACUTE Ø PPD + 2 Ø R.D.s
1 Ø R.D.	= 2 OBLIQUE Ø PPDs + 2 ACUTE Ø PPDs

Table 1: Properties of the Geometrical Elements, with Golden Section ***Ø*** *= $^{(\sqrt{5}+1)}/_{2}$ = 1.618...*

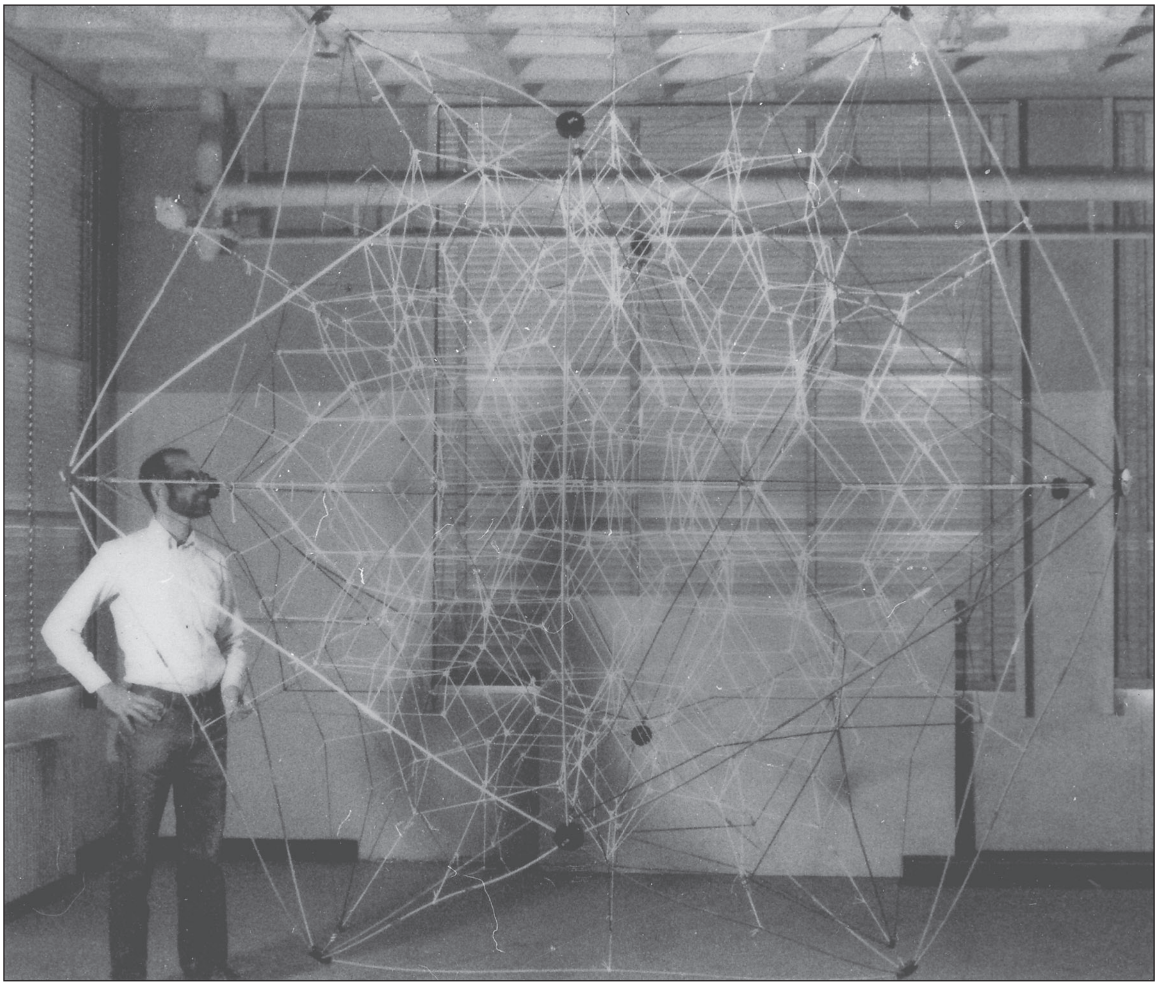

Figure 20: Structural Model of Centralised Tensile Lattice - all ties are of equal length and lie in parallel bundles

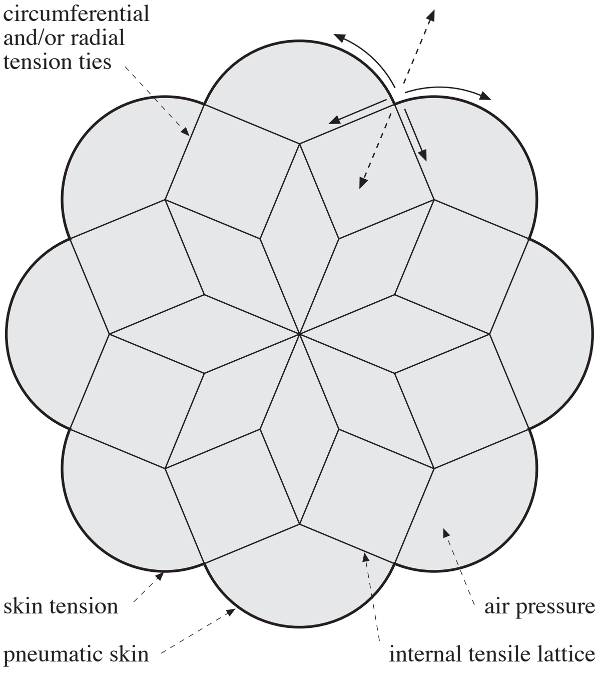

Figure 21: Structural Principle of Centralised Tensile Lattice structured Pneumatic Enclosures

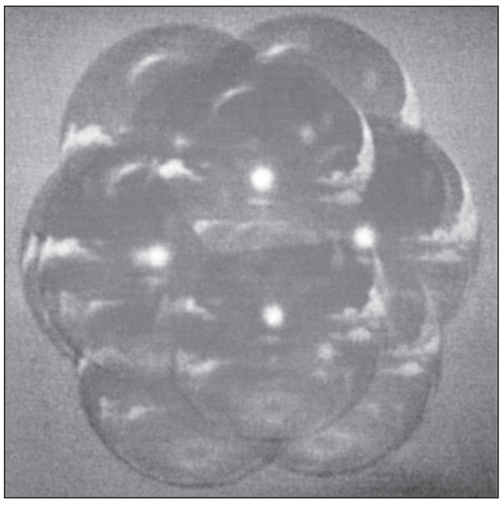

Figure 23: Icosahedral Array of Interpenetrating Spheres tangential to and coincident at the Centre (courtesy Simon Ferneyhough)

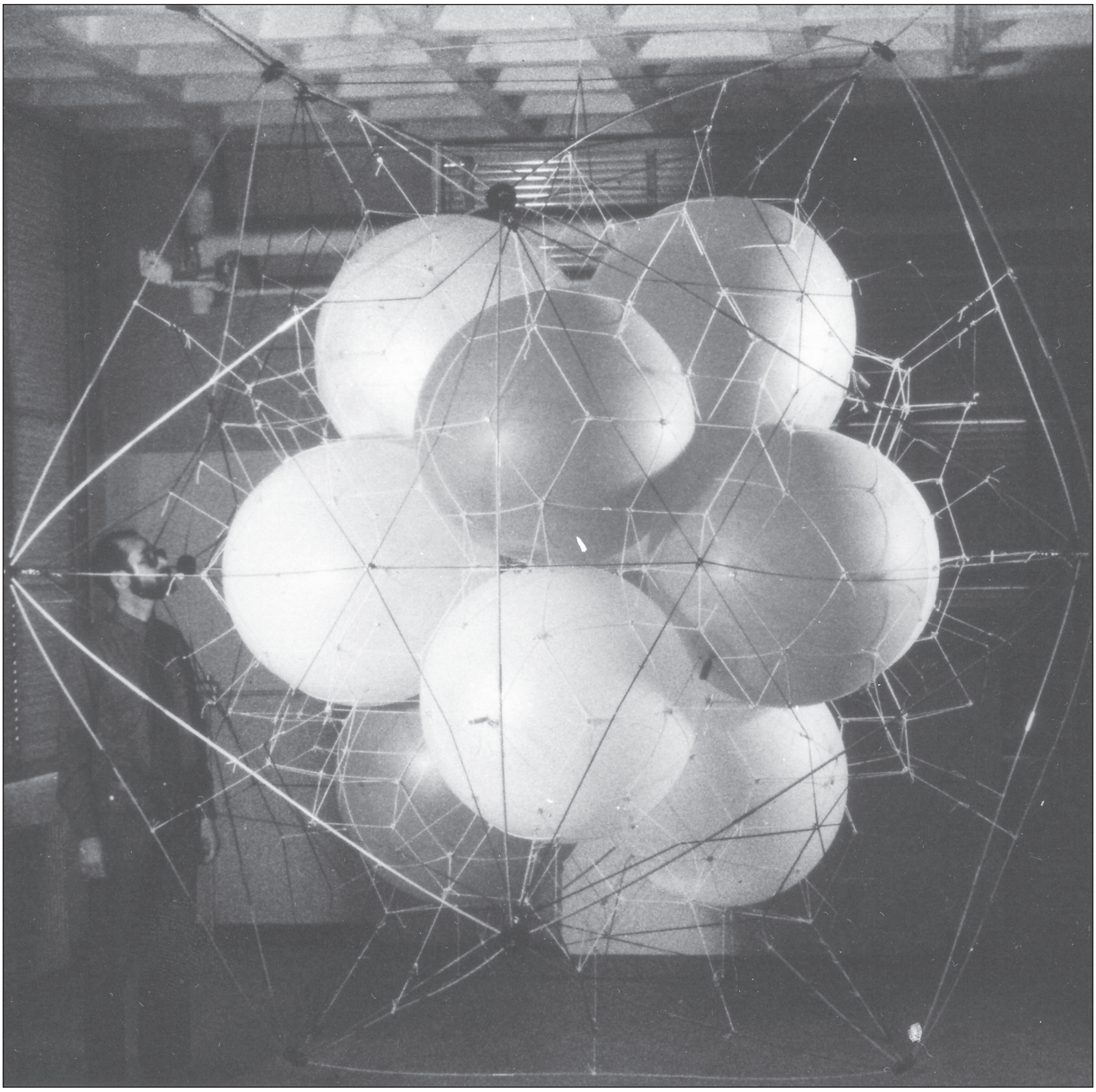

Figure 22: Structural Model of Icosahedral Array of Twelve Pneumatic Enclosures inside Centralised Tensile Lattice - each pneumatic enclosure occupies a regular rhombic triacontahedral void created by the expansion; secondary tensile lattices could be developed in each of these

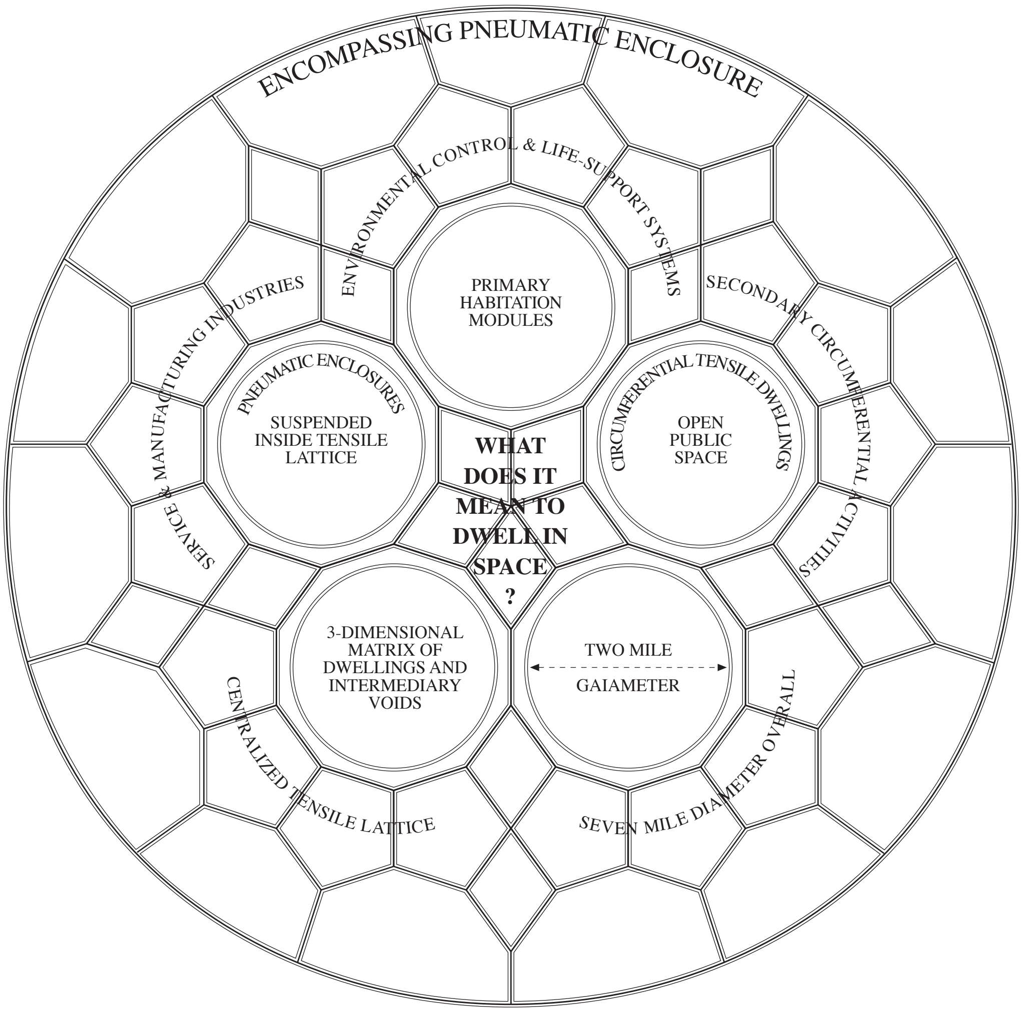

Figure 24: Schematic of the Integral Space Habitation

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