793.00 **Tree Structures**

793.01 Among nature's most efficient—and therefore most beautiful—designs are the structuring of the great trees. To examine the structural effectiveness of trees we can make an experiment. Take two suitcases, each weighing 50 pounds, one in each hand. Try to hold them out horizontally at arm's length. It is easy for our arms to hang them vertically from our shoulders, but the more horizontally they are held, the more difficult. It is almost impossible to hold out 50 pounds horizontally. Yet look at a tree's shoulders where the branches are attached. Look at the branch of a tree with the same girth as that of your shoulder when your arm is extended and flexed. Such a tree branch may weigh 500 pounds—ten times what you can hold out horizontally. Many larger-shouldered tree branches weighing five tons and more are held out horizontally. "Wing root" is an aeronautical engineering term for shoulder—that is, where the plane's airframe fuselage joins the jet-pod-carrying aluminum wing. These air transport wing roots accomplish great load-bearing tasks with very low weight ratios. The way trees hold out five-ton branches while yielding in streamline and flexing gracefully without breaking in great winds is a design accomplishment unparalleled in aeronautical engineering—even in the wing roots of jumbo jets and supersonic fighters. How can a tree do that? Biological structures cope hydraulically with all compressional loadings.

793.02 The paramount function of trees is to expose as much leafage as possible under varying wind conditions in order to impound Sun radiation. By a complex of relationships with other biologicals, this impoundment supports life on our planet, since few mammals can directly convert Sun energy into life support. Since the function of trees requires maximum leafage exposure, their progeny will prosper best when planted outside the shadow of the parent. Each tree seed is a beautiful flying machine designed to ride the wind until reaching propitious soil. Because few seeds will find propitious sites in this random distribution, the tree launches many thousands of seeds. The seeds contain the geometric design instructions for associating the locally available resources of air and water and the atomic chemistries of the locally available soil and rock in the environs of seed-landing.

793.03 Seeds contain coded programs for associating local atoms in triple-bonded crystal structures. Triple-bonded structures have high tensile capabilities, and when further interbonded they produce long, overlapping, fibrous sacs to be filled with local water and air derivatives. These closepacked, liquid-filled fibrous sacs compound first to produce the "wood" of the tree's roots and trunk. What nature ships in the seeds are the DNA-RNA coded instructions on how to utilize the resources of the locally occurring water, gases, and chemical elements at the planting site. The high-tensile fiber sacs are filled with liquid sap developed from water brought in from the roots by osmosis. By one-way capillary valving the hydrogen and oxygen of the water combine with the carbon- and oxygen-laden gases of the atmosphere to produce the hydrocarbon crystal cells of the tree while at the same time giving off to the atmosphere oxygen atoms with which the growth of mammals will be respiratorially sustained.

793.04 Enormous amounts of water are continuously being elevated through the one-way, antigravity valving system. The tree feeds the rain-forming atmosphere by leaking atomized water out through its leaves while at the same time sucking in fresh water through its roots. The tree's high-tensile fiber cell sacs are everywhere full of liquid. Liquids are noncompressible; they distribute their local stress loadings evenly in all directions to all the fiber cell sacs. The hydraulic compression function firmly fills out the predesigned overall high-tensile fiber shaping of the tree. In between the liquid molecules nature inserts tiny gaseous molecules that are highly compressible and absorb the tree's high-shock loadings, such as from the gusts of hurricanes. The branches can wave wildly, but they rarely break off unless they are dehydratively dying—which means they are losing the integrity of their hydraulic, noncompressible load-distribution system. Sometimes in an ice storm the tree freezes so that the liquids cannot distribute their loads; then the branches break off and fall to the ground.

793.05 In trees the liquids distribute the loads and the gases absorb the shocks in an overall high-tension crystalline fiber network predesigned by the DNA-RNA programming. The system transmits its hydraulic load-distribution impulses through each liquid-filled cell's contacts with adjacent liquid-loaded sacs. Starting with one tetrahedral bud "shoot," the tree grows as a series of concentric tetrahedral cones. Revolved tetrahedra generate cones. The constant reorienting of the direction from which the Sun radiation is coming, the frequent shift in the wind direction, and the consequent drag forces on the tetra-tree produce a conic revolution effect on the tree growth. Each year a new cambium layer cone grows over the entire outside of the previous year's tetra-cone. Each branch of the tree also starts as a tetrahedral shoulder cone sprouting out of the main tree cone.

793.06 This high-tension sac's web design with its hydraulic compression coping and pneumatic shock absorbing is much the same structural system nature employs in the design of human beings. To be sure, with humans the liquid does not freeze under normal environmental conditions; nature creates a good-health temperature control of 98.6 degrees F. for all its humans. Instead of the larger tetra cone form, over which the tree builds from the roots outward into its successive live layers, nature introduced in the mobile mammals the skeleton around which all their hydraulically actuated muscles and cushioning cells are grown in crystalline patterns as scheduled by the DNA-RNA program and as thereafter automated by genetic coding.

793.07 When humans tried to make solid crystalline machinery and ship it from here to there over the ground, the objects could move only very slowly without being shattered. So pneumatic tires were put on the wheels so as to distribute the working loads throughout all the freely moving compressional molecules, which in turn distribute the workload energies over the whole uniformly tensioned surface of the high-tensile tire casing. The aeronautical engineers finally adopted nature's biological structuring strategies to cope with 150 tons of fully loaded jumbo jets coming out of the sky to land at 150 miles per hour—with the music going and the people putting on their coats, paying no attention to the extraordinary engineering accomplishment. The plane's tires are pneumatic. Rubber makes the first contact. Pneumatics take the shock load. Next the hydraulic struts distribute the shock loading evenly through metered orifices, and all the shock load energy is thereafter distributed as heat through the high conductivity aluminum walls of the hydraulic system. The heat is completely dispersed by the metal surfaces. Only in the landing gear of great airplanes have humans employed nature's really beautiful structuring of crystalline tension in complement with hydraulic compression and pneumatic elasticity for shock absorption.

794.00 **Geodesic Domes**

794.01 The great structural systems of Universe are accomplished by islanded compression and omnicontinuous tension. *Tensegrity* is a contraction of *tensional integrity* structuring. All geodesic domes are tensegrity structures, whether the tension- islanded compression differentiations are visible to the observer or not. Tensegrity geodesic spheres do what they do because they have the properties of hydraulically or pneumatically inflated structures.

794.02 Pneumatic structures—such as footballs—provide a firm shape when inflated because the kinetically accelerated atmospheric molecules are trying to escape and are impinging outwardly against the skin, stretching outwardly into whatever accommodating roundness has been designed into the omniembracing tension system. (Compare Sec. 760.) When more molecules are introduced into the enclosure by an air pump, their overcrowding increases the pressure. A fleet of ships maneuvering under power needs more sea room than does another fleet of ships moored side by side. The higher the speed of the individual ship, the greater the minimum turning radius and the more sea room required. This means that the enclosed and pressurized molecules in pneumatic structural systems are accelerated in outward-bound paths by the addition of more molecules by the pump; without additional room each must move faster to get out of the way of the others.

794.03 Pressurized liquid or gaseous molecules try to escape from their confining enclosure. When a football is kicked on one outside spot the outward-bound molecules impact evenly on the entire inside surface of the football's flexible skin. The many outward-bound impactings force the skin outwardly and firmly in all directions; the faster the molecules move, the more powerful their impact, and the harder and more resilient the football. The effect is dynamic; there is no firm or static condition. The outward forces are met by the compressive embracement of the tensile envelope enclosure.

794.04 Geodesic domes are designed as enclosing tensile structures to meet discretely—ergo, nonredundantly—the patterns of outwardly impinging forces. A fishing net's mesh need be no finer than that through which the smallest fish worth catching cannot pass. If we know exactly the size of the fish we wish to catch, and how many of them are going to hit the net, exactly where, at what force, at what angle, and when, we then have a model for the realistic engineering analysis of geodesic domes.

794.05 The conventional engineering profession has been analyzing geodesics strictly in terms of compression, on a crystalline, non-load-distributing, "post and lintel" basis. For this reason the big geodesic domes erected so far have been many times overbuilt, way beyond the appropriate safety factor of 2 :1 as adopted by aeronautical science. The building business uses safety factors of 5 or 6:1. The greater the ignorance of the art, the greater the safety factor demanded by probability mathematics. The greater the safety factor, the greater the redundance and the less the freedom of load distribution.

794.06 We have a mathematical phenomenon known as a geodesic. A geodesic is the most economical relationship between any two events. A special case geodesic finds that a seemingly straight line is the shortest distance between two points in a plane. Geodesic lines are the shortest surface distances between two points on the outside of a sphere. Spherical great circles are geodesics.

794.07 A great circle is a line formed on the surface of a sphere by a plane passing through the sphere's center. The Earth's equator is a great-circle geodesic; so too are the Earth's meridians of longitude. Any two great circles of the same system must cross each other twice in a symmetrical manner, with their crossings always 180 degrees apart.

794.08 Each of any three great circles of a sphere not having common polar crossings must cross each of the others twice. This makes for a total of four crossings for each of the three great circles and a total of six crossings for the whole set of three great circles; the whole set of three great circles entirely divides the entire sphere into four hemispherically opposed pairs of similar spherical triangles, and—in one special case—into the eight similar spherical triangles of the regular spherical octahedron. All cases are thus omnitriangular spherical octahedra, regular or irregular.

794.09 Because both ends of spherical chords always impinge on their sphere at identical angles, molecules of gas reactively accelerate chordally away from one another in a spherical enclosure, trying to proceed in straight-line trajectories. The molecules must follow the *shortest-distance,* geodesic great-circle law, and the angular reflectance law; they will carom around the inside of the sphere or football or balloon only in circular paths describing the greatest diameter possible, therefore always in the planes of great circles except as deflected by other forces.

794.10 When two force vectors operating in great-circle paths inside a sphere impinge on each other at any happenstance angle, that angle has no amplitude stability. But when a third force vector operating in a third greatcircle path crosses the other two spherical great circles, eight great-circle-edged triangles are formed with their four sets of two inherent, opposite-hemisphered, mirror-image triangles.

794.11 With successive inside-surface caromings and angular intervector impingements, the dynamic symmetry imposed by a sphere tends averagingly to equalize the angular interrelationships of all the millions of triangle-forming sets of those three great circles. The intershunting triangulation in greatcircle paths automatically tends averagingly to produce a spherically closed system of omnisimilar triangles. This means that if there were only three great circles, they would tend swiftly to interstabilize comprehensively as the spherical octahedron, all of whose surface angles and arcs average as 90 degrees.

794.12 If we successively shoot at the same high velocity three steel ball bearings of the same size and weight into a smoothly walled, spherical steel container, and if we do that shooting through a carefully timed pop-open-and-pop-closed hole, and if we aim the ball bearing gun as far away from the sphere center as the pop-open hole permitted, each of the three balls would start describing a great-circle path of bouncings off the sphere. Each would have to cross the other four times and would carom off each other as well, swiftly to work toward the spherical octahedron.

794.13 Because each of the three gas molecules must have its reactor molecule, we will always have six initial great circles operative in the pressurized pneumatic containers; all the additional molecules will be six-teamed, and each team of six will increase the system frequency by one, and all the teams will averagingly parallel one another.

794.14 The great-circle chords of all polyhedra are always found to be systematically developed out of sets of exactly six great-circle chords—never more or less. These six vectors are the six vectors of the energy quantum. The 12 vector-edged chords of the octahedron equal the two sets of six chord vectors: two quanta. The 30 vector- edged chords of the icosahedron equal the five sets of six chord vectors: five quanta. In the tetrahedron one quantum of structurally invested energy encloses one unit of volume. In the octahedron one quantum of structurally invested energy encloses two units of volume. In the icosahedron one quantum of energy invested in structure encloses almost four units of volume. Of the three prime structural systems of Universe, the tetrahedron is the strongest per unit of volume enclosed; the octahedron is "middling"; and the icosahedron is least strong, but encloses the greatest volume per unit of invested energy. Whenever nature uses the icosahedron, the maximum volume enclosure per units of invested energy is the principal function served. For this reason all pneumatic and hydraulic structuring of nature employs icosahedral spherical geometry. When maximum structural strength per unit of invested energy is the principal function served, nature uses the tetrahedron. When the principal function to be served is a balance of strength and volume, nature uses the octahedron as her preferred structural system.

794.15 A vast number of molecules of gas interacting in great circles inside of a sphere will produce a number of great-circle triangles. The triangles, being dynamically resilient, mutually intertransform one another to evolve an "averaging" of the random- force vectors, resulting in angular self-interstabilizing as a pattern of omnispherical symmetry. The aggregate of all the inter-great-circlings resolves typically into a regular pattern of 12 pentagons and 20 triangles, or sometimes more complexly into 12 pentagons, 30 hexagons, and 80 triangles described by 240 great-circle chords.

794.16 This is the pattern of the geodesic tensegrity sphere. The numbers of hexagons and triangles and chords may be multiplied in regular arithmetical or geometrical series, but the 12—and only 12—pentagons will persist as constants, as will the number of triangles occur in multiples of 20, and the number of edges in multiples of 6.

794.17 In the geodesic tensegrity sphere each of the entirely independent, compressional-chord struts represents two oppositely directioned and force paired molecules. The paired-outward caroming of the two chord ends produces a single radially outward force of each chord strut. The tensegrity compressional chords do not touch one another: they operate independently, each trying to escape outwardly from the sphere, but they are restrained by the spherical tensional integrity's closed-network system of great- circle connectors, which alone can complete the great-circle paths between the ends of the entirely separate, non-directly-interconnecting, compressional chords. Were the chordal struts to be pushing circumferentially from the sphere, their ends would touch one another or slide by one another, but the tension lines show clearly that the struts each pull away from their nearest neighbor and strain to escape radially outward of the system.

794.18 Central angles of great circles are defined by two radii, the outer ends of which are connected by both an arc and a chord—which arc and chord are directly proportional to each unique such central angle. The chord and two radii form an isosceles triangle. The distance between the mid-arc and the mid-chord is called the *arc altitude.* Every point on a great-circle arc is at full-radius distance from the sphere's center. In developing the triangular subgridding of the icosahedral geodesic prime structural system, the greatcircle arc edges of the icosahedron (each of which has a central angle of 63 degrees, 26 minutes, and several seconds) are equally subdivided into two, three, or four equal-arc increments—or as many more equal-arc increments as the engineering calculation finds desirable in consideration of all the optional variables, such as the diameter of the structure, the structural properties of the materials with which it is to be produced, and the logistics of delivery, installation, and assembly.

794.19 **Frequency:** Whatever the number of the equal subdivisions of the icosa arc—whose subdivision points are to be interconnected with a threeway omnitriangulated grid of great-circle arcs—that icosa arc edge subdivision number is spoken of as the *frequency,* of the system. The higher the frequency of the system, the lesser in dimension will each of the arc, chord, and arc-altitude increments become. All these dimensions covary at identical rates and are therefore uniformly proportional for any given frequency. Uniform dimensions, chord factors, and ratios may be listed for any size dome; the only numerical variable in geodesic spheroidal structures is that of the system's radius.

794.20 Because each islanded compression strut in a tensegrity sphere addresses its adjacent (but untouched) struts at an angle of approximately 60 degrees, that strut is aimed at but does not reach the midpoints of the adjacent struts. Each of the struts is a chord of the sphere, with its ends at greater distance from the center of the sphere than the radial distance of the midpoint of the chordal strut-that difference in distance being exactly that of the arc altitude. The arc altitude decreases as the system frequency is increased, which occurs logically as the system radius increases.

794.21 The mid-girth of each chordal compression strut is proportional to its length and is always substantial. The strut is most efficient when cigar-shaped and pin-ended. As the frequency increases and the arc altitude decreases, there develops a special size geodesic sphere, wherein—employing the most economical material for the struts—the mid-girth of the chordal strut is exactly the same as the arc altitude, at which point the pin- ends of the struts approaching at 60 degrees may exactly touch the mid-girths of the impinged-upon struts. But this kind of touching does not mean pushing against, because the struts (as their tension slings show) are trying to escape radially outward from the dome center. What this touching does is to dampen the vibratory resonance of the tensegrity sphere.

794.22 One of the impressive behavioral characteristics of tensegrity spheres, witnessed at low frequencies, is that when any two islanded struts 180 degrees apart around the sphere are pulled outwardly from one another, the whole sphere expands symmetrically. When the same two 180-degrees-apart struts are pushed toward one another, the whole sphere contracts symmetrically. When the polar pulling apart or pushing together ceases, the tensegrity sphere assumes a radius halfway between the radii of the most pullingly expandable and pushingly contractable conditions; that is, it will rest in dynamic equilibrium.

794.23 When the tension-member lengths between the islanded struts are everywhere the same, the twanging of any of them sounds the same vibration note as any and all the others. Tightening any one tension member or increasing the length of any one strut tightens the whole system uniformly, as is tunably demonstrable. The equilibrium state, which tensegrity spheres spontaneously assume, is the state wherein all the parts are most comfortable but are always subject to spherical oscillatability. Thus the coming into contact of the pin-end cigar struts with the neighboring struts' mid-girth points provides a condition at which—if the pin-point is locked to the mid-strut—it will be prevented from leaving its most energetically efficient state of repose, and the locking together will prevent either the expansion or contraction of the sphere and will mute its resonance and deaden its springiness.

794.24 At the low-frequency, push-pull, contraction-expansion susceptible state, tensegrity spheres act like basketballs. Bouncing them against the floor makes them contract locally, after which they spring back powerfully to their original shape, which impels them back against gravity. Geodesic spheres are in strict physical fact true pneumatic structures with a discrete number of oppositely paired molecules—and their respective atomic colonies—all averagingly aggregated together in the form of the islanded struts instead of being in their invisible gaseous state.

795.00 **Reduction to Practice**

795.01 We can take advantage of the fact that lumber cut at the "two-by-four" size represents the lumber industry's most frequently used and lowest-cost structural lumber. The average length of the two-by-fours is 12 feet. We can take the approximately two- inch dimension as the mid-girth size of a strut, and we can use an average of 10-foot lengths of the tensilely strongest two-by-four wood worked by the trade (and pay the premium to have it selected and free of knotholes). We can then calculate what size of the spherical dome—and what frequency—will produce the condition of "just-kissing" contact of the two-by-four ends of the islanded two-by-four chordal struts with the mid-girth contact points of one another. This calculates out to a 12-frequency, 72-foot-diameter sphere that, if truncated as a three-quarter sphere, has 20 hexagonal openings around its base, each high enough and wide enough to allow the passage of a closed body truck.

795.02 We calculated and produced such a 72-foot, three-quarter-sphere geodesic dome at the Edwardsville campus of Southern Illinois University in 1962. The static load testing of all the parts as well as the final assembly found it performing exactly as described in the above paragraphs. The static load testing demonstrated performance on the basis of the load-distributing capabilities of pneumatics and hydraulics and exceeded those that would have been predicted solely on the basis of continuous compression.

795.03 As the world's high-performance metallic technologies are freed from concentration on armaments, their structural and mechanical and chemical performances (together with the electrodynamic remote control of systems in general) will permit dimensional exquisiteness of mass-production-forming tolerances to be reduced to an accuracy of one-hundredth-thousandths of an inch. This fine tolerance will permit the use of hydraulically pressure-filled glands of high-tensile metallic tubing using liquids that are nonfreezable at space-program temperature ranges, to act when pressurized as the discontinuously isolated compressional struts of large geodesic tensegrity spheres. Since the fitting tolerances will be less than the size of the liquid molecules, there will be no leakage. This will obviate the collapsibility of the air-lock-and-pressure-maintained pneumatic domes that require continuous pump-pressurizing to avoid being drag-rotated to flatten like a candle flame in a hurricane. Hydro-compressed tensegrities are less vulnerable as liquids are noncompressible.

795.04 Geodesic tensegrity spheres may be produced at enormous *city-enclosing* diameters. They may be assembled by helicopters with great economy. This will reduce the investment of metals in large tensegrity structures to a small fraction of the metals invested in geodesic structures of the past. It will be possible to produce geodesic domes of enormous diameters to cover whole communities with a relatively minor investment of structural materials. With the combined capabilities of mass production and aerospace technology it becomes feasible to turn out whole rolls of noncorrosive, flexible-cable networks with high-tensile, interswaged fittings to be manufactured in one gossamer piece, like a great fishing net whose whole unitary tension system can be air-delivered anywhere to be compression-strutted by swift local insertions of remote-controlled, expandable hydro-struts, which, as the spheric structure takes shape, may be hydro-pumped to firm completion by radio control.

795.05 In the advanced-space-structures research program it has been discovered that—in the absence of unidirectional gravity and atmosphere—it is highly feasible to centrifugally spin-open spherical or cylindrical structures in such a manner that if one-half of the spherical net is prepacked by folding below the equator and being tucked back into the other and outer half to form a dome within a dome when spun open, it is possible to produce domes that are miles in diameter. When such structures consist at the outset of only gossamer, high-tensile, low-weight, spider-web-diameter filaments, and when the spheres spun open can hold their shape unchallenged by gravity, then all the filaments' local molecules could be chemically activated to produce local monomer tubes interconnecting the network joints, which could be hydraulically expanded to form an omniintertrussed double dome. Such a dome could then be retrorocketed to subside deceleratingly into the Earth's atmosphere, within which it will lower only slowly, due to its extremely low comprehensive specific gravity and its vast webbing surface, permitting it to be aimingly-landed slowly, very much like an air-floatable dandelion seed ball: the multi-mile-diametered tensegrity dome would seem to be a giant cousin. Such a space- spun, Earth-landed structure could then be further fortified locally by the insertion of larger hydro-struttings from helicopters or rigid lighter-than-air-ships—or even by remote- control electroplating, employing the atmosphere as an electrolyte. It would also be feasible to expand large dome networks progressively from the assembly of smaller pneumatic and surface-skinning components.

795.06 The fact that the dome volume increases exponentially at a third-power rate, while the structural component lengths increase at only a fraction more than an arithmetical rate, means that their air volume is so great in comparison to the enclosing skin that its inside atmosphere temperature would remain approximately tropically constant independent of outside weather variations. A dome in this vast scale would also be structurally fail-safe in that the amount of air inside would take months to be evacuated should any air vehicle smash through its upper structure or break any of its trussing.

795.07 In air-floatable dome systems metals will be used exclusively in tension, and all compression will be furnished by the tensionally contained, antifreeze-treated liquids. Metals with tensile strengths of a million p.s.i. will be balance-opposed structurally by liquids that will remain noncompressible even at a million p.s.i. Complete shock-load absorption will be provided by the highly compressible gas molecules—interpermeating the hydraulic molecules—to provide symmetrical distribution of all forces. The hydraulic compressive forces will be evenly distributed outwardly to the tension skins of the individual struts and thence even further to the comprehensive metal- or glass-skinned hydro-glands of the spheroidally enclosed, concentrically-trussed-together, dome-within- dome foldback, omnitriangulated, nonredundant, tensegrity network structural system.

795.08 Design Strategies: All the calculations required for the design of geodesic domes may be derived from the three basic triangles of the three basic structural systems:
-the 120 right spherical triangles of the icosahedron,
-the 48 right spherical triangles of the octahedron, and
-the 24 right spherical triangles of the tetrahedron.
All the great-circle behaviors occurring around the whole sphere take place within just one of those three basic right triangles and repeat themselves in all others.

795.09 The data mathematically developed within the three basic triangles become constants for spheres of any size. What we need to know structurally is the length of the chordal lines between any two adjacent points in the three-way great-circle grid and the angles at which they intersect. The spherical surface angles of the sphere and the central angles may all be expressed in the same decimal fractions, which remain constant for any size sphere since they are fractions of a unit finite whole system. We assign the name *chord factors* to all the constant lengths of a sphere's connecting lines, whether between any two spherical surface points or between two concentric spheres that are intertriangularly trussed. We assign the word *frequency* to the number of uniform-edge subdivisions of the spherical arc edges of the basic spherical triangles.

795.10 There is a set of unique chord factors for each frequency. There are six alternate ways of organizing the triangular subgridding, some of which permit planar base cutoffs of the sphere at other than its equator. Various fractions of the sphere are permitted, as some produce more overall structural economy for differing applications than others. The most economical total lengths for a given frequency are also the most equilibriously comfortable—that is, where it requires the least energy to maintain its integrity under any and all environmental conditions.

795.11 Competent designing of geodesic tensegrity domes also requires monitoring the evolving increases in performance of the various chemical materials and metal alloys available. The full design science responsibility includes developing, prototyping, testing, production, engineering, tooling, manufacturing, transporting from factory to use point, assembly, and removing and recycling of the materials: only from consideration of each such successive cycle can we learn how to do it again more efficiently and satisfactorily to society. I.e., 60 degrees. The nucleus of a square would have a completely different distance to its corners than the corners would have to each other.

Next Chapter: 800.00