PCT

WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification 7 :
E04B 1/344, E04H 12/18, 5/02, A61F 2/06, A61B 17/16, 17/02, A61F 13/20, 2/04

A2

(11) International Publication Number: **WO 00/12832**

(43) International Publication Date: 9 March 2000 (09.03.00)

(21) International Application Number: PCT/US99/19457

(22) International Filing Date: 26 August 1999 (26.08.99)

(30) Priority Data:
09/140,510 26 August 1998 (26.08.98) US

(71) Applicant *(for all designated States except US)*: MOLECULAR GEODESICS, INC. [US/US]; 20 Hampden Street, Boston, MA 02119 (US).

(72) Inventors; and
(75) Inventors/Applicants *(for US only)*: CLIFFORD, Dale, Timothy [US/US]; 311 Lamartine Street, Boston, MA 02210 (US). INGBER, Donald, E. [US/US]; 71 Montgomery Street, Boston, MA 02116 (US).

(74) Agent: ANASTASI, John, N.; Wolf, Greenfield & Sacks, P.C., 600 Atlantic Avenue, Boston, MA 02210 (US).

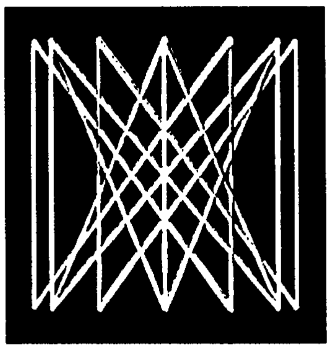
(81) Designated States: JP, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
Without international search report and to be republished upon receipt of that report.

(54) Title: RADIALLY EXPANDABLE DEVICE

(57) Abstract

An expandable device is provided that includes a plurality of elongated members that are positioned and arranged to define a lattice structure having crossing points (or nodes) along interior positions of the elongated members. Preferably, the lattice structure is a hyperboloid of revolution. The device includes a plurality of flexible interconnectors located at the crossing points for securing one elongated member to another. The device is radially compressible and expandable. The device may include flexible joiner elements at that join at least two elongated members together at their ends to form an apex. The device may be used in a variety of applications including medical applications such as surgical retractors, space creators, endoluminal prosthesis, such as catheters, dilators or stents, mechanisms for expanding stents, controllably catheters, drains or valves and connectors for hollow organs. The device may also be used in building and construction applications such as emergency shelters, housing structural supports, receptacles, masts and cooling tower support structures.



FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania
AM	Armenia
AT	Austria
AU	Australia
AZ	Azerbaijan
BA	Bosnia and Herzegovina
BB	Barbados
BE	Belgium
BF	Burkina Faso
BG	Bulgaria
BJ	Benin
BR	Brazil
BY	Belarus
CA	Canada
CF	Central African Republic
CG	Congo
CH	Switzerland
CI	Côte d'Ivoire
CM	Cameroon
CN	China
CU	Cuba
CZ	Czech Republic
DE	Germany
DK	Denmark
EE	Estonia
ES	Spain
FI	Finland
FR	France
GA	Gabon
GB	United Kingdom
GE	Georgia
GH	Ghana
GN	Guinea
GR	Greece
HU	Hungary
IE	Ireland
IL	Israel
IS	Iceland
IT	Italy
JP	Japan
KE	Kenya
KG	Kyrgyzstan
KP	Democratic People's Republic of Korea
KR	Republic of Korea
KZ	Kazakstan
LC	Saint Lucia
LI	Liechtenstein
LK	Sri Lanka
LR	Liberia
LS	Lesotho
LT	Lithuania
LU	Luxembourg
LV	Latvia
MC	Monaco
MD	Republic of Moldova
MG	Madagascar
MK	The former Yugoslav Republic of Macedonia
ML	Mali
MN	Mongolia
MR	Mauritania
MW	Malawi
MX	Mexico
NE	Niger
NL	Netherlands
NO	Norway
NZ	New Zealand
PL	Poland
PT	Portugal
RO	Romania
RU	Russian Federation
SD	Sudan
SE	Sweden
SG	Singapore
SI	Slovenia
SK	Slovakia
SN	Senegal
SZ	Swaziland
TD	Chad
TG	Togo
TJ	Tajikistan
TM	Turkmenistan
TR	Turkey
TT	Trinidad and Tobago
UA	Ukraine
UG	Uganda
US	United States of America
UZ	Uzbekistan
VN	Viet Nam
YU	Yugoslavia
ZW	Zimbabwe

RADIALLY EXPANDABLE DEVICE

Field of the Invention

The present invention relates generally to an expandable and contractable device and, more particularly, to a three-dimensional self-supporting lattice structure capable of expansion and retraction.

Background of the Invention

Many applications in industry, science, medicine and engineering call for expandable or retractable structures which are lightweight, porous, flexible and resilient. To meet these requirements, structures may be required to withstand compression, tension, shear and torsion. These forces usually act in combination to cause bending or failure of the structure.

According to U.S. Patent No. 4,825,225, a unique geometric shape which distributes applied forces across the entire structure is a hyperboloid of revolution of one sheet. An example of a hyperboloid of revolution of one sheet is shown in Figure 1, in which a hyperbolic curve **1** is rotated about axis **2** to define a solid surface. A hyperboloid of revolution of one sheet is characterized in that it is both a parabolic surface and a surface of revolution. A property unique to the hyperboloid of revolution of one sheet is that through any point on the surface of the hyperboloid there pass two distinct lines which lie entirely in the surface. These lines are called rulings and surfaces which contain rulings are called ruled surfaces.

In the medical field, many applications, such as a surgical retractor, may require a strong, yet expandable, structure. A surgical retractor is a device that is inserted through an incision during surgery in order to spread apart or separate the walls of an incision, or displace an organ to create work space or prevent organ injury. In many cases, it is desirable that the retractor be insertable into a narrow, slit-like incision (or incision of other shape), yet be capable of expansion to a much different shape, e.g., a large circular aperture. In addition, the retractor should be non-bulky so that it may be used in tight spaces and does not interfere with the surgical procedure. A surgical retractor desirably contains open or lattice-like side walls to permit access by medical instruments.

Retractors of the prior art include inflatable sleeves, as described in U.S. Patent

No. 4,984,564, and inflatable balloons as described in U.S. Patent No. 5,439,476. These devices may be awkward to use in a surgical setting and can require additional equipment, e.g., pumps for inflation of the balloons, in order to operate. Typically, the side walls of the prior art devices cannot be modified to form side ports large enough for the introduction of surgical instruments. Furthermore, the prior art retractors generally do not provide an accurate or reliable degree of control during expansion and contraction.

U.S. Patent No. 2,313,164 describes a surgical retractor having an expandable annular frame which expands using a scissoring action between sets of pivotally mounted blades. The device is relatively bulky and rigid. In particular, is it unable to be compacted into a flat configuration which may be inserted into a slit-like incision as may be needed in a surgical procedure. The device also does not have side walls with side ports large enough to accommodate surgical instruments.

Endoluminal prostheses, such as catheters, dilators or stents, also generally have an expandable lightweight structure for holding open a hollow organ. Prior art devices are made of braided or woven filaments, which are extended in an axial direction in the collapsed state and shortened in the axial direction in the expanded state. Such devices are disclosed, for example, in U.S. Patent Nos. 5,562,725; 5,741,333; and 5,503,636. A disadvantage of these devices is that they are relatively limited in their range of expansion and range of strength. Also the devices may not be locked at incremental stages of expansion. Such devices are capable of holding open small vessels, but generally lack the strength and expansion capability to hold apart large organs.

Other devices have been prepared by “zigzag” wires which have been linked in succession to form an extended tubular device as disclosed in U.S. Patent Nos. 5,683,448 and 5,665,115. These devices also suffer from the same limitations noted above, namely, a limited range of expansion capability and limited availability for side port access.

Summary of the Invention

According to the invention, a radially expandable and compressible device is provided which contains elongated members (or struts) that are arranged to form a lattice structure. The elongated members may intersect one another at points along their length, where they can be secured together by flexible interconnectors. The interconnectors permit a wide range of motion of the elongated members to enable the expansion and compression of the structure.

In one aspect of the invention, an expandable device is provided. The device includes a plurality of elongated members interconnected to form a first lattice structure. Some of the elongated members intersecting at least one other elongated member at interior positions along the length of both intersecting elongated members to define nodes. The device further including a flexible interconnector located at some of the nodes. The flexible interconnectors connecting the intersecting elongated members and permitting motion between the intersecting elongated members to enable radial compression or expansion of the first lattice structure.

By "elongated member" as that term is used herein, it is meant an element such as a rod, strut or stick that spans the surface of the structure. It is not intended to suggest processing history of the member.

By "hyperboloid of revolution" as that term is used herein, it is meant a surface defined by the geometric shape of a hyperboloid of revolution, which is formed by rotation of a hyperbola around a central axis.

By "node" as that term is used herein, it is meant the location of overlap of two elongated members in the hyperboloid of revolution structure. It also is used to indicate the intersection of the two elongated members at the crossover point.

By "point" or "apex", as those terms are used herein, it is meant the location where two or more elongated members meet at their termini. The expandable device of the invention may, but is not required to, possess apices or points.

The device is capable of a range of motion from a rest state to a use state. In particular, it is capable of a range of motion such that in a collapsed state the elongated members are substantially axially aligned and the device is substantially cylindrical, and in an expanded state the elongated members are substantially perpendicular to the axis and the device is substantially planar. The motion may be characterized in that upon radial expansion, the device is shortened in the axial direction.

The expandable device is particularly suitable for use as a medical device, such as surgical retractor, endoluminal prosthesis, such as catheters, dilators or stents. Other suitable applications include expanding reamers, cement plugs, a cylindrical space for use as a medical drain or catheters, controllable valves for catheters and drains, connectors for hollow organs, e.g., the intestines, artificial sphincters, and stents to hold open both linear and branched lumens of vessels.

Because of the variety of shapes attainable by the expandable structure of the invention, it also may be used in a number of other industrial and construction applications. Exemplary applications include as packaging, exhibit structures, emergency structures, residential framing systems, concrete framework and reinforcement, the supportive structure for membrane coated cooling towers and deployable space applications. It may also be used as an expandable receptacle for collection or storage in particular; and in particular, it may be used as a feminine hygiene product.

The following naming conventions are used in the application. The "nodes" of a structure are the points of intersection of two or more elongated members, joint by a flexible pivoting means or interconnector. A structure is defined by the number of nodes located on the interior of a single elongated member. The "points" of a structure are the apices formed by the joining of the ends of two or more elongated members. A structure is defined by the number of apices or points formed at the top or bottom of the structure. There are always the same number formed both top and bottom. Thus, a structure having three internal nodes and twelve points is designated as "12p3n". Also, the terms rod, strut or elongated member and the like are used interchangeably throughout.

In preferred embodiments, the elongated members are positioned and arranged to form a hyperboloid of revolution.

In preferred embodiments, the interconnector is selected from the group consisting of flexible bands, splines, x-joints, a ball and socket joints, and flexible connectors tethered to the respective crossing points of the elongated members and flexible pins or the interconnector is integral with the elongated member, and may comprise regions of differing structure or composition.

In preferred embodiments, the joinder elements are selected from the group consisting of springs, flexible tubing, shape-memory hinges and wire or the elongated members and the joinder elements are integral with each other or the integral device is comprised of a unitary wire.

In other preferred embodiments, the elongated members are hollow and the joinder elements comprise a continuous wire fed through the hollow elongated members. The nodes may be evenly or irregularly spaced along the length of the elongated member.

An elongated member is selectively omitted to thereby provide an opening in the surface of the hyperboloid surface defined by the elongated members.

In preferred embodiments, the position and number of nodes and elongated members are selected to obtain a preselected expansion ratio defined as ratio of the largest inner diameter to smallest outer diameter or the position and number of nodes and elongated members are selected to obtained a preselected curvature of the hyperboloid surface of the device or the position and number of nodes and elongated members are selected to obtained a preselected axial shortening during expansion.

Other objects embodiments and advantages of the present invention will become apparent from the following detailed description when taken in connection with the accompanying drawings. It is to be understood that the drawings are designed for the purpose of illustration only and are not intended as a definition of the limits of the invention.

Brief Description of the Drawing

The present invention is described with reference to the Drawing, which is presented for the purpose of illustration only, which is in no way limiting of the invention, and in which:

Figure 1 is a three-dimensional illustration of a hyperboloid of revolution of one sheet;

Figure 2 is an illustration of the folding sequence of the expandable structure of the invention from a fully compact bundle (Figure 2A) to an expanded hyperbolic volume (Figure 2B) to a fully extended plane (Figure 2C);

Figure 3A is a side-view illustration of the expandable device of the invention; and

Figure 3B is a top-view illustration of the expandable device of the invention;

Figure 4 is a illustration of one embodiment of the invention;

Figures 5A - 5E are schematic illustrations of various pivoting interconnections for use in the expandable device of the invention;

Figures 6A - 6C are schematic illustrations of x-joint pivoting interconnections for use in the expandable device of the invention;

Figures 7A - 7B illustrate various joinder elements for use in the expandable device of the invention;

Figure 8 is an illustration of an expandable device molded as an integral unit;

Figure 9 is an illustration of an expandable device in which the nodes are located so as to form gaps on the device surface;

Figure 10 is an illustration of one embodiment of the invention prepared from a continuous wire;

Figure 11 is series of a computer generated structures providing a sample of possible forms that can be obtained in the expandable devices of the invention;

Figure 12 is an illustration of regular (12A) and semi-regular (12B) structures of the expandable device;

Figure 13 is an illustration of one embodiment of the invention;

Figure 14 is a schematic illustration of an embodiment of the invention having discontinuous elongated members;

Figures 15A - 15C illustrates the principle of triangulation in stabilizing rhomboid subelements of the expandable device;

Figures 16A - 16B are illustrations of locking mechanisms including shape memory braces (16A) and external clamping (16B);

Figure 17 is an illustration of the deformation (17A) and recovery (17B) that is possible in the expandable device of the invention;

Figure 18 is a plan view of a surgical retractor of the invention;

Figure 19 is an illustration on one use of the expandable device as a feminine hygiene collector;

Figure 20 is an illustration of a convention wire spanned cooling tower demonstrating a hyperbolic structure;

Figures 21A - 21B are schematic illustrations of an expandable column formed by the end-to-end stacking of expandable modules of the invention in the extended (21A) and collapsed (21B) states;

Figure 22 is a schematic illustration of various joining architectures for a plurality of modules at respective points (22A), along elongated elements defining a single point (22B) and along elongated elements defining neighboring points (22C);

Figure 23 is a schematic illustration of a branched modular structure;

Figure 24 are illustrations of methods of joining expandable modules in the formation of columns, spirals, arches, knots and sheets;

Figures 25 A - 25B are plan views of multinodular expandable sheets of the invention;

Figure 26 is an illustration of a modular expanding device which has been mapped onto the surface of a polyhedron;

Figure 27 schematically illustrates an expandable device including a bladder attached to its exterior; and

Figure 28 schematically illustrates an expandable device with an internal bladder.

Detailed Description of the Invention

The present invention provides a stable three-dimensional, self-supporting lattice structure that contains elongated members or struts. In preferred embodiments, the elongated members define the surface of a hyperboloid of revolution of one sheet. The structure is capable of undergoing a folding sequence such as that demonstrated in Figure 2. The range of motion of the device permits unfolding from a substantially cylindrical, compact bundle flattened into a substantially planar array (see, Figure 17A), to a substantially cylindrical bundle (Figure 2A), to an expanded hyperbolic volume (Figure 2B), and to a flat plane (Figure 2C). As the structure is deployed from is contracted or bundled state, there is a regular polygon (as viewed from the top or bottom of the structure as well as from a horizontal section cut through any nodal plane) that expands until the structure reaches its planar state. The radius reaches a maximum in the planar state and has a minimum in the bundled state. The height of the structure is proportional to the degree of expansion. Expansion ratios are high and may exceed 1:35. Due to flexible interconnectors (discussed herein below), the device can take on a flattened, cylindrical or non-regular form. Alternatively, the device may be presented in an open form that can be made to controllably contract.

The expandable device is described with reference to Figure 3. Figure 3A is a side view of the expandable device of the invention depicting elongated members **20**, interconnectors **22** and joinder elements **24**. Figure 3B is a top view of the expandable device depicting the inner diameter (I.D.) and outer diameter (O.D.) of the device. The inner diameter is defined by a circular cross-section of the device at its smallest point, while the outer diameter is defined by a circular cross-section of the device at its largest point. Because of the hyperbolic nature of the surface of the device, the inner and outer diameters differ in location and size. The device is radially expandable and compressible along arrows **26**.

Flexible interconnectors **22** are located at crossover points along the length of the elongated members. A "crossover point" may be alternatively referred to as a "node" and represents a point where two or more elongated members intersect in the structure. The interconnector secures the two or more elongated members at the node, but also provides for a flexible range of motion between the members. The interconnectors of the expandable device should have sufficient flexibility to permit the device to move from a "rest state" (position where no forces are applied) to a "use state" (position where the device has been expanded or compressed into a desired shape). This may be less than the full range of motion that is possible. The device will typically be required to collapse into a substantially cylindrical or flat bundle and expand into a hyperbolic shape. The interconnectors are chosen to allow the desired movement and, in preferred embodiments, are chosen to allow the elongated members to move in a manner having more than one degree of freedom of movement. Due to the flexible nature of the interconnectors joining the members, all loads transmitted through the interconnectors are axial, that is there is no moment or bending induced throughout the joint. "Flexibility" is used to refer to a range of motion in the device. It does not require that the interconnector be constructed of flexible, e.g., bendable materials, but rather that it be constructed and/or arranged with elements that permit flexibility in the expansion dynamics.

By "degree of freedom of motion or movement" as that term is used herein it is meant the number of variables needed to define the location of a point on the surface of the device as it moves from a contracted to an expanded state. For example, where two rods are joined at a cross-over point by a pin that holds the two rods in a rotational relationship with respect to one another, the rods are capable of a scissoring motion in a flat plane only. Such in-plane motion does not provide the wide range of movement desired in the device.

According to the invention, the elongated members are joined by flexible interconnectors that provide an additional degree of freedom other than that permitted by an ordinary pin connection. This degree of freedom may be an out-of- plane rotation as referenced from the plane of rotation permitted by an ordinary pin connection. This additional motion provides the flexibility in the structure needed for the wide range of motion desired.

Joinder elements **24** may be located at ends of elongated members **20** where two or more elongated members meet to form an apex. As with interconnectors **22**, the joinder elements are chosen to allow the elongated members to fully fold and unfold through the full range of motion desired. The joinder elements are flexible and permit motion of the rods, such that the rods are capable of moving out of the plane defined by a simple scissoring motion, *i.e.,* more than one degree of freedom. For the purposes of clarity, only a portion of interconnectors **22** and joinder elements **24** have been included in Figure 3. It is understood that substantially all of the apices and nodes may be joined by joinder elements and interconnectors, respectively, in order obtain a stable device. However, not all apices and/or nodes are required to be joined as described. It is contemplated that selected nodes and/or apices could be left free (or unjoined) without compromise to the structural or mechanical integrity of the expandable device or without impairing its ability to expand and contract.

A particular advantage of the expandable device of the present invention is that the device is deformable even in its fully contracted state due to the flexible nature of the interconnectors and optional joinder elements. The bundled device may be pressed into a planar configuration, yet regain its original shape once the pressure is removed. Another feature of the invention is the resting state of the device. Based upon the placement and number of elongated elements and the nature of the interconnectors, the device will have a "resting state" -- a degree of expansion which the device will freely attain absent an opposite restraining force. That resting state may be chosen by use of flexible interconnectors of a particular angle or having a selected amount of prestress.

Another embodiment of the invention is shown in Figure 4. Referring to Figure 4, the device includes a plurality of elongated members **40** positioned and arranged to define a hyperboloid of revolution having crossing points (or nodes) **42** along interior positions of the elongated members. A plurality of flexible interconnectors **44** permitting more than one degree of freedom of motion are located at the crossing points **42** for securing one elongated member to another. The device is radially compressible and expandable along arrows **46**. The axis is labeled by arrow **48**. Significantly, the device does not terminate in apices, but rather with divergence of the elongated members. The structure is fully compressible and expandable according to the invention. The lack of apices may be desirable in those applications where one wishes to anchor the device into the surrounding tissue or environment.

The device may be constructed on any scale desired by the user, commensurate with the intended application. Thus, the elongated rods may be on the order of meters (m), centimeters (cm), millimeters (mm) or even microns (μm), depending on the application. The structure may be formed of continuous elements or of discontinuous elements that are connected at the interconnector to form the elongated member. In cases where the elongated member is comprised of small subelements, the interconnector desirably restrains motion at the node to prevent inward buckling of an elongated member. The elongated member may be made up of a plurality of discontinuous members connected at the interconnector.

The elongated members may have any cross-sectional geometry, providing that the requisite range of motion is possible. The elongated members may be round, oval, triangular, rectangular or of other more complex geometries. Circular cross sections are a preferred embodiment. The elongated member may be linear or they may be curved. The curvature of the rods is small; *i.e.,* less than about 20%.

An advantage of the present invention is that the elongated members can be constructed from materials having a range of mechanical properties. Thus, the elongated members may be rigid or they may possess a degree of flexibility. The elongated members desirably has sufficient strength and stiffness to be self-supporting. In some embodiments, it may be desirable to have some flexibility or bending ability in the elongated member. For example, where the expandable device is locked into a configuration and force is applied, it may be desirable for the elongated members to be able to bend in response to the applied force.

The elongated members further are constructed from materials commensurate with their intended applications. Thus, for example, the elongated members are constructed of biocompatible materials when used as a medical device; but are constructed from other materials, e.g., wood, metal, polymer and ceramics, when used in construction, industrial or other applications. The elongated rods may be made of surgical stainless steel, high molecular weight polypropylene or polyethylene and derivatives thereof and titanium and its alloys. The elongated rods may also be made of elastomeric material to provide an energy absorbent structure.

The interconnectors are selected to permit radial expansion of the device. The interconnectors may provide motion having more than one degree of freedom between the elongated elements. As discussed above, such ranges of motion may include an in-plane scissoring and an out-of-plane rotation. Exemplary interconnectors for rods **20'** and **20"** are shown by Figure 5 and include flexible materials, such as elastic bands (element **50** in Figure 5A), splines, such as press fit splines (element **52** Figure 5B), ball and socket joints (elements **54, 58** in Figures 5C and 5E) and tethers (element **56** in Figure 5D). Tethers are flexible lengths of wire, rope and the like secured to the respective nodes of the elongated members. Other possible interconnectors include flexible pin joints and integral hinge features in a unitary structure (see discussion herein below). Note that “flexible” interconnectors do not necessarily require flexible construction materials. In particular, a ball and socket joint is made of rigid materials.

Flexible interconnectors also include an “x-joint” **100** as is shown in Figures 6A - 6C. The x-joint **100** may be a molded sleeve with hollow arms **102**. The x-joint is constructed from materials that are flexible, such as elastic polymers. The arms may accommodate discontinuous struts **104** as shown in Figure 6A, so as to create an elongated member from subcomponent pieces. In this embodiment, the node of the elongated element is located at the x-joint. Alternatively, the hollow x-joint may have sufficient interior room to accommodate two continuous elongated elements to form the node. In another embodiment, the x-joint **100** may be used for joining continuous elongated members **106**, as shown in Figure 6B. The x-joint is split to form slit **108, 108'** along its length for accommodating both elongated elements **106** at the node. In yet another embodiment, the flexible interconnector **100** is solid. Discontinuous elongated members **110** houses a hollow shaft **112**, which may or may not continue along the length of the rod. The x-joint engages the shaft **112** of the elongated members **110**, as shown in Figure 6C.

The joinder elements also are flexible to permit opening and closing of the angle defined by the apices of the device and in- and out-of-plane motion. Exemplary joinder elements are shown in Figures 7A - 7B. Suitable joinder elements include hinges, such as shape-memory alloy hinges, springs, elastic tubing. Elastic tubing is selected to fit snugly over the elongated members.

Shape memory alloy or polymer hinges, such as Nitinol hinges, are particularly useful as joinder elements in certain embodiments of the invention. The hinge permits the device to self-open, to self-close or to hold a desired shape with or without external controller mechanisms. These hinges are prepared from a metal or polymer which is deformable, but is restored to an original preset shape by a solid state phase change caused by heating. The hinge is preset to provide any desired shape which is triggered at a predesignated temperature. Thus, a Nitinol hinge **200** inserted into elongated element **202** opens up to any desired angle, **θ**, as shown in Figure 7B. Once expanded, they can become fairly rigid. The Nitinol hinges can be arranged to allow the device to stabilize at a plurality of predetermined circumferences during its deployment. A variety of different hinges with different opening angles may be deployed as a means of actuating and stabilizing the device at different sizes. For example, in a structure with nine points, there could be three groups of three Nitinol hinges located on the top points of the structure with varying predetermined shapes, e.g., 15°, 30° and 60°. The bottom points could have a predetermined shape of an angle of 0° which would effectively close the device. Each actuator angle is triggered at a different temperature. The Nitinol hinge may be designed to actuate at ambient temperatures. Alternatively, an electrical current may be applied to the device and the hinge may be heated through resistance heating to permit actuation at any temperature.

In another embodiment, the joinder element may be a wire **210** which is strung through a hollow elongated element **201** as shown in Figure 7A. The wire may form a continuous line through the elongated members of the expandable device to thereby form a highly stable structure. The wire may be nylon cord, metal wire or any other type of cord or cable.

In another embodiment of the invention, the elongated members, the interconnectors and optional joinder elements may be prepared as an unitary article. In this manner, the interconnector elements **74** and elongated members **75** (and the optional joinder elements **76**) may be prepared by injection molding, solid free form fabrication (SLA) and self-assembly techniques (as described by the Whitesides group, see below). The molding is preferably a flat sheet, as illustrated in Figure 8. The sheet may be folded back on itself and joined at ends **70**, **72** to form a cylinder. In preferred embodiments, the interconnector elements **74** are flexible and elastic, *i.e.,* they permit movement in more than one degree of freedom. The material used for the elongated element **75** is stiffer and provide greater mechanical support and integrity to the structure. The different material properties of the elongated and interconnector elements may be accomplished by using different materials or by treating the materials to a different process. For example, the elongated elements may be a polymer **77** having a higher degree of crosslink than a polymer **78** used to form the interconnector elements. See, inset A. Higher degree of crosslink may be accomplished by thermal processing or use of additional crosslinking agents and initiators. Alternatively, the interconnector may be molded into a shape **78** which imparts greater flexibility. The interconnector may also be processed post-fabrication to include slits **79** and/or cut-outs **80** in the node to create flexibility. See, insert B. The molding process may also provide a thin skin or film between the struts. The skin could be made of the more flexible polymer, *i.e.,* the polymer **78** used for the interconnectors, so that expansion is possible.

The expandable device **10** may be constructed from continuous lengths of wire as shown in Figure 9. A continuous wire **140** is bent into a "zigzag" configuration. The wire is then wound so that it winds up on itself in a plurality of revolutions until ends **142, 144** are joined. Cross-overs **145** formed in the process are joined using the pivoting interconnectors described herein.

An alternative embodiment is described in Figure 10. The expandable device **10** includes a plurality of zigzag wires **150**, that have been joined after a single revolution to form a simple circular band **152**. A plurality of bands **152** may then be superimposed so that the apices of each zigzag wire are offset from its neighbor's by a selected angle, N, indicated in Figure 10. Crossover nodes **155** formed in the process are joined using the flexible interconnectors described herein.

In another embodiment of the invention, the expandable device may be cut from a single sheet. The pattern could be stamped out of a single sheet, then wound around and attached to itself to form the desired shape.

Many variations in design are possible and are within the scope of the present invention. The construction of the device allows for a wide variety of forms to be constructed, all of which are radially expandable and contractible. Variations to the structure include the degree of axial shortening which occurs to the device upon expansion (radius of height change to expansion), the ratio of the inner and outer diameters of the structure, the expansion ratio (ratio of largest inner diameter to smallest outer diameter during deployment) and the radius of parabolic curvature of the surface of the device. These and other features of the device may be modified by varying the number and length of elongated members, the number of nodes and/or the node spacing.

For example, as the number of elongated members is increased and the nodal configuration remains constant, the ratio of the height change to expansion is decreased -- that is, the decrease in height during an unfolding operation is smaller as the number of struts in increased. The interior diameter of the device at full volume, that is, the movement or position during deployment when the interior volume is the greatest, also increases. The addition of elongated members to the device increases the interior diameter at the midpoint of the structure (for a symmetrical structure), in turn increasing the radius of parabolic curvature of the surface. As the radius is increased, the form of the structure approaches an expanding cylinder having little change in height upon expansion.

As the number of nodes increases (all other factors remaining constant), the ratio of inner diameter to outer diameter (I.D./O.D.) decreases, that is the inner diameter decreases relative to the outer diameter. Increased nodes results in a structure having a greater degree of curvature. The greater degree of curvature will also cause the structure to undergo a significant change in height (axial contraction) as the device expands radially.

These relationships are illustrated in the computer generated structures shown in Figure 11. For example, as predicted a structure with a relatively small number of elongated rods, 6p4n, has a very small inner diameter and a large difference in the inner to outer diameter. Compare the narrow waisted 6p4n structure with the adjacent 12p4n structure. As predicted, by increasing the number of elongated members, the radius of curvature of the surface increases and approaches that of a cylinder.

Next compare the structures identified as 12p4n, 12p7n, and 12p9n. Each is composed of the same number of elongated elements, but contain an increasing number of nodes. As predicted, the inner diameter of the structure decreases relative to the outer diameter and the curvature of the surface increase.

Distinctive shapes may also be governed by placement of the nodes along the elongated elements. Thus, where the nodal placement is symmetrically placed along the elongated element, a uniform or regular structure is obtained, characterized by its symmetric shape. Alternatively, where nodal placement is unsymmetrically placed along the elongated element, the resulting structure is semi-regular and characterized has axial symmetry. However, there is no symmetry above and below any nodal planes. Exemplary regular and semi-regular structures are shown in Figure 12A and 12B, respectively. Where the number of nodes is even, the structure is prismatic, that is, having parallel, congruent or similar polygons as bases. Where an odd number of nodes is employed, the structure is anti-prismatic, that is, having parallel bases rotated with respect to one another. Thus, it is apparent that selection of the location and number of nodes provides a high degree of control over the form, dynamics and mechanical behavior of the device.

In another embodiment of the invention, the nodes may be grouped in a manner to form porosity, characterized by regions of close placement of elongated members on the surface and wider regions of spacing therebetween. In order to obtain various openings **130**, or sideports, in the latticework surface of the device, the nodes are placed in alternating close space arrangements **132** and spaced-apart arrangements **134**. The size of the openings is, thus, controlled by the arrangement of the nodes. An exemplary structure is shown in Figure 13. The gap may be desirable in some intended applications of the device. For example, the device may be used as a surgical retractor. The retractor may be used to hold back the walls of the body cavity. An organ requiring medical attention may be placed through the opening **130** allowing free and unencumbered access by medical personnel. Alternatively, when used as temporary shelter or residential housing framing, the opening **130** may be used as entrances or windows in the structure.

In another aspect of the invention, the structure may include discontinuous elongated members, resulting in apertures or openings in the surface of the device, such as shown in Figure 14. With reference to Figure 14, a simple expanding device having three apices and two nodes is shown. Elongated members **60** are continuous and elongated members **62** and **64** are discontinuous (discontinuity is denoted by dashed lines). The discontinuity of members **62,64** results in side port **66** in the structure. The opening may be desirable in some intended applications of the device. For example, the device may be used as a surgical retractor. The retractor may be used to hold back the walls of the body cavity. An organ requiring medical attention may be placed through the side port **66** allowing free and unencumbered access by medical personnel.

Alternatively, when used as temporary shelter or residential housing framing, the side port **66** may be used as entrances or windows in the structure.

In some embodiments, the device may be covered, in whole or in part, with a membrane, fabric or shrink wrap. The covering may be used as a tensile element to strengthen the structure or to lock deployment at a predetermined position. Alternatively, the fabric skin could be able to expand with the device. Fabric may be used to close a subset of facets (surfaces) on the device. The membrane may be continuous or discontinuous, and may be applied in strips or bands. In certain embodiments, the membrane may be porous or permeable .

A means for locking the expanded device at a desired degree of expansion is also provided. In the above descriptions, it may be desirable to use an element that has a limited range of motion or that "locks" into position once it reaches a predetermined degree of expansion or contraction as pivoting interconnections or joinder elements. In general, the structures may be made rigid by triangulation of the rhomboids lying in the surface of the hyperboloid of revolution. The principle is illustrated in Figure 15. By spanning the opposing corners of a rhombus, the further expansion of the rhombus is prevented. Where the spanning member is compressible, but not extensible, such as cable **160** of Figure 15A, then the system is tensely triangulated. Where the spanning member is not compressible, such as strut **161** of Figure 15B, then the spanning member is compressively triangulated. The device is made rigid and/or not further expandable by addition of triangulating members to the device at a interconnector or nodal location or between two points. Note that the use of two such members spanning all four corners of the rhombus renders the device completely fixed, and incapable of further expansion or contraction. The triangulation member may be flexible (Figure 15A) or rigid (Figure 15B).

In another embodiment of the invention, a retractable triangulation member may include a rachet members **162**, **164**, as shown in Figure 15C. The locking member may also be a hinged triangulation member **165**, such as illustrated in Figure 15D. The hinged triangulation member is capable of becoming rigid or locking at a predetermined angle, denoted as angle **166** in Figure 15D. Here, the angle is shown as 180°, but it is understood that any angle can be employed.

In another embodiment, Nitinol hinges are used, either as joinder elements which become rigid at a preset angle upon heating (as shown in Figure 7B) or placed in a vertice of a rhombus for stabilizing and immobilizing the device, as shown in Figure 16A. Alternatively, a temperature-sensitive alloy may be used which exhibits a varying degree of expansion at different temperatures. In still yet another embodiment of the invention, the device may be immobilized by attaching an external clamp or cable to the device as shown in Figure 16B. Fabric may be used in a similar manner to stabilize the device. In yet another embodiment of the invention, the locking member is included in the interconnector as a locking hinge. Thus, the interconnector serves both to joint neighboring elongated members and to lock the device at a predetermined degree of expansion.

In another aspect of the invention, a means for contracting the device is provided. One technique involves creating a loop assembly by passing a string through a number of the device's nodes and, more preferably, through all of the nodes located on a horizontal plane. The loop assembly may be pulled thereby causing the elongated members to rotate about the node in a manner that contracts the device.

In yet another aspect of the invention, means for controllable expanding and contracting of the device are provided. Exemplary tools for expansion include a worm drive which converts linear motion into radial expansion. Alternative methods of expansion include Nitinol hinges that allow self-expansion and/or contraction without external controls. The invention, therefore, can provide a direct, mechanical, quantifiable degree of expansion and contraction. Thus, the user can read the exact degree of expansion by a gauge or other device once the device is actuated by a worm drive or other device. Conventional balloon deployment does not provide direct response measurement.

The particular details of a device may be driven by its intended use.

For use as a medical device for insertion into a body, the elongated members may have a length in the range of about 10 μm to 10 cm, and preferably 0.1-5 cm. For use in a medical device, the elongated rods are constructed from biocompatible materials, that is, materials which do not cause irritation. Suitable materials include surgical steel, high molecular weight polyethylene and polypropylene and titanium and titanium alloys. In addition, an elongated member or a portion thereof may be removed as discussed hereinbelow to form an aperture, for separation of a body region from the rest of the body cavity or for insertion of medical instruments. In preferred embodiments for the medical device, it is desired to use shape memory hinges that are actuated at a predetermined temperature. The hinges are deformable at a pre-selected temperature, but can be treated to actuate at a variety of temperatures. Once expanded, they can become fairly rigid. This then allows the device to be stabilized at a plurality of predetermined positions during its deployment.

In preferred embodiments, the expandable device is configured as a surgical retractor. The device may be covered with a fabric or membrane to protect organs or partition the body cavity. The membrane may be waterproof or it may comprise a hydrogel that swells when wet to form a smooth coating which protects organs of the body. The hydrogel can lubricate and moisturize the tissue of contact to prevent drying. The bottom of the retractor (the portion inserted first into the body cavity) may be equipped with one or more feet, protruding outwardly from the surface of the retractor. The foot may be an integral extension of the elongated members or it may be added to the device as a separate element. The foot is used to engage with the surrounding tissue of the body to secure its position.

When the surgical retractor (or any other medical device capable of insertion into the body) is fully contracted, it may be pressed flat so that its axial cross-section is no longer circular, but rather linear. This is advantageous, because the device may be manipulated and deformed to accommodate the size and shape of the opening in the body. With reference to Figure 17, where elements of the device are identified as in Figure 3, it may be deformed to insert into a linear incision (Figure 17A) and then recover its cross-section for use as a surgical retractor (Figure 17B). For this purpose, it is desirable that the interconnector be flexible. The ability of the device to be compacted to fit through a narrow linear incision of a small circular incision makes it extremely useful for minimally-invasive surgery in humans and animals. For example, it may be inserted through a circular trochar.

In particular, the expandable device may be constructed to aid in gall bladder surgery. In this embodiment, the device is constructed to have an open lattice design which provides access to the interior of the device through its sidewall, e.g., by "side ports". Side ports may be introduced in a number of ways and also are useful in a number of additional embodiments. For example, struts may be selectively eliminated or shortened as illustrated in Figure 14, or the nodal placement may be selected to provide openings in the walls of the device as illustrated in Figure 9. Such a geometry would permit the medical professional to isolate the gall bladder within the expandable device and retain or hold back other body organs.

It may also be desirable, and possible, to deploy a retractor/constrictor device, or multiple retractor/constrictor devices, within a previously deployed retractor. With reference to Figure 18, a second retractor **180** may be positioned within a first retractor **182** which is the expandable device of the invention. Elongated members, interconnectors and joinder elements are numbered as in Figure 3. The retractor may be designed to hold optics and cutters, such as cutter **184**. A number of tools could be deployed within the device similar to a thread cutter on a sewing machine. The surgeon could reach in with a grabber and pull tissue through a prepositioned cutter. The device may be designed to perform as an electrosurgery component. It could be used as a local insulating field so as not to conduct current to other components implanted in other parts of the body. Alternatively, it could be used to form a conductive field, if needed. This may depend on the types of materials used in the structure and on the membrane and skins used.

The device may be used in a variety of medical applications, including a surgical space creator for gall bladder surgery, a stent including multimodular branched structure for large branch off of a main vessel, a non-balloon expander for use with a conventional stent expansion that permits continuous blood flow, a controllable drain valve for surgical drains, a catheter that does not kink and an expandable reamer. The added benefit of the expandable device used as a non-balloon expander is that blood flow is not occluded during operation. Anther benefit is the ability to provide control over a wide range of expansion not available in existing medical balloon catheters.

In another embodiment, the expandable device is used as a feminine hygiene product. The device is illustrated in Figure 19. According to the embodiment, the device is equipped with a collector **180,** such as a balloon or other receptacle, at one end of an expandable device **182**. The device is capable of insertion into the vagina and expansion once inserted to retain its position. The expandable device may be coated to improve comfort or it may be equipped with a pneumatic device **184** or swellable polymer which expands to immobilize the device in the vagina and to improve comfort to the user. It is expected that the device would form a seal, thus preventing leakage.

For use as an emergency shelter, the elongated members may have a length on the order of meters, and may be sized to accommodate one or more persons or animals. The elongated members may be constructed of lightweight materials, such as carbon fibers, wood or aluminum. In addition, the elongated members may be selected to provide an aperture in the structure, as shown in Figure 14 and discussed herein below, for entry and exit. The emergency structure includes a membrane made of fabric, plastic or other sheeting materials, for protecting the inhabitants from exposure. The membrane may further serve as an integral tensile component to prevent overextension of the structure and further strengthen the structure. The shelter may further include a locking mechanism for retaining the shelter in the expanded shape. The locking mechanism is preferably reversible.

The expandable device may be used for storage and as a collection receptacle. The device could be stored compactly in the collapsed state and expanded for use. The device may be covered with fabric or sheeting to improve its capability in collecting and storing.

In another aspect of the invention, the device may be an expanding reamer. The expanding reamer is attached to a motor and a shaft and further includes a cutting means attached to an external surface of the device. The device is constructed of substantially rigid elongated members to provide a sturdy structure. Further, the choices for interconnectors and optional joinder elements are made to provide a rigid, sturdy structure. The design exhibits excellent torsional ability necessary for applications such as an expanding reamer.

The expandable device of the invention may be used as a building framing system. The device is sized for use as a building and the elongated members are made up of conventional building materials, such as wood, reinforcing steel, metals and plastic. The system includes a locking mechanism which holds the framing system in place and stabile once the desired degree of expansion is obtained.

In one aspect of the invention, the device is a deployable supportive structure for cooling towers. The device is sized for use as a cooling tower and further includes a membrane coating an outer surface of the tower. Figure 20 is a picture of a convention net cooling tower illustrating the hyperbolic shape of the cooling tower. The structure is constructed and arranged so that an elongated member spans the hyperboloid surface. It may be desirable to construct the elongated member from discontinuous subelements. Each subelement is connected by an x-joint interconnector to form the elongated elements and hyperboloid surface.

In yet another aspect of the invention, the device is an exhibit structure. The exhibit structure is constructed of strong, yet light weight, materials and has an integral fabric skin.

In another aspect of the invention, more than one of the devices can be joined to create multimodular structure which also are capable of expansion and contraction. A single expandable device or "module" may be joined to another module by sharing comment structural elements or nodes to create multimodular hollow expansion/contraction structures having a variety of forms.

In one embodiment of the invention, a plurality of modules are stacked end-on-end to form an extended columnar structure , as is illustrated in Figure 21. The a multimodular device may be deployable as a mast. The device is made up of a plurality of expandable devices **190**, **192**, **194** stacked end-to-end. The column is characterized in that, it is an axially extending configuration (Figure 21A) in the axially extended state and may be fully compacted so that the expandable modules compact planarly for storage. (Figure 21B). The deployable mast may be used in space applications, where it is desired to have lightweight, yet compact, weight bearing structures.

Figure 22 illustrates the joining of two modules (expandable device of the invention) in a variety of ways. Figure 22A shows the joining of the modules **190**, **192** (of Figure 21A) at respective points or apices **320**, **330** of the devices to form node **360**. Figure 22B illustrates the joining of the modules **192**, **194** (of Figure 21A) at intermediate locations **340**, **350** of the respective elongated members **300**, **310** to form node **360**. The joining point at **340**, **350** of the respective modules results in a new node **360** for the structure. The nodes can be located on pairs of elongated members forming an apex, as shown in Figure 22B, or they may be located on pairs of elongated members spanning neighboring apices **365**, **370**, as shown in Figure 22C. The modules are joined with flexible interconnectors as described above for the individual expandable device. Because of the flexibility in node **360**, the multimodular structure also expands and contracts as described above for the individual modules.

Alternately, the modules may be joined by sharing common structural elements to create multimodular hollow structures with a variety of forms, including cylindrical and branched arrangements. Figure 23 illustrates a "Y-tube" **400** formed from the joining of three modules **410**, **420**, **430** at their ends. Note that each of the modules **410**, **420**, **430** bridge the other two to form the "Y". These structures could be used, for example, as stents to hold open a branch point along a major blood vessel, as well as a lumen. It should also be apparent that arches, spirals and knots may be constructed from a plurality of modular expandable structures by orienting one module so regular polygons defining a horizontal cut through a nodal plane **500** of itself and a neighboring modular structures **510** are offset by an angle **520**. The value of the angle defines an arch, as shown in Figure 24A. Where the modules vary in two directions, a spiral or a knot may be formed. Examples of such multimodular arches, spirals and knots are shown in Figure 24. The structures are expected to expand and contract in a manner similar to the single module. Arches and spirals will expand similar to the modular unit from which it is assembled.

In another aspect of the invention, modules may be joined to form collapsible fields or sheets and sandwiches. A sheet arrangement is accomplished by joining the points of individual, adjacent expandable modules. A two-dimensional plan view is shown in Figure 25. Figure 25A shows a plurality of six pointed modules **30** joined in a space filling arrangement to form a hexagonally tiled field **32**. The field **32** collapses into a bundle or expands into a flat sheet with openings **34** defined by the inner diameter of a single expandable structure in the expanded state. Figure 24B shows a field **36** constructed of a combination of six-pointed modules **30** and four-pointed modules **38**. The resulting surface contains voids **39**, which may accommodate 12-pointed structures. As for the field in Figure 25A, field **36** is capable of collapse into a bundle or expansion into a flat sheet. These fields may be prepared with varying degrees of porosity, derived from the overall tiling pattern and local side port pattern. The porosity can also be changed by compressing the field. The inner diameter of the individual modules is a function of the degree of expansion. Thus, the fields may act as a kinetic filter, whose porosity changes by expanding or compressing the structure.

In another embodiment of the invention, the modules are semi-regular structures, as defined herein above. The semi-regular structures can be arranged in the field to form clastic (dome) and anticlastic (saddle) curvatures.

In yet another aspect of the invention, the fields of Figure 25 may be stacked into layers to form sandwich configurations. When fields **36** are stacked, voids **39** become channels.

In yet another embodiment of the invention, the expanding device may map to the surface of a polyhedron. By this it is meant that the apices of an expanding device define the vertices of a polygon. A plurality of expanding devices may be combined, each defining a face of a polyhedron. The device is capable of changing from a fully contracted state to a fully expanded state. An example of such a mapped polygon structure is shown in Figure 26. Figure 26 shows a four module structure which contains individual expanding 6p5n structures which are used to define a truncated tetrahedron.

Figure 27 illustrates another embodiment of the invention in which a pouch or bladder **530** is attached to the exterior surface of the expandable device. The bladder is constructed to expand upon being filled with fluid or air. The filled bladder can provide cushioning in addition to as other functions, as described further below. The bladder may cover a portion of the exterior surface or essentially the entire exterior surface as required by the application. In certain applications, it can be advantageous to attach a series of bladders to different portions of the exterior surface. The respective bladders in the series may have varying degrees of expansion to impart different properties, such as variable cushioning, across the structure of the device as required.

The expandable device with a bladder is useful in a number of applications. For example, the device can be used as a surgical retractor that provides cushioning to organs displaced within the body. In this application, once the device is positioned inside the body, the bladder can be filled with air via an external pump connected to the bladder with tubing. In another application, the bladder is constructed with a permeable outer skin and the device can be used to deliver fluid to body tissue. In this application, the bladder may be filled with medicine or water from an external source after being appropriately positioned in the body. The fluid then permeates through the outer skin of the bladder to the surrounding tissue. Alternatively, the bladder could be designed to absorb fluid through its permeable outer skin. The bladder also may be used in conjunction with any other devices and structures described herein including larger scale structures such as emergency shelters, building framing systems, amongst others.

Another embodiment of the invention is illustrated in Figure 28 in which the lattice structure of the expandable device surrounds an internal bladder **540**. In this embodiment, forces provided by the internal bladder can cause the device to expand or retract. For example, filling the internal bladder with fluid or air can cause the device to expand. Alternatively, emptying fluid or air from the bladder can cause the device to contract. The degree to which the device expands or retracts in response to forces from the bladder depends upon the structure of the lattice, for example the number of nodes, the type of interconnector, and the like. These lattice structure parameters can be selected to provide the desired expansion/contraction required by the application. In preferred cases, the device is designed to expand and contract uniformly.

The expandable device with an internal bladder can be used in a number of applications. For example, the device can be used as a kinematic container that changes its shape to fit the size of its contents and, thus, efficiently utilizes storage space. Other applications include artificial organs, such as an artificial bladder. The device may also be used for stent delivery with the bladder serving as a balloon and the external structure as a casing. In this application, the uniform expansion of the device provides an advantage over traditional balloon and casing assemblies which typically bulge at the ends during expansion and can cause deformation of the stent.

The devices described herein may be prepared in a variety of ways.

The devices may be assembled in conventional manner used to assemble medium-to-large sized devices. This includes manual and machine-assisted assembly of the individual component elongated members, interconnectors and optional joinder elements. In particular, the design of the devices may be aided by the use of computer-added design (CAD) programs. Such programs are able to identify the number and positioning of nodes, the number and length of elongated members required to obtain a desired structure, to obtain a desired ratio of inner to outer diameter and/or to obtain a desired expansion profile.

The devices may also be prepared using self assembly techniques. In a self assembly method, a mask containing a predetermined pattern is stamped on a flat or curved surface using soft lithographic techniques. The mask is a two-dimensional quasi-crystal of molecules, such as alkanethiols, that self-assemble when apposed to a flat or curbed surface coated with gold of other metals. The patterned mask may be used to guide formation of a metal structure using electrochemical deposition of metal followed by dissolution of the substrate, for example by wet-chemical etching, to form a three-dimensional microstructure. Tubular material that can itself be chemically etched, in this case, the mask, acts as a protectant and defines the final form of the material that remains. The hinging mechanism or interconnectors are typically formed by thinned regions in the metallic struts. Examples of this technique can be found in Jackman *et al.*, *Science*, **280**:2089 (June 1998); Jackman *et al.*, *J. Microelectomech. Syst.* 7(2):261 (June 3, 1998); Terfort *et al.*, *Nature* **386**:162 (March, 1997); and U.S. Patent No. 5,776,748.

What is claimed is:

1. An expandable device, comprising:

a plurality of elongated members interconnected to form a first lattice structure, some of the elongated members intersecting at least one other elongated member at interior positions along the length of both intersecting elongated members to define nodes; and

a flexible interconnector located at some of the nodes, the flexible interconnectors connecting the intersecting elongated members and permitting motion between the intersecting elongated members to enable radial compression or expansion of the first lattice structure.

2. The expandable device of claim 1, wherein the elongated members are arranged to define a hyperboloid of revolution.

3 The expandable device, of claim 1, wherein some of the elongated members are joined at their respective ends to an end of at least one other elongated member by flexible joinder elements thereby forming an apex.

4. The expandable device of claim 1, wherein the flexible interconnector permits more than one degree of freedom of motion.

5. The expandable device of claim 1, wherein the expandable device is capable of a range of motion from a rest state to a use state.

6. The expandable device of claim 1, wherein the expandable device is capable of a range of motion such that in a collapsed state the elongated members are substantially axially aligned along a longitudinal axis of the device and the device is substantially cylindrical, and in an expanded state the elongated members are substantially perpendicular to the longitudinal axis and the device is substantially planar.

7. The expandable device of claim 1, characterized in that upon radial expansion, the device is shortened in length.

8. The expandable device of claim 1, wherein the flexible interconnector is selected from the group consisting of flexible bands, splines, x-joints, ball and socket joints, flexible connectors tethered to the respective nodes of the elongated members, and flexible pins.

9. The expandable device of claim 1, wherein the flexible interconnector and the elongated member are an integral structure.

10. The expandable device of claim 9, wherein the integral structure comprises regions of differing structure or composition.

11. The expandable device of claim 9, wherein the integral structure is prepared using a technique selected from the group consisting of molding, solid free form fabrication, casting or micro self-assembly techniques.

12. The expandable device of claim 3, wherein the flexible joinder elements are selected from the group consisting of springs, flexible tubing, shape-memory hinges and wire.

13. The expandable device of claim 3, wherein the flexible joinder elements comprise Nitanol.

14. The expandable device of claim 3, wherein the elongated members and the flexible joinder elements are an integral structure.

15. The expandable device of claim 14, wherein the integral structure is comprised of a unitary wire.

16. The expandable device of claim 14, wherein the integral structure is prepared using a technique selected from the group consisting of molding, solid free form fabrication, casting or micro self-assembly techniques.

17. The expandable device of claim 3, wherein the elongated members are hollow.

18. The expandable device of claim 17, wherein the flexible joinder elements comprise a continuous wire fed through the hollow elongated members.

19. The expandable device of claim 1, wherein the elongated members are comprised of a material selected from the group consisting of surgical stainless steel, high molecular weight polypropylene, polyethylene and respective derivatives thereof, and titanium and its alloys.

20. The expandable device of claim 1, wherein the elongated members are comprised of a material selected from the group consisting of wood, metal, polymer and ceramics.

21. The expandable device of claim 1, wherein the elongated members have a cross-section selected from the group consisting of triangular, rectangular, oval and round.

22. The expandable device of claim 1, wherein the elongated members are curved.

23. The expandable device of claim 1, wherein the elongated members are comprised of a plurality of discontinuous members connected at the interconnector.

24. The expandable device of claim 1, wherein a position, and a number of nodes and elongated members are selected to obtain a preselected expansion ratio defined as a ratio of the largest inner diameter to smallest outer diameter.

25. The expandable device of claim 2, wherein a position, and a number of nodes and elongated members are selected to obtained a preselected curvature of the hyperboloid surface of the device.

26. The expandable device of claim 1, wherein the position, and a number of nodes and elongated members are selected to obtained a preselected axial shortening during

expansion.

27. The expandable device of claim 1, wherein the nodes are evenly spaced along a length of the elongated member.

28. The expandable device of claim 1, wherein the nodes are irregularly spaced along a length of the elongated member.

29. The expandable device of claim 1, wherein the structure includes an opening in an external surface.

30. The expandable device of claim 29, wherein the nodes are arranged to provide the opening in the external surface.

31. The expandable device of claim 29, wherein an elongated member is selectively omitted to provide the opening in the external surface.

32. The expandable device of claim 1, further comprising a locking mechanism for fixing the expandable device at a predetermined degree of expansion.

33. The expandable device of claim 32, wherein the locking mechanism comprises a polymer.

34. The expandable device of claim 32, wherein the locking mechanism comprises a shape memory alloy.

35. The expandable device of claim 34, wherein the device comprises two or more shape memory locking mechanisms and said mechanisms are treated to actuate to different degrees of expansion.

36. The expandable device of claim 1, wherein the plurality of elongated members comprise a plurality of wires, each of said wires arranged in a zigzag configuration

having apices that define circular bands, the plurality of zigzag wires being aligned along a longitudinal direction such that the circular bands are superimposed on each other and the apices of each zigzag wire are offset from neighboring apices along a circle defining a transaxial cross-section of the device.

37. The expandable device of claim 1, further comprising a membrane covering an outer surface of the device.

38. The expandable device of claim 37, wherein the device is a shelter.

39. The expandable device of claim 1, wherein the device is a medical or veterinary device and the device is sized for insertion into a body.

40. The expandable device of claim 39, wherein the device is constructed for use as a stent.

41. The expandable device of claim 39, wherein the device is a multimodular branched structure.

42. The expandable device of claim 40, wherein the device is constructed for use as an expander for a conventional expansion stent.

43. The expandable device of claim 39, wherein the device is constructed for use as a surgical retractor.

44. The expandable device of claim 39, wherein the device is constructed for use as a surgical space creator.

45. The expandable device of claim 39, wherein the device is constructed for use as a medical drain.

46. The expandable device of claim 39, wherein the device is constructed for use as

a controllable valve on a drain.

47. The expandable device of claim 39, wherein the device is constructed for use as a connector for hollow organs.

48. The expandable device of claim 39, wherein the device is an expanding reamer and further comprises a cutting means attached to an external surface of the device.

49. The expandable device of claim 1, wherein the device is constructed for use as a feminine hygiene product and further comprises a collector at an open end of the expandable device.

50. The expandable device of claim 43, further comprising a pneumatic coating on an external surface of the expandable device.

51. The expandable device of claim 1, wherein the device is a residential framing system that is sized for use as a building.

52. The expandable device of claim 1, wherein the device is a supportive structure for cooling towers that is sized for use as a cooling tower and further comprises a membrane coating an outer surface of the tower.

53. The expandable device of claim 1, wherein the device is used as a deployable mast, comprised of a plurality of lattice structures stacked end on end and characterized in that the mast may be compacted planarly.

54. The expandable device of claim 1, wherein the device is an exhibit structure and is comprised of light weight materials.

55. The expandable device of claim 1, wherein the structure can be mapped onto the surface of a polyhedron and thereby made to expand.

56. The expandable device of claim 1, further comprising a bladder attached to an exterior surface of the first lattice structure.

57. The expandable device of claim 56, wherein the bladder includes a permeable outer skin.

58. The expandable device of claim 56, wherein the device is used to deliver fluid to or absorb fluid from body tissue.

59. The expandable device of claim 1, further comprising a bladder internal of the first lattice structure.

60. The expandable device of claim 59, wherein the expandable device is used as a kinematic container.

61. The expandable device of claim 59, wherein the expandable device is used for stent delivery.

62. The expandable device of claim 59, wherein the expandable device is used as an artificial bladder.

63. The expandable device of claim 1, further comprising additional lattice structures joined with the first lattice structure to form a plurality of lattice structures, each additional lattice structure formed from a plurality of interconnected elongated members, some of the elongated members intersecting at least one other elongated member at interior positions along the length of both intersecting elongated members to define nodes, each lattice structure including a flexible interconnector located at some of the nodes, the flexible interconnectors connecting the intersecting elongated members and permitting motion between the intersecting elongated members to enable radial compression or expansion of the respective lattice structures.

64. The expandable device of claim 63, wherein the plurality of lattice structures are

joined at respective apices.

65. The expandable device of claim 63, wherein the plurality of lattice structures are joined at a position along a pair of elongated members defining an apex.

66. The expandable device of claim 63, wherein the plurality of lattice structures are joined at a position along a pair of elongated members located on adjacent apices.

67. The expandable device of claim 63, wherein the plurality of lattice structures are joined to form a column.

68. The expandable device of claim 63, wherein the plurality of lattice structures are joined to form an arch.

69. The expandable device of claim 63, wherein the plurality of lattice structures are joined to form a spiral.

70. The expandable device of claim 63, wherein the plurality of lattice structures are joined to form a knot.

71. The expandable device of claim 63, wherein the plurality of lattice structures are adjacent to one another and joined to form a field.

72. The expandable device of claim 71, wherein the plurality of lattice structures used in the formation of the field comprise the same number of points.

73. The expandable device of claim 71, wherein the plurality of lattice structures used in the formation of the field comprise differing numbers of points.

74. The expandable device of claim 71, wherein the plurality of lattice structures are arranged to form a space filling field.

75. The expandable device of claim 71, wherein the plurality of lattice structures are arranged to form a field comprising voids.

76. The expandable device of claim 71, further comprising a plurality of fields joined to form a sandwich structure.

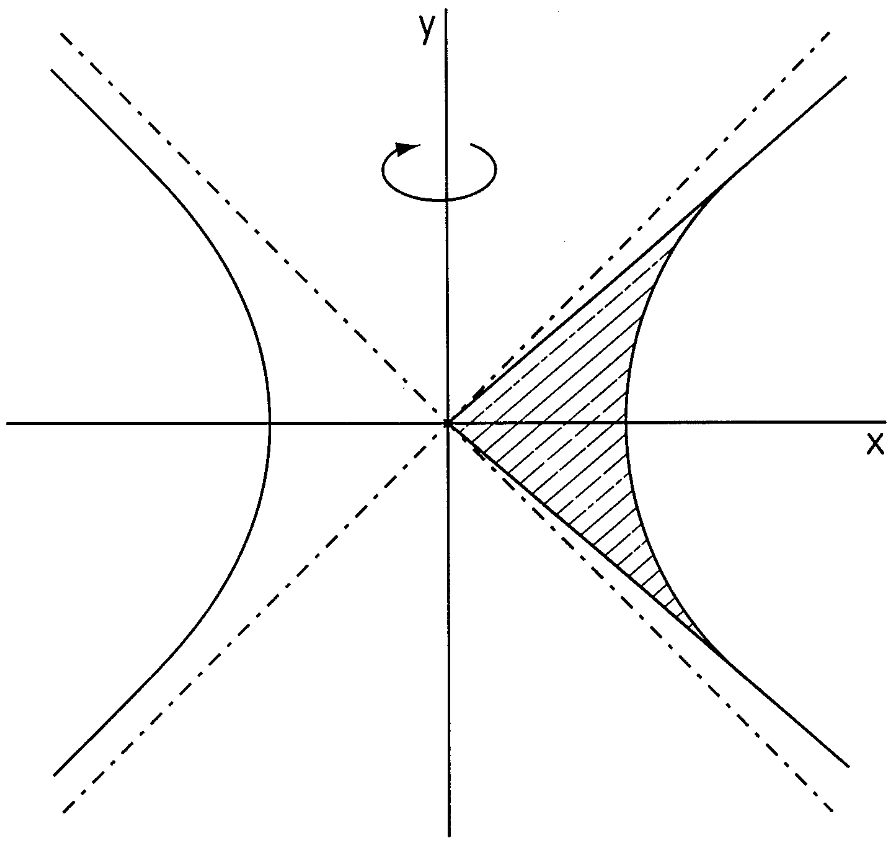


Fig. 1

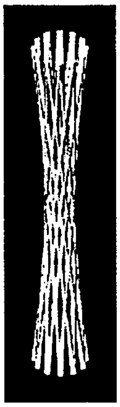


Fig. 2A

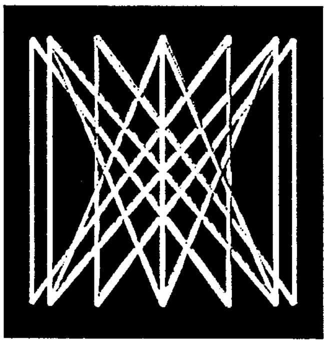


Fig. 2B

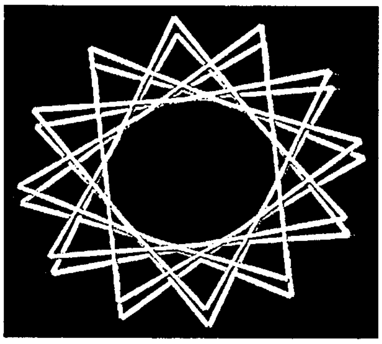


Fig. 2C

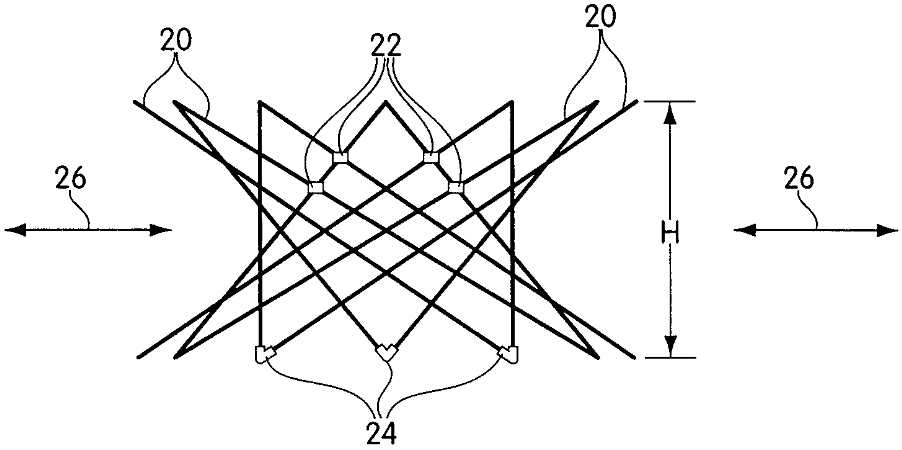


Fig. 3A

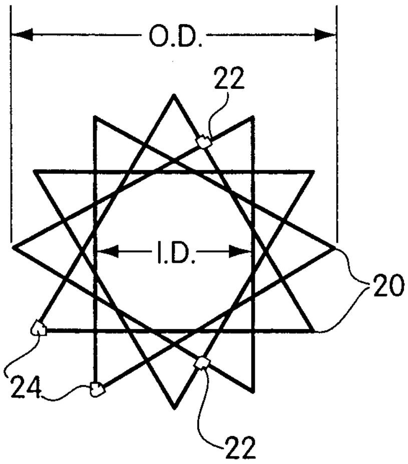


Fig. 3B

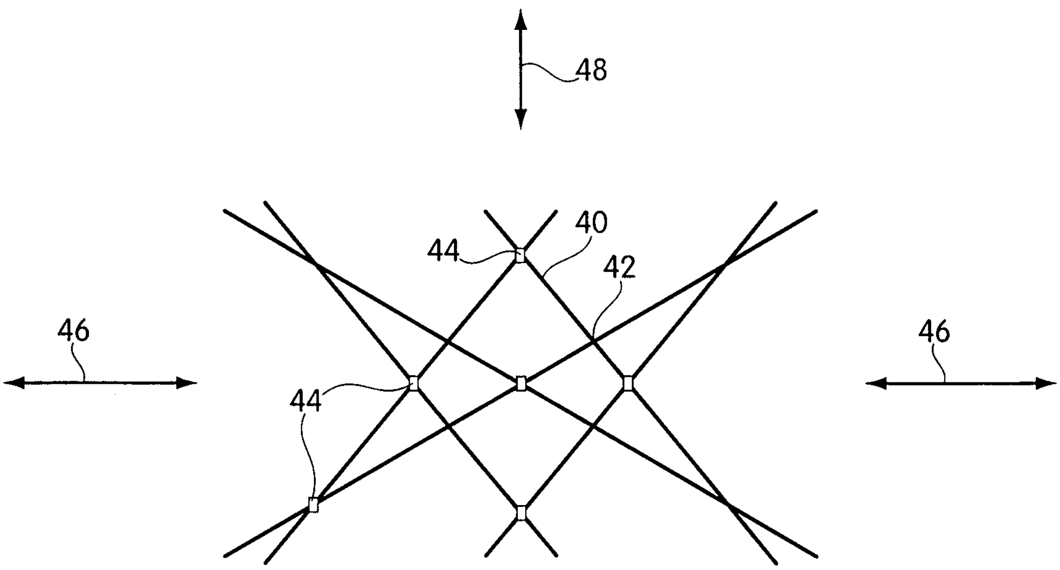


Fig. 4

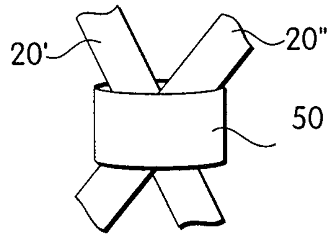


Fig. 5A

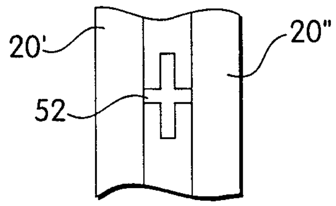


Fig. 5B

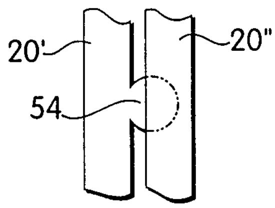


Fig. 5C

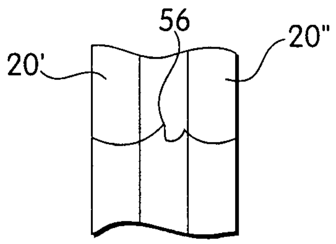


Fig. 5D

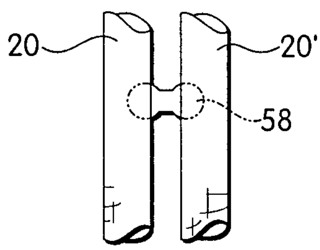


Fig. 5E

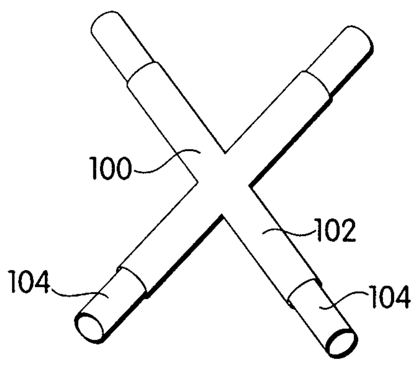


Fig. 6A

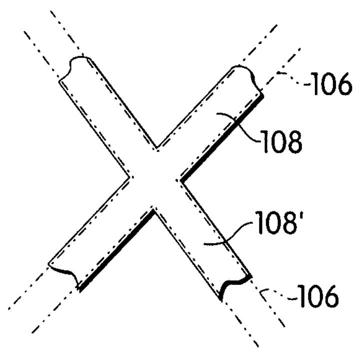


Fig. 6B

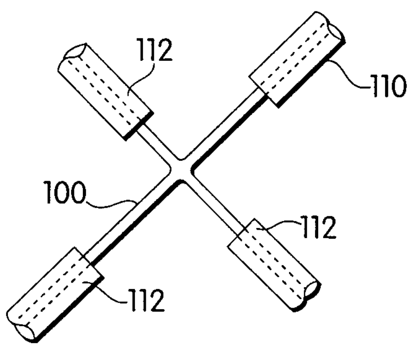


Fig. 6C

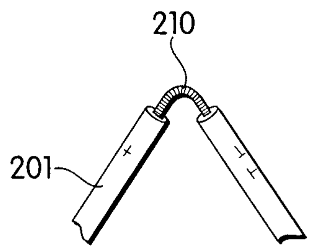


Fig. 7A

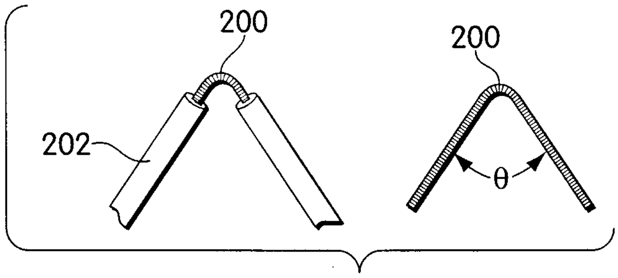


Fig. 7B

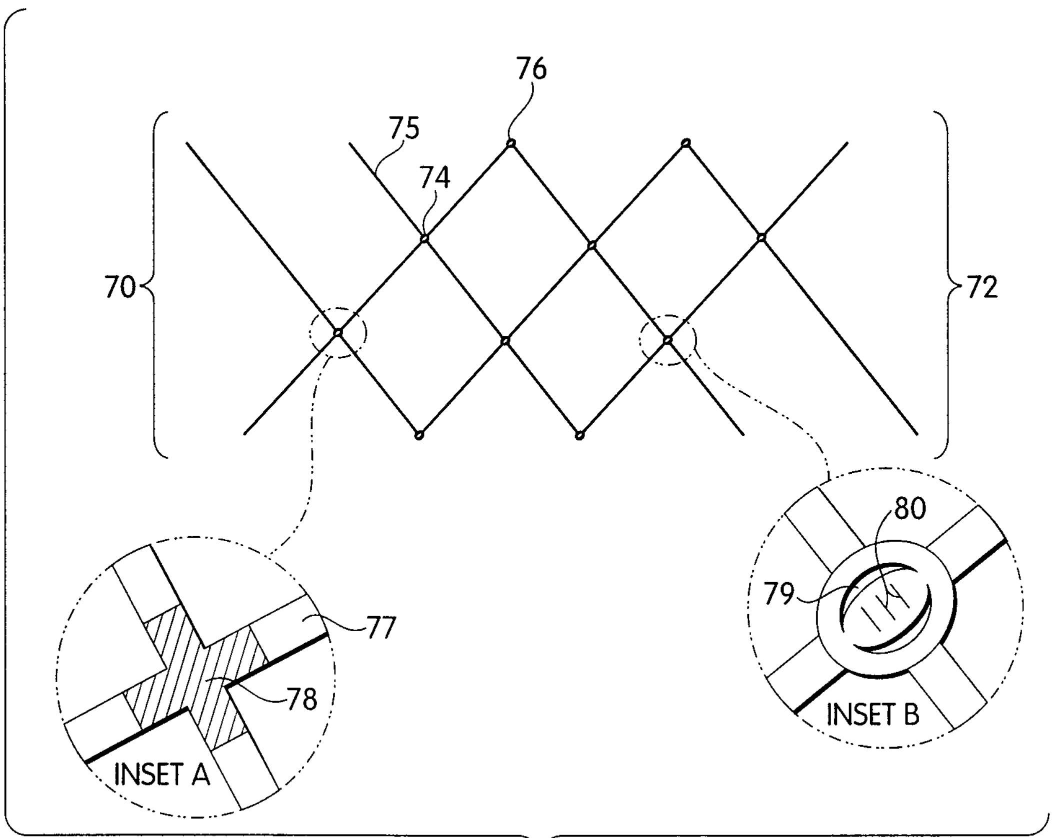


Fig. 8

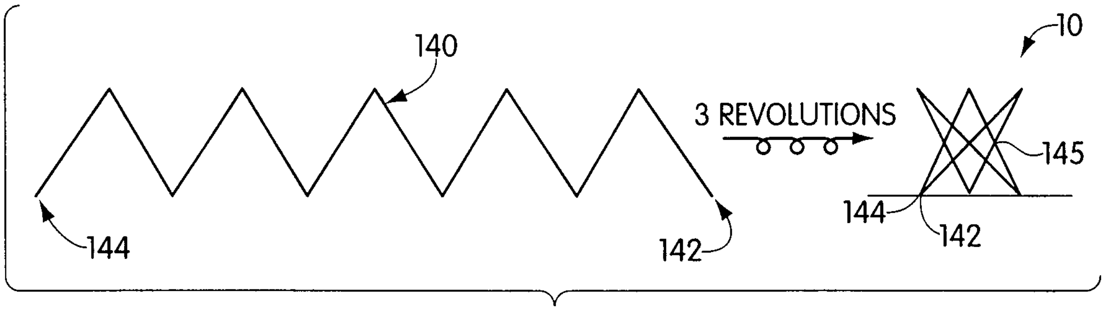

140
3 REVOLUTIONS
10
145
144
142
144
142

Fig. 9

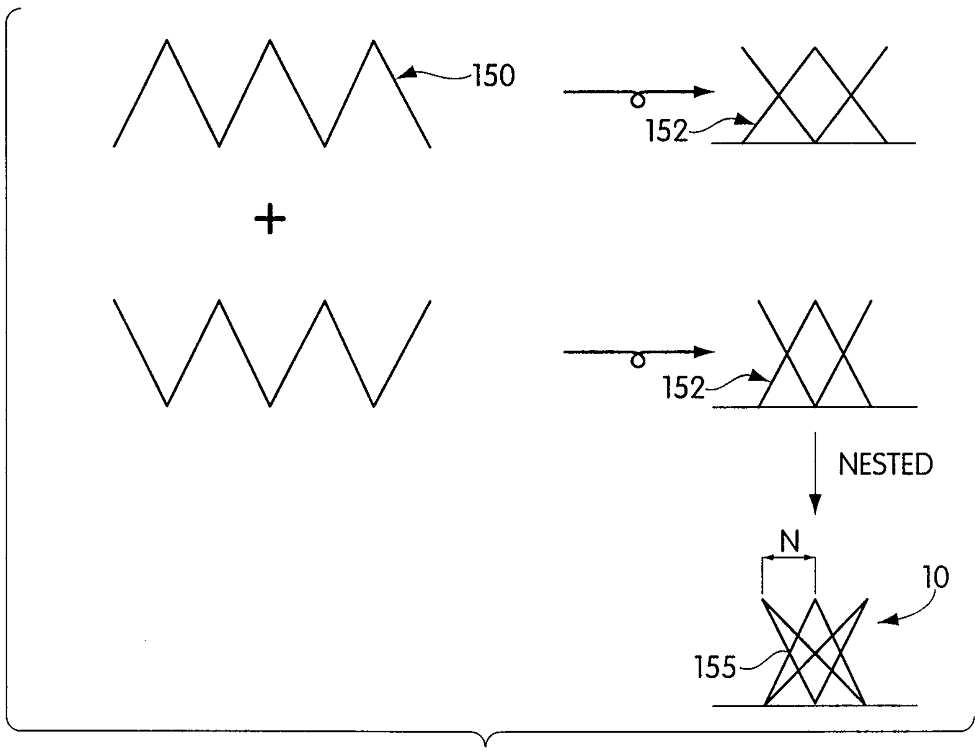

150
152
+
152
NESTED
N
10
155

Fig. 10

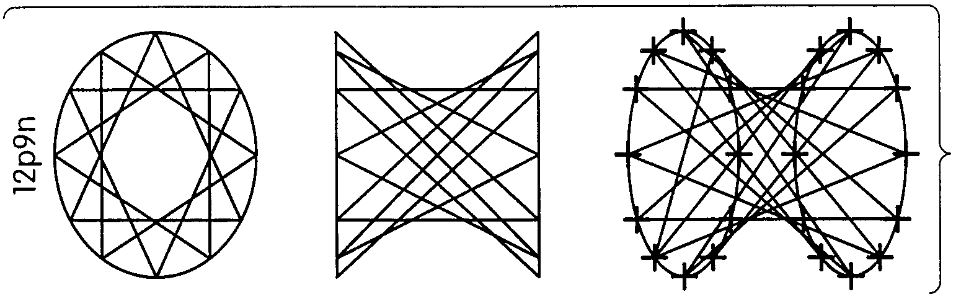


Fig. 11D

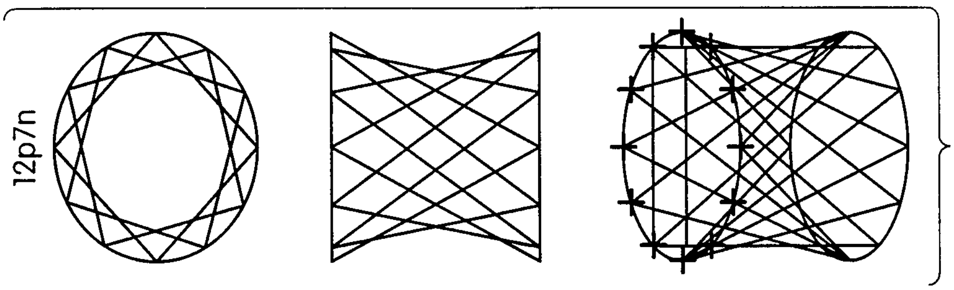


Fig. 11C

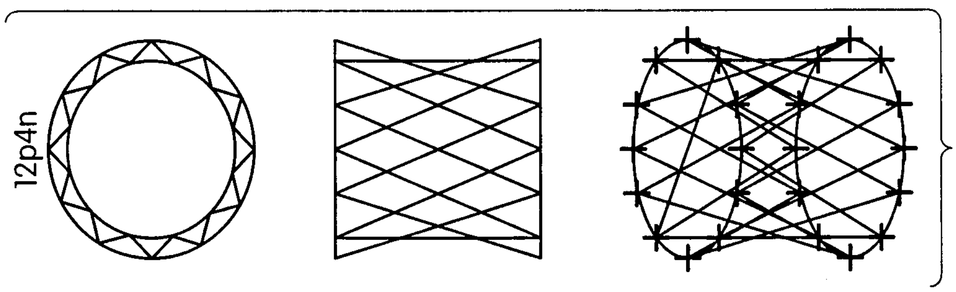


Fig. 11B

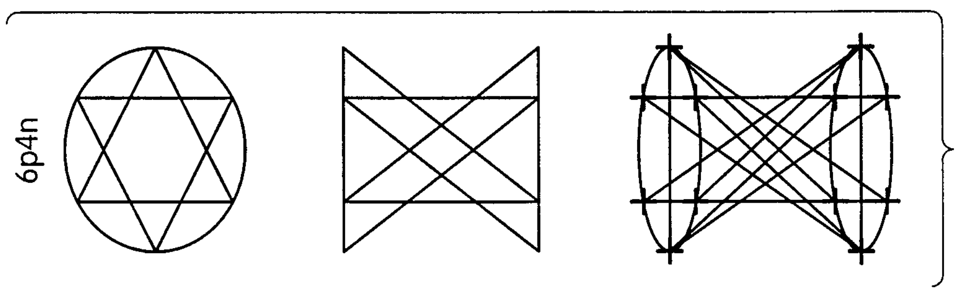


Fig. 11A

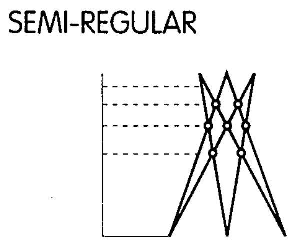


Fig. 12A

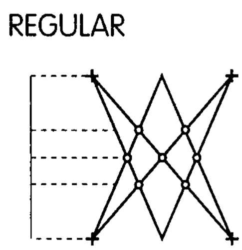


Fig. 12B

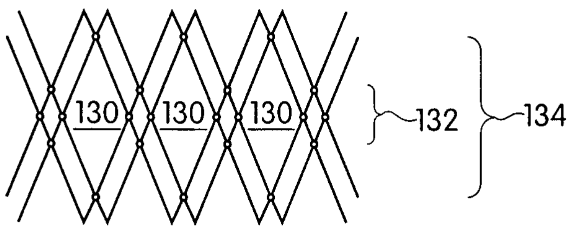


Fig. 13

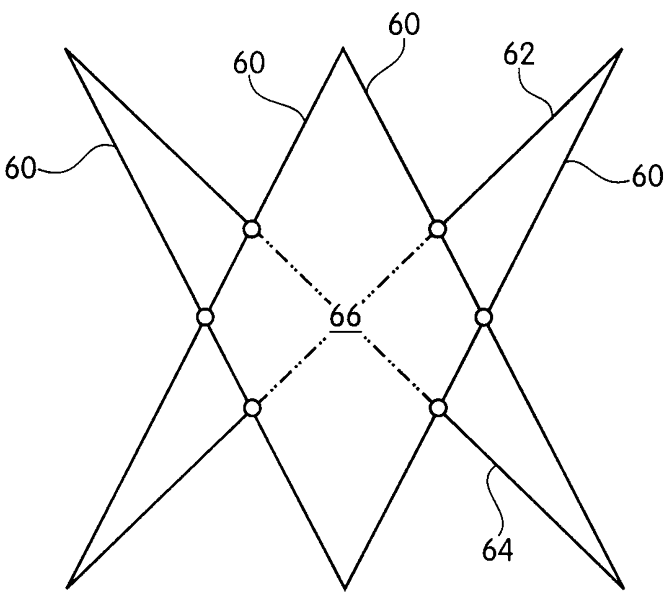
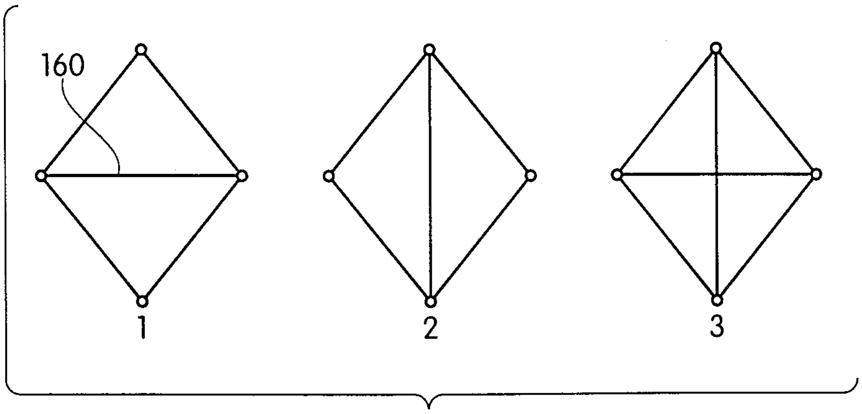
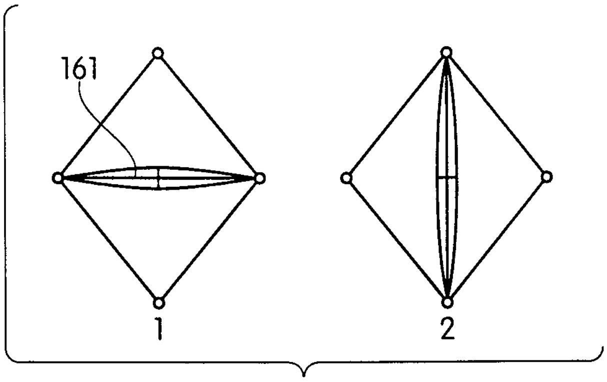


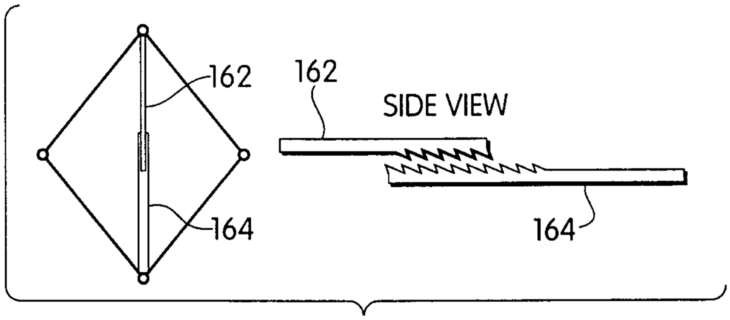
Fig. 14



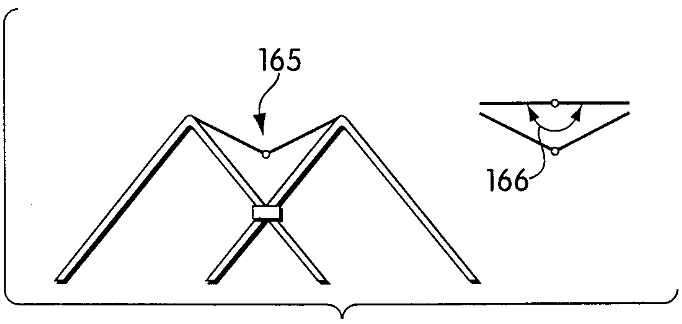
15A



15B



15C



15D

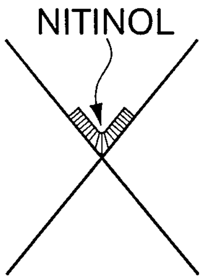


Fig. 16A

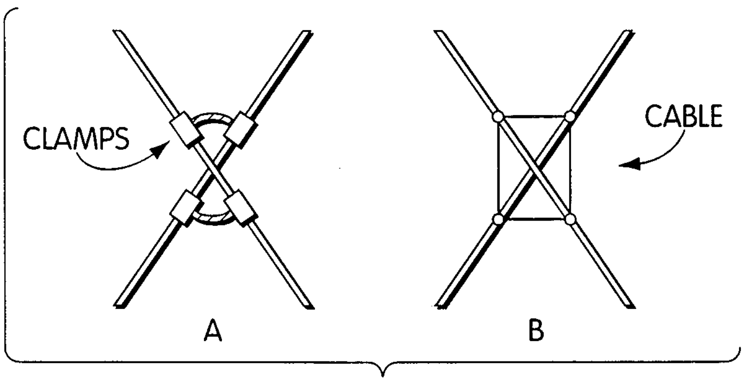


Fig. 16B

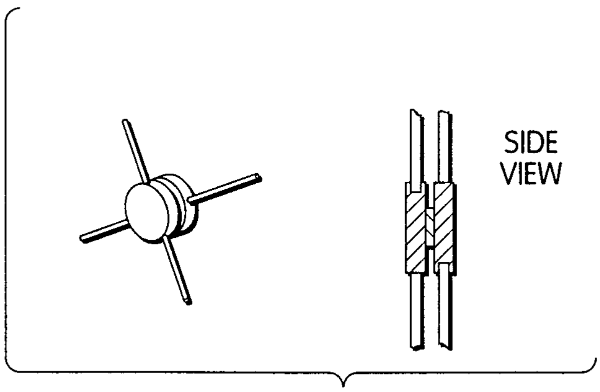


Fig. 16C

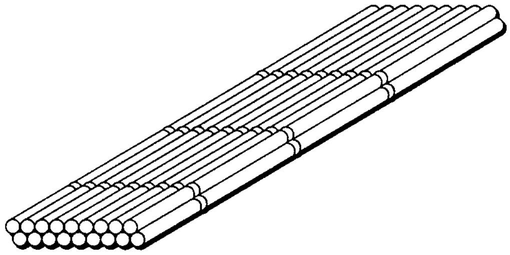


Fig. 17A

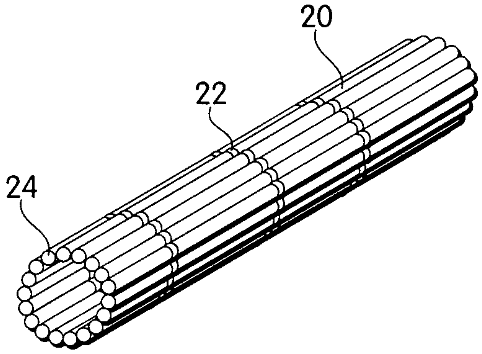


Fig. 17B

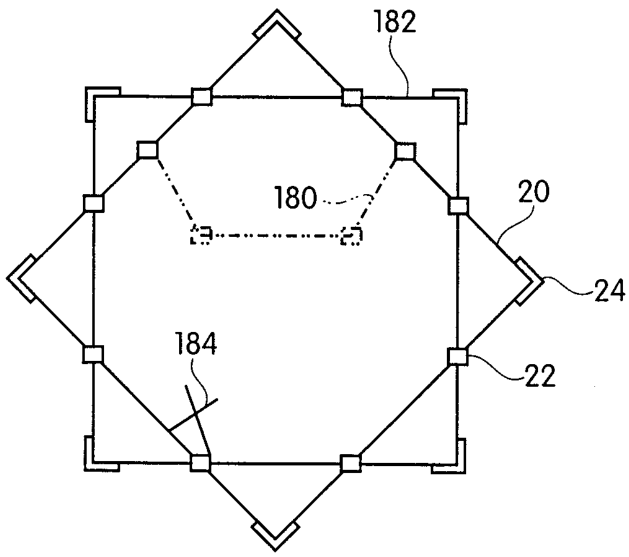


Fig. 18

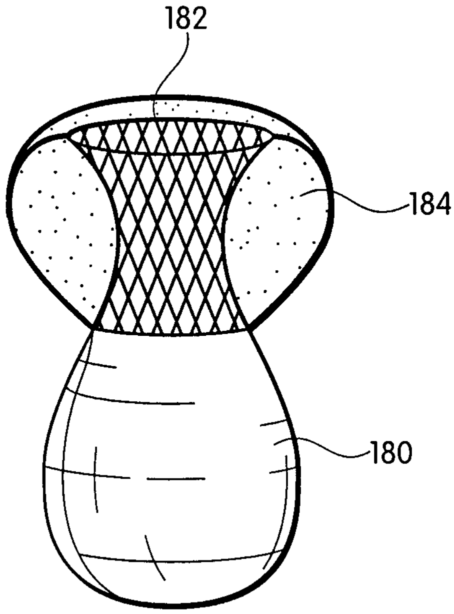


Fig. 19

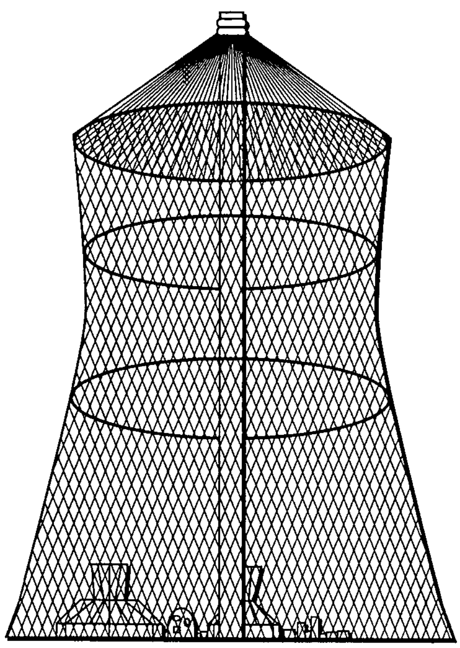


Fig. 20

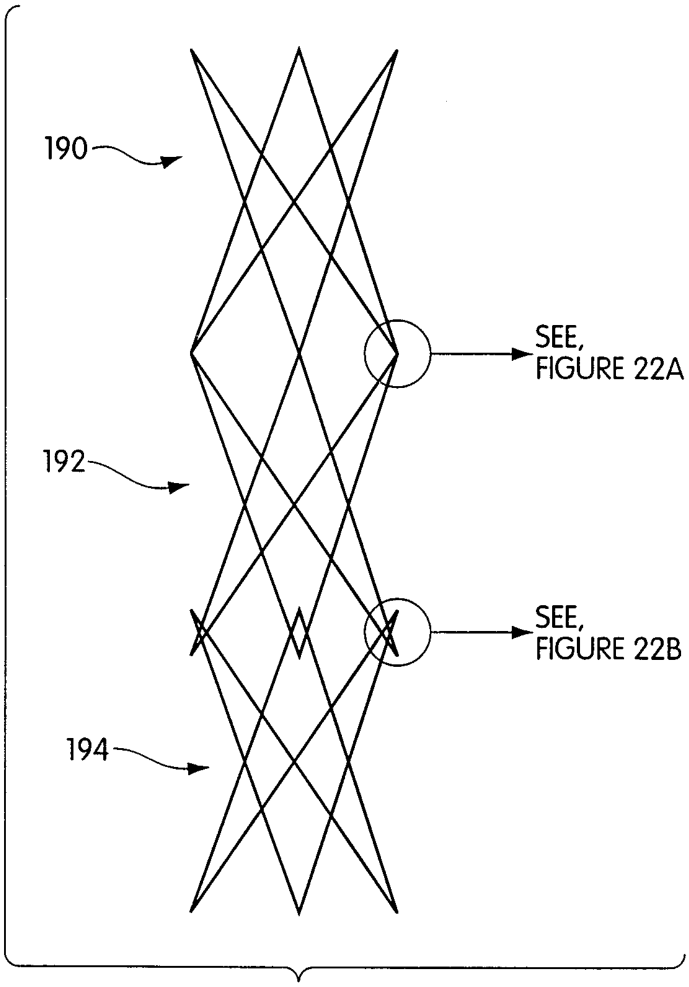


Fig. 21A

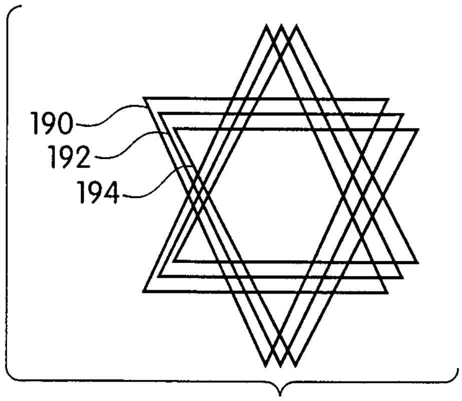


Fig. 21B

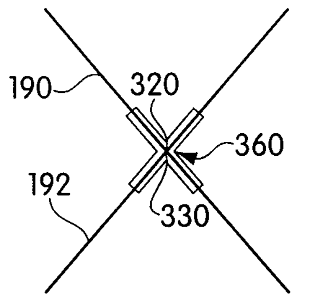


Fig. 22A

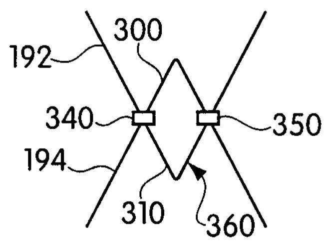


Fig. 22B

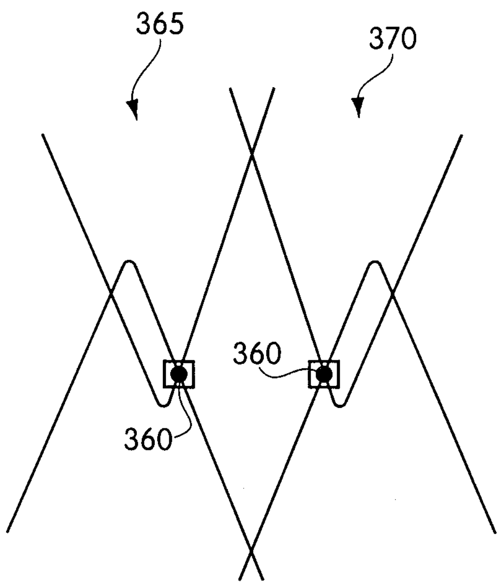


Fig. 22C

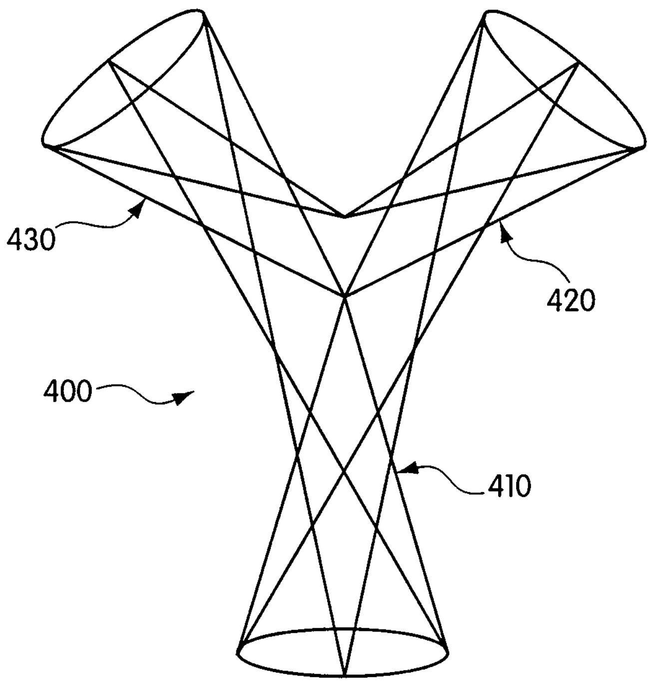


Fig. 23

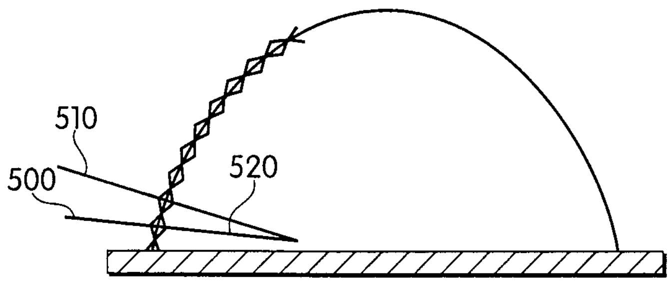


Fig. 24A

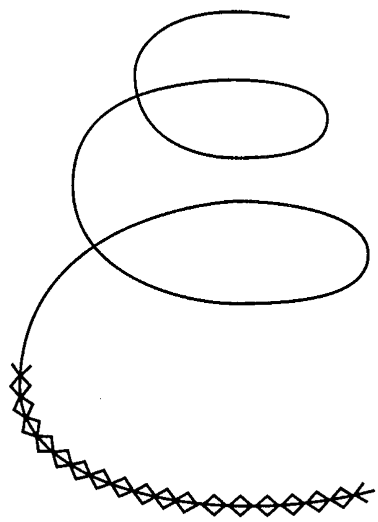


Fig. 24B

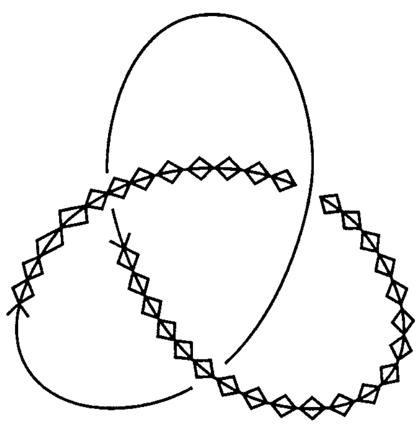


Fig. 24C

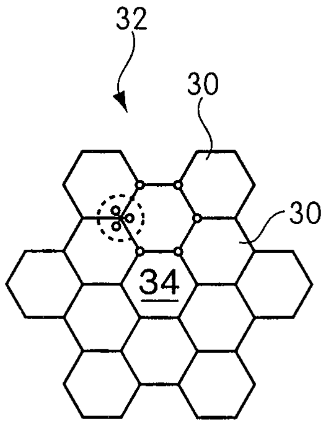


Fig. 25A

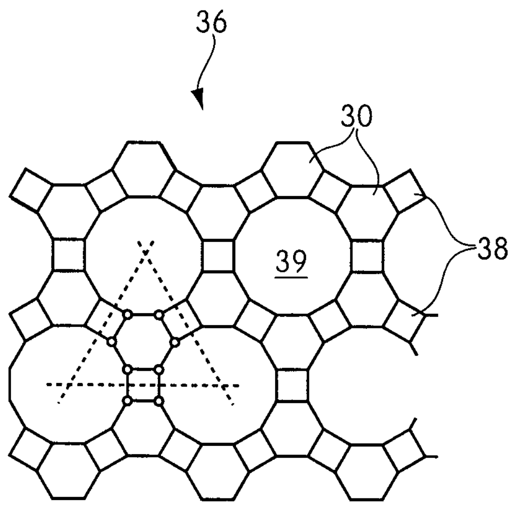


Fig. 25B

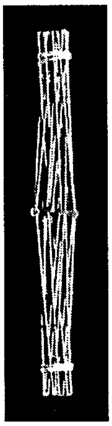


Fig. 26A

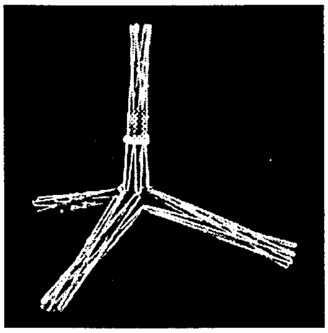


Fig. 26B

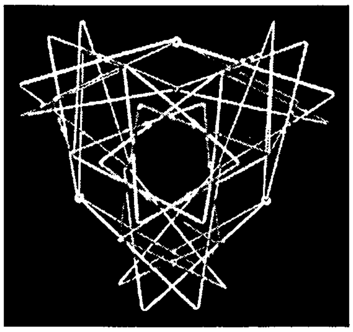


Fig. 26C

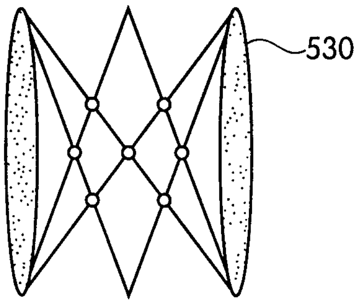


Fig. 27

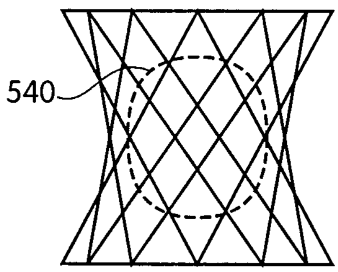


Fig. 28