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(54) **ARCHITECTURAL MEMBRANE STRUCTURES AND METHODS FOR PRODUCING THEM**

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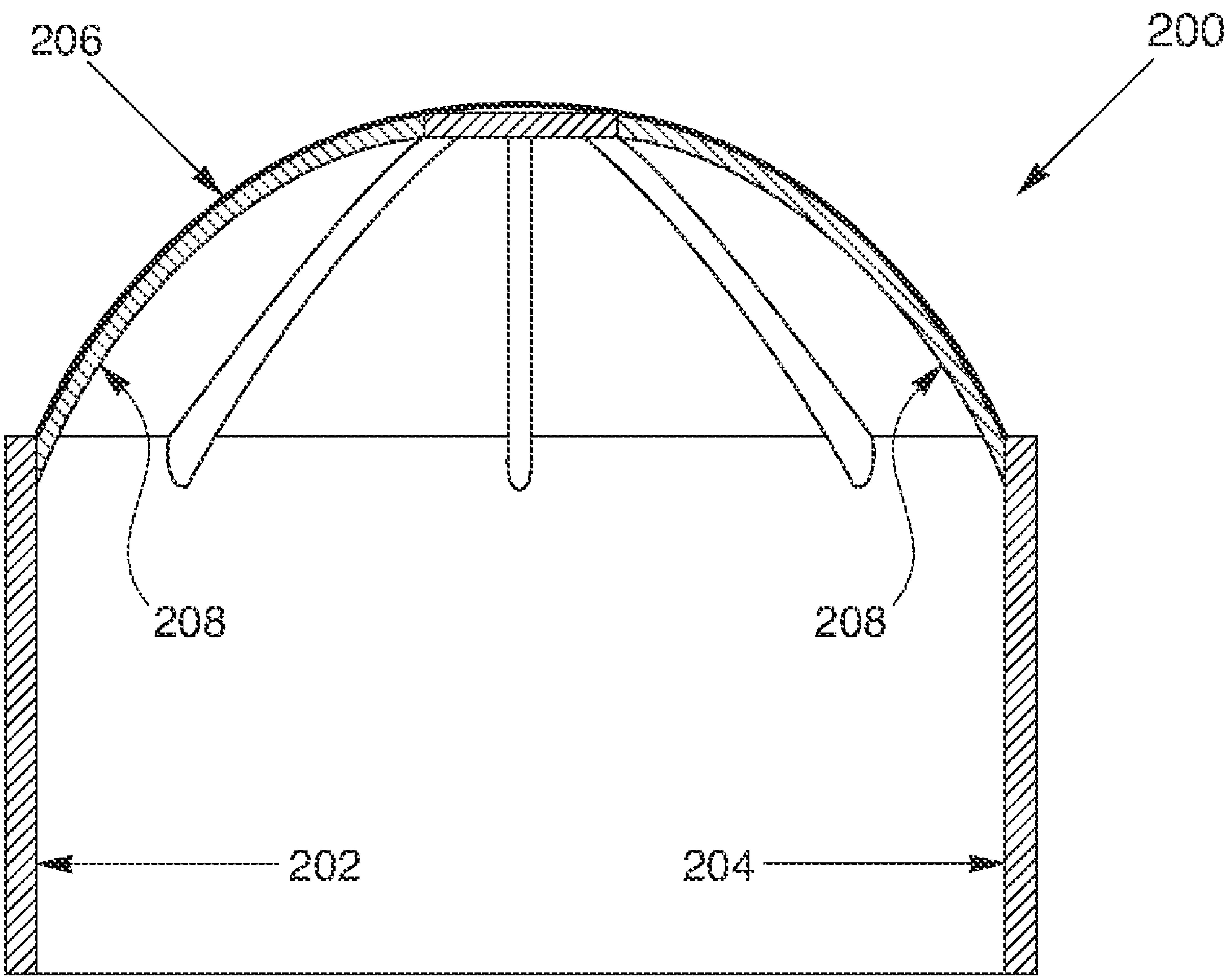
(57) **ABSTRACT**

An architectural membrane structure preferably includes an aerogel material disposed, for example, between two outer layers. The aerogel can be in monolithic or granular form or can be present in an aerogel composite. A method for manufacturing an architectural membrane structure includes securing an insert, e.g., an aerogel blanket, composite or granular aerogel, between a first and second layer. The architectural membrane structure can be used as a tensioned panel in envelopes such as roofing, overhangs, canopies or in other architectural or structural fabric applications.



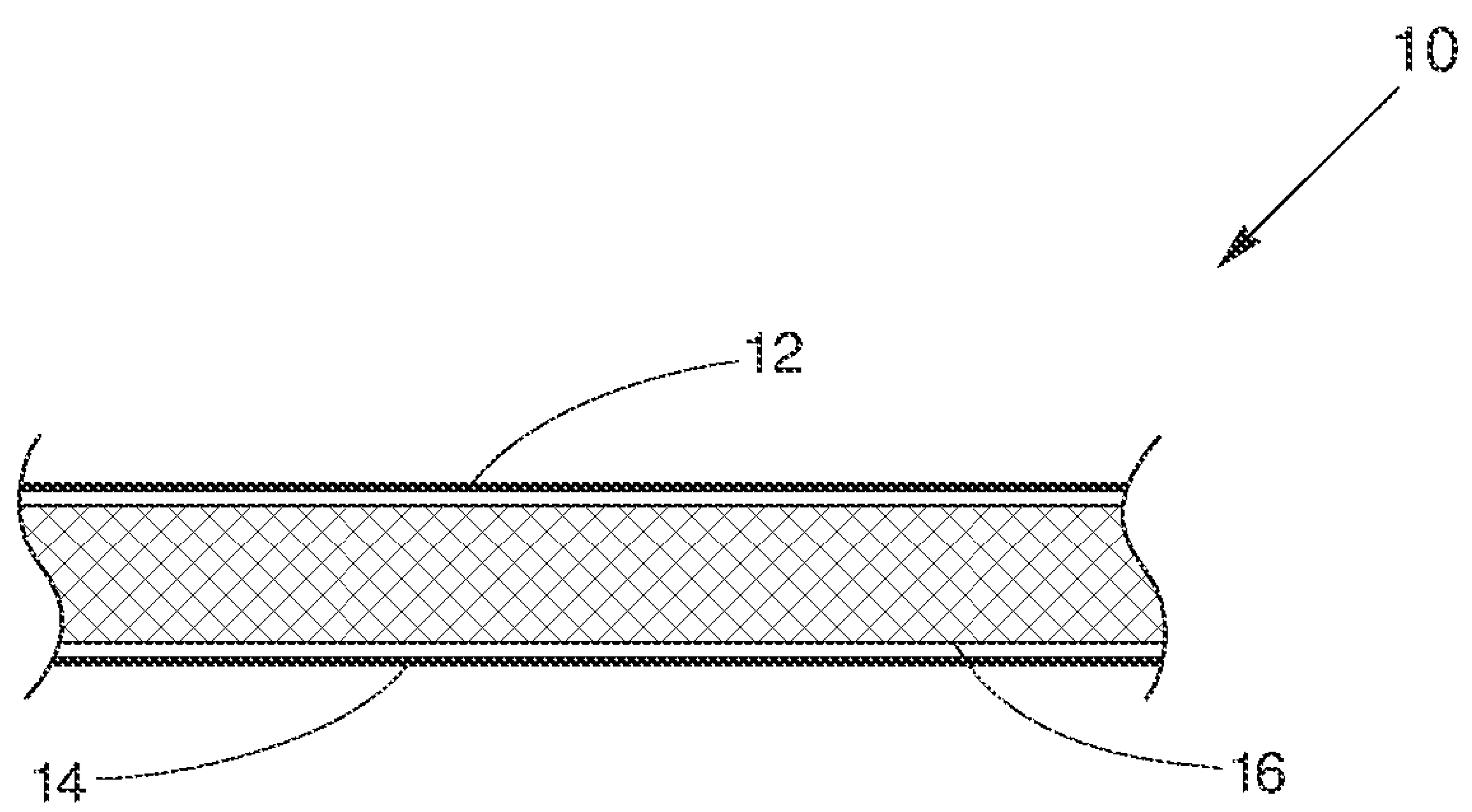


Fig. 1

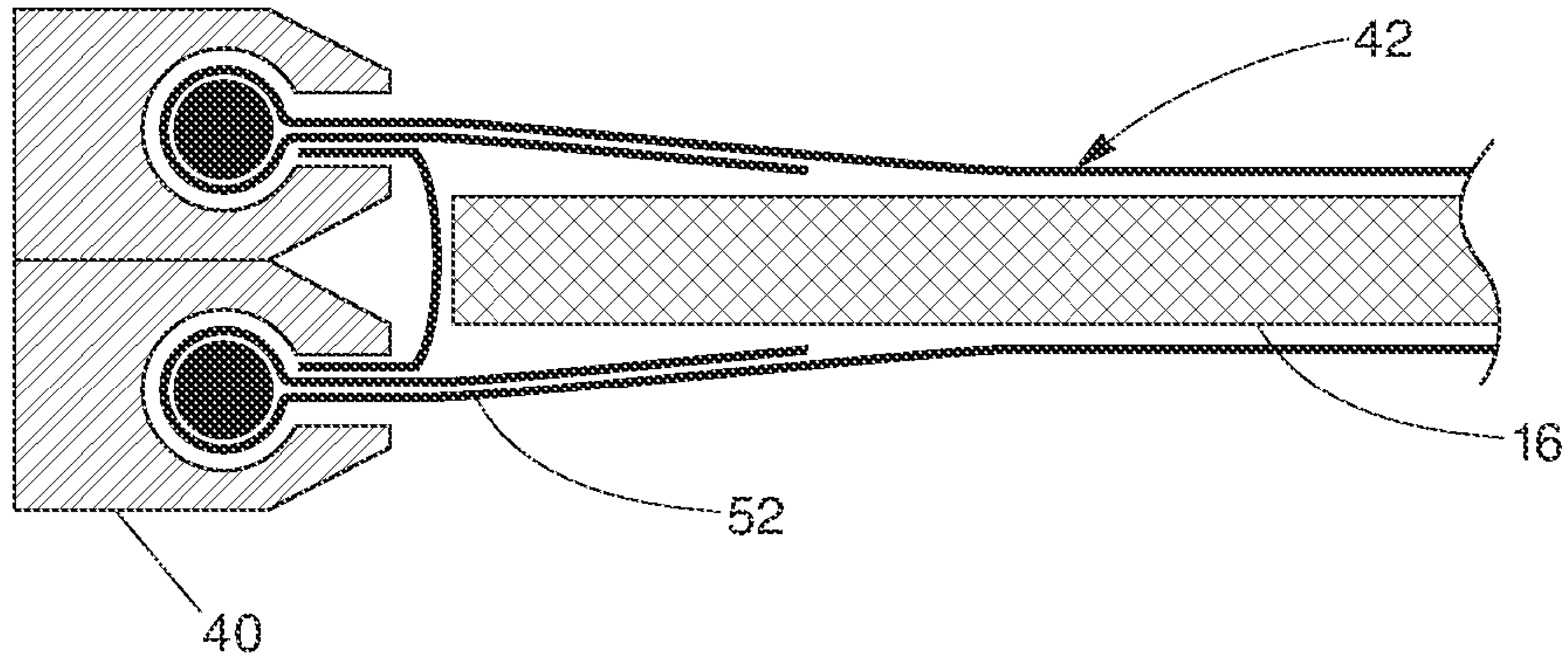


Fig. 2

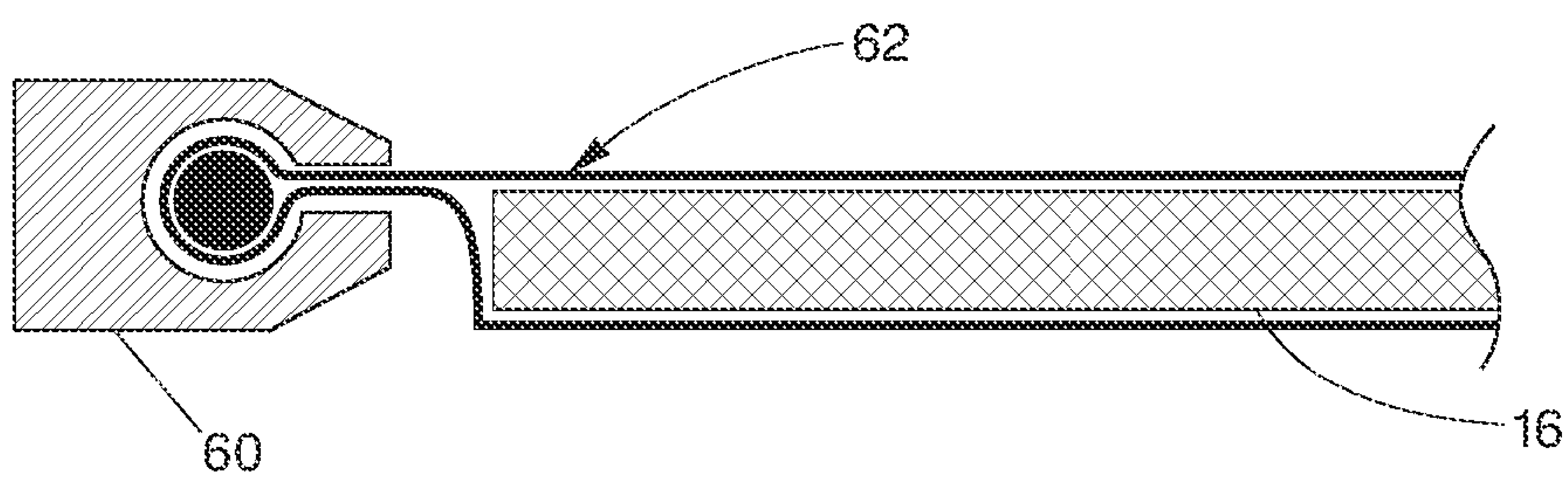


Fig. 3

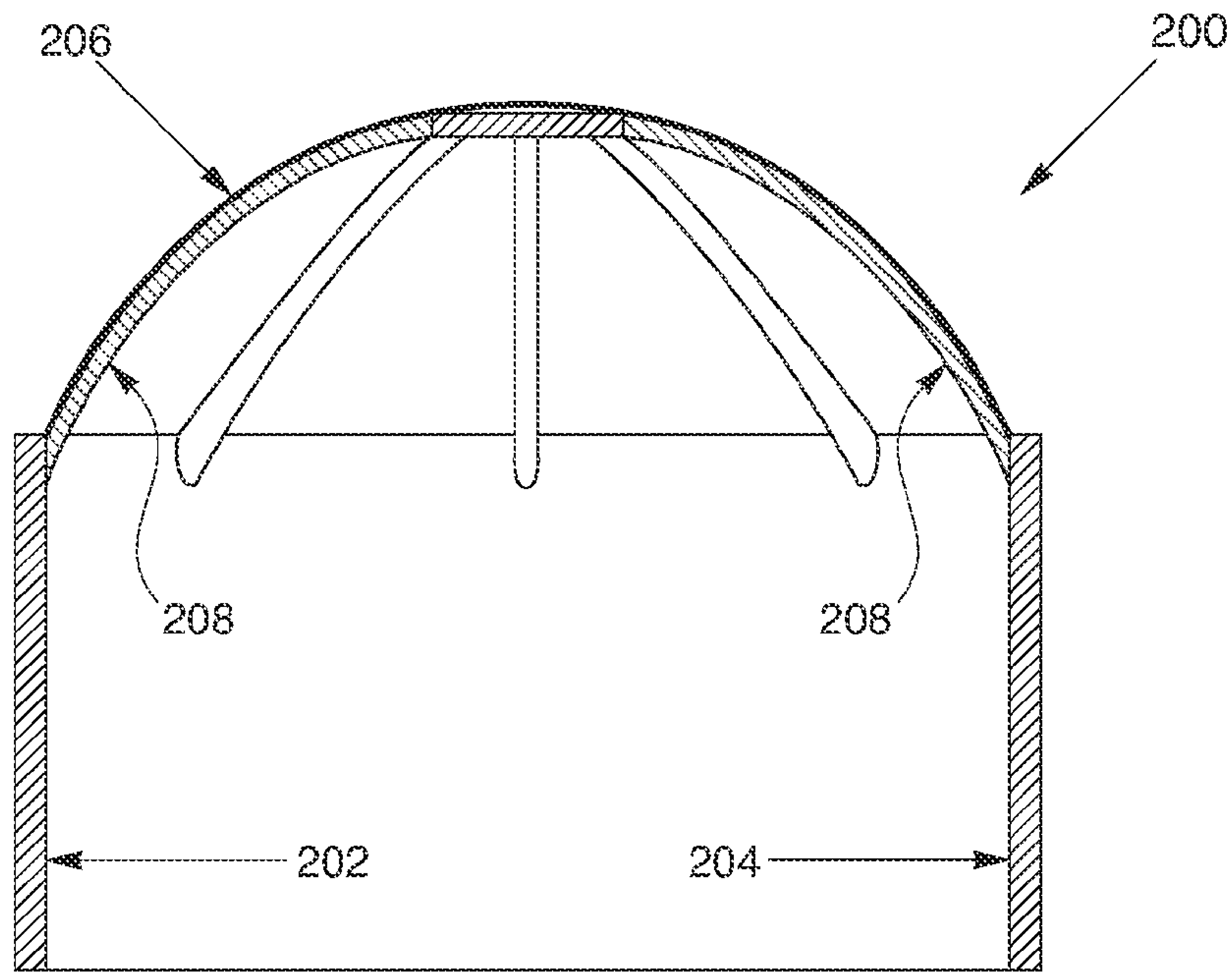


Fig. 4A

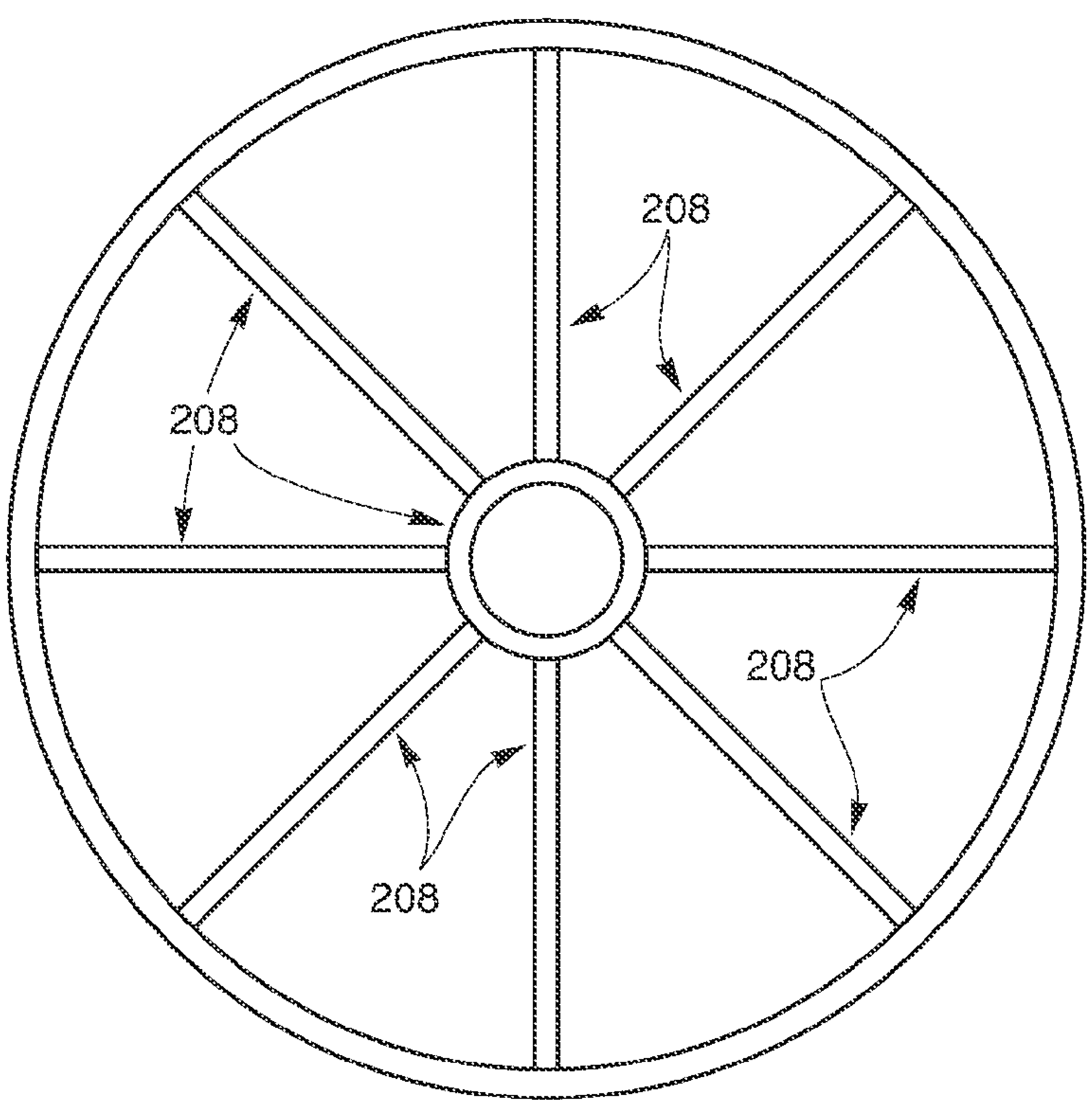


Fig. 4B

ARCHITECTURAL MEMBRANE STRUCTURES AND METHODS FOR PRODUCING THEM

RELATED APPLICATIONS

[0001] This application claims the benefit of U.S. Provisional Application No. 60/896,664, filed Mar. 23, 2007; U.S. Provisional Application No. 60/896,904, filed Mar. 24, 2007; and U.S. Provisional Application No. 60/908,057, filed Mar. 26, 2007. The teachings of these applications are incorporated herein by reference in their entirety.

BACKGROUND OF THE INVENTION

[0002] Architectural membranes, also known as tensile or tensioned structures, are increasingly used in building airports, storage facilities, arenas, activity centers, sports or gathering venues, domes, museums, housing and so forth. Architectural membranes provide great design flexibility in roofing, canopies, overhangs and other envelope structures. They can be custom fabricated to various shapes. Pre-assembled modules also are available.

[0003] Examples of existing designs that incorporate architectural membranes include the Talisman Center in Calgary, Canada, the Millennium Dome in the United Kingdom, the Denver International Airport, air-supported roofs such as the one used at the Indianapolis RCA dome, and many others.

[0004] Architectural membranes can be characterized with respect to their lighting, energy, durability or acoustic properties and for fire performance using known techniques, codes and industry standards, such as, for instance, those developed by the American Society for Testing and Materials (ASTM). Light transmission and spectral reflectance, for example, can be determined using ASTM E424; acoustical properties using ASTM E-90; and fire performance using ASTM E-108 or ASTM E-84.

[0005] Existing architectural membranes include those known under the name Sheerfill® provided by Saint-Gobain Corporation. Generally Sheerfill® architectural membranes are based on woven Teflon®-coated fiberglass fabrics. In actual installation, Sheerfill® architectural membranes often are used in conjunction with one or more additional liners designed, for instance, to minimize acoustical disturbances. Characteristics of several types of Sheerfill® architectural membranes are described, for example, in Birdair's Technical Specification & Fabric Characteristics, available from www.birdair.com, the teachings of which are incorporated herein by reference in their entirety.

[0006] Generally, envelopes based on architectural membranes are lighter than permanent structures, can be more easily erected and dismantled, and tend to withstand destructive forces such as earthquakes.

[0007] Designing with architectural membranes often takes into account some of the same criteria, e.g., basic loading, wind pressures and others considered when designing conventional buildings. Such criteria are defined by local building codes or model codes having jurisdiction. In addition, the design process can also include principles relating to the tensile geometry of the membrane, shape generation, biaxial behavior, stress and structural analyses, and so forth.

[0008] With an increased demand for energy conservation and "green" construction materials and practices, a need continues to exist for light architectural membranes that maintain the flexibility in design and applications for which they are normally used and yet deliver improved light transmission and good thermal insulation. A need also exists for systems having improved acoustic and high reflectance, e.g., UV reflectance, properties.

SUMMARY OF THE INVENTION

[0009] The invention generally relates to a structure that can be employed in architectural and/or structural fabric applications. Many preferred aspects of the invention relate to an architectural membrane structure that includes a material having insulating or light transmission properties, and preferably both.

[0010] Materials that can be incorporated in the architectural membrane structures of the invention include aerogels and other materials such as, for instance, porous, e.g., microporous or nanoporous materials. In specific examples, the material is granular. In other examples, the material is a monolith, or a composite material. In yet other examples, the material has a thermal conductivity (k-value) that remains substantially the same and preferably decreases with load and/or compression. In further examples, the structure includes a load bearing insulator.

[0011] In specific implementations of the invention the architectural membrane structure is a multi-ply structure. For instance, the structure comprises a first layer, a second layer and a material such as monolithic or particulate aerogel, or an aerogel composite, between the first and second layers. Arrangements in which aerogel, or another suitable material, is adhered or otherwise affixed to a single layer also can be employed.

[0012] Aspects of the invention also are directed to an architectural membrane structure having a thermal conductivity or k-value that remains essentially the same or decreases with load and/or compression.

[0013] In many implementations, architectural membranes of the invention have one or more of the following properties: a light transmittance greater than 0.25, preferably greater than 0.5%, and up to 0.80% and higher; a reflectance of at least 60%, preferably of at least 70%, more preferably 80% and more; a solar gain coefficient of at least 0.05; an R value in the range of from 3 to 38; and/or others, as further described below.

[0014] Embodiments of the invention also relate to a method for manufacturing an architectural membrane structure. In one example, the method comprises securing an aerogel material between a first and second layer.

[0015] Embodiments of the invention can be used in architectural or structural envelopes such as roofing, canopies, walls, overhangs, air-supported structures, e.g., cushions or pillows, and other construction elements, where the structure disclosed herein can replace existing architectural membranes, which are made of flexible, coated or laminated structural fabric or film and can meet imposed load requirements and transmit the loads to supporting elements.

[0016] As with conventional architectural membranes, the structure of the invention is lightweight, has tensile properties suitable for fabric structure technology and can support fair amounts of accumulated snow. It can be designed for various shapes and applications and can have good durability and fire resistance properties. In many cases, the structure is translucent, decreasing or minimizing the need for indoors lighting. Preferably it has good insulating properties and can help reduce heating and/or cooling requirements and costs. In some embodiments, the invention makes possible the use of lighter, more translucent fabric elements to obtain the same overall strength and at costs lower than existing insulating systems.

[0017] For example, the sandwich-type composite disclosed herein can be thinner than existing systems that employ Sheerfill® membranes. The three-ply arrangement utilized in some aspects of the invention also can be simpler and easier to manufacture than some of the existing membrane systems which include four or more layers. In many cases, when the bottom membrane or layer of the sandwich-type composite of the invention is installed and tensioned, it is structurally in use and can, therefore, serve as a barrier to the space enclosed so that fit and finish may be safely undertaken early on during the building process.

BRIEF DESCRIPTION OF THE DRAWINGS

[0018] In the accompanying drawings, reference characters refer to the same parts throughout the different views. The drawings are not necessarily to scale; emphasis has instead been placed upon illustrating the principles of the invention. Of the drawings:

[0019] FIG. **1** is a cross sectional view of an architectural or structural composite of the invention, showing outer layers and insert, or inner layer.

[0020] FIG. **2** is a cross sectional view of an arrangement including a fastening system securing an architectural or structural composite of the invention.

[0021] FIG. **3** is a cross sectional view of another arrangement including another version of a fastening system securing an architectural or structural composite of the invention.

[0022] FIG. **4**A is a cross sectional side view of a construction including a roof that can employ the composite of the invention.

[0023] FIG. **4**B is a plan view of the construction shown in FIG. **4**A.

DETAILED DESCRIPTION OF THE PREFERRED EMBODIMENTS

[0024] The above and other features of the invention including various details of construction and combinations of parts, and other advantages, will now be more particularly described with reference to the accompanying drawings and pointed out in the claims. It will be understood that the particular method and device embodying the invention are shown by way of illustration and not as a limitation of the invention. The principles and features of this invention may be employed in various and numerous embodiments without departing from the scope of the invention.

[0025] The invention generally relates to architectural and/or structural elements, more specifically to "fabric structures" also referred to herein as "architectural membrane structures", "architectural structures" or simply as "structures" or "composites", the last two terms being used interchangeably. In many embodiments the invention relates to an architectural structure that is flexible and multi-plied, i.e., has two or more plies.

[0026] In some aspects the structure is a tensioned or tensile structure which typically carries tension stress only, without compression or bending. In specific examples, the structure disclosed herein meets a proposed Industry Standard for carrying tension or shear only in the plane of the membrane.

[0027] In other aspects the structure can be used as a substitute for existing architectural membranes employed in structural fabric applications, such as, for example, tensile membranes, air-supported architectural membranes, cushions or pillows, pleated membranes, tensegrity supported membranes, truss and dome supported flexible claddings, building facades, roofs, building envelopes, and so forth. Existing architectural fabrics may be classified as permanent structures or movable structures and the composite disclosed herein can be utilized in combination with or as a substitute for both.

[0028] In specific implementations of the invention, the composite or structure includes a first layer, a second layer, these layers being also referred to herein as "outer layers", and an inner layer, also referred to herein as "insert layer" or "insert" between the first and second layers. Shown in FIG. **1**, for example, is three-ply structure **10** which includes outer layers **12** and **14** and insert **16** sandwiched in-between. With respect to actual envelope installations, the outer layers can be referred to as the bottom and top layers, with the top layer facing outwardly from the interior of the architectural structure. One or both outer layers can be provided with one or more liners or coatings. When installed one or both layers can be tensioned.

[0029] Additional plies and/or inserts can be employed. For instance, a first insert can be found stacked on a first layer and covered with a second layer which, in turn, supports a second insert, covered with another layer, with optional inserts and further layers disposed above.

[0030] In some aspects of the invention, one or more interior layer(s) (not shown in FIG. **1**) can be present, e.g., interspersed, within the insert. In other aspects at least one additional outer layer, (also not shown in FIG. **1**) is disposed above or below the top or bottom layer, respectively.

[0031] These layers can be used to improve properties desired in the overall structure, e.g., to increase overall strength, increase wear resistance, provide desirable acoustic, solar and/or light properties. Interior layers and/or additional outer layers can span the entire surface of the structure or can be provided in specific regions.

[0032] The outer layers can be the same or different. Existing fabric or architectural membranes, or layers thereof, can be employed. One or both outer layers can be reinforced fabric membranes. Non-structural outer layers also can be used. One or both outer layer(s) can include a liner or can itself be a composite. Membranes used in air-supported structures also can be utilized as one or both outer layers.

[0033] The outer layers are sized and shaped to meet construction and design specifications and can have the same or different thickness. The layer thickness can be, for example, at least about 0.10 millimeters (mm) and up to about 60 mm. Commonly, the layers have a thickness within the range of from about 22 mm to about 40 mm.

[0034] In one example, one or both outer layers include woven materials. In another example, one or both outer layers are non-woven.

[0035] In preferred aspects of the invention, at least one and preferably both outer layers are translucent. Outer layers having structural, fire, UV, mold, water and/or weather resistance are preferred.

[0036] Materials that can be employed to fabricate one or both outer layers include but are not limited to fiberglass, mesh materials, e.g., metal mesh, fibrous batting, aramids, olefins, nylon, acrylics, polyester, natural fibers, e.g., cotton, halopolymers, e.g., polytetrafluoroethylene (PTFE), available, for example, under the tradename of Teflon®, and so forth, as well as combinations of materials. Foils such as, for example, those made from ethylene tetrafluoroethylene (ETFE), available, e.g., under the designation of Tefzel® from Dupont also can be used.

[0037] Whether woven or non-woven, the first and/or second layer(s) can be coated with PTFE, vinyl, e.g., polyvinyl chloride (PVC), silicone, urethanes, acrylics, titanium dioxide (TiO_2), other materials or combinations thereof. The coating can be applied by painting, dipping, spraying, vapor deposition techniques, lamination or other processes known in the art.

[0038] In one embodiment, at least one and preferably both outer layers are fabricated from Sheerfill® membrane materials available from Saint-Gobain Corporation. Other commercially available PTFE-coated fiberglass membranes that can be used include Solus® membranes from Taconic International Ltd., Duraskin® from Verseidag Seemee US Inc. or PTFE-coated fiberglass membranes from Chukoh Chemical Industries LTD. Also suitable are expanded woven PTFE (ePTFE) membranes such as those known under the tradeneame of Tenara® from W. L. Gore Assoc. Inc.

[0039] Commercially available silicone-coated fiberglass membranes that can be utilized include Archifab® from Fabrimax, Atex® from Interglas and Sky® 300 from Ferrari Textiles. Silicone-coated polyester membranes are those being developed by PD Interglas. Solution-dyed polyester membranes are commercially available as Weatherman FR® by Safety Components Fabric Technologies Inc or Fireset HUV® from Glen Raven Custom Fabrics L.L.C.

[0040] Olefin-based membranes include those known under the name of Nova-Shield® by Engineered Coated Products, Twillium® by Inter Wrap and Landmark® by Synthesis Fabrics. Examples of olefin open weave lock-knit mesh include Polytex® from Solarfab Inc. and Coolaroo® from Gale Pacific. Woven polyvinylidene fluoride (PVDF) is commercially available from Duckers & Friends under the designation of Fugalux®.

[0041] Commercially available acrylic-coated polyesters that can be employed to form the first and/or second layers include Main Street® from John Boyle, Avenue® from Graniteville Specialty Fabrics and Holiday® from Marchem coated Fabrics Inc.

[0042] Photovoltaic membranes such as Power-Film® from PowerFilm Inc. and Power Plastics® from Konarka Technologies can also be used.

[0043] One or both outer layers also can be made from other materials that are flexible and preferably strong enough for architectural tensile membrane applications.

[0044] Optionally, either or both outer layers is/are coated with an ultraviolet (UV) reflecting film, a dye or scratch-resistant film or another suitable coating.

[0045] If additional outer layers and/or interior layers are employed, they can be fabricated from materials such as those disclosed herein or from other suitable materials.

[0046] Arrangements using an insert secured, e.g., by adhesion, to one layer also can be employed. For instance, an architectural membrane structure can consist of a single layer lined by the insert or can include a layer having the insert secured to it.

[0047] In many implementations of the invention, the architectural membrane structure includes aerogel or another porous, preferably nanoporous, material. In some examples, the material can be provided as a liner to one or both outer layers. In preferred embodiments, the material is present in the insert layer which can consist, consist essentially of or can comprise aerogel and/or another porous material.

[0048] Aerogels are low density porous solids that have a large intraparticle pore volume. Generally, they are produced by removing pore liquid from a wet gel. However, the drying process can be complicated by capillary forces in the gel pores, which can give rise to gel shrinkage or densification. In one manufacturing approach, collapse of the three dimensional structure is essentially eliminated by using supercritical drying. A wet gel also can be dried using an ambient pressure, also referred to as non-supercritical drying process. When applied, for instance, to a silica-based wet gel, surface modification, e.g., end-capping, carried out prior to drying, prevents permanent shrinkage in the dried product. The gel can still shrinks during drying but springs back recovering its former porosity.

[0049] Product referred to as "xerogel" also is obtained from wet gels from which the liquid has been removed. The term often designates a dry gel compressed by capillary forces during drying, characterized by permanent changes and collapse of the solid phase network.

[0050] For convenience, the term "aerogel" is used herein in a general sense, referring to both "aerogels" and "xerogels".

[0051] Aerogels typically have low bulk densities (about 0.15 g/cm^3 or less, preferably about 0.03 to 0.3 g/cm^3), very high surface areas (generally from about 300 to about 1,000 square meter per gram (m^2/g) and higher, preferably from about 600 to about 1000 m^2/g), high porosity (about 90% and greater, preferably greater than about 95%), and a relatively large pore volume (about 3 milliliter per gram (mL/g), preferably about 3.5 mL/g and higher). Aerogels can have a nanoporous structure with pores smaller than 1 micron (μm). Often, aerogels have a mean pore diameter of about 20 nanometers (nm). The combination of these properties in an amorphous structure gives low thermal conductivity values (e.g., 9 to 16 (mW)/m·K at a mean temperature of 37° C. and 1 atmosphere of pressure). Aerogels can be nearly transparent or translucent, scattering blue light, or can be opaque.

[0052] A common type of aerogel is silica-based. Aerogels based on oxides of metals other than silicon, e.g., aluminum, zirconium, titanium, hafnium, vanadium, yttrium and others, or mixtures thereof can be utilized as well.

[0053] Also known are organic aerogels, e.g., resorcinol or melamine combined with formaldehyde, dendredic polymers, and so forth, and the invention also could be practiced using these materials.

[0054] Suitable aerogel materials and processes for their preparation are described, for example, in U.S. Patent Application No. 2001/0034375 A1 to Schwertfeger et al., published on Oct. 25, 2001, the teachings of which are incorporated herein by reference in their entirety.

[0055] The aerogel material employed can be hydrophobic. As used herein, the terms "hydrophobic" and "hydrophobized" refer to partially as well as to completely hydrophobized aerogel. The hydrophobicity of a partially hydrophobized aerogel can be further increased. In completely hydrophobized aerogels, a maximum degree of coverage is reached and essentially all chemically attainable groups are modified.

[0056] Hydrophobicity can be determined by methods known in the art, such as, for example, contact angle measurements or by methanol (MeOH) wettability. A discussion of hydrophobicity in relation to aerogels is found in U.S. Pat.

No. 6,709,600 B2 issued to Hrubesh et al. on Mar. 23, 2004, the teachings of which are incorporated herein by reference in their entirety.

[0057] Hydrophobic aerogels can be produced by using hydrophobizing agents, e.g., silylating agents, halogen- and in particular fluorine-containing compounds such as fluorine-containing alkoxysilanes or alkoxysiloxanes, e.g., trifluoropropyltrimethoxysilane (TFPTMOS), and other hydrophobizing compounds known in the art. Hydrophobizing agents can be used during the formation of aerogels and/or in subsequent processing steps, e.g., surface treatment.

[0058] Silylating compounds such as, for instance, silanes, halosilanes, haloalkylsilanes, alkoxysilanes, alkoxyalkylsilanes, alkoxyhalosilanes, disiloxanes, disilazanes and others are preferred. Examples of suitable silylating agents include, but are not limited to diethyldichlorosilane, allylmethyldichlorosilane, ethylphenyldichlorosilane, phenylethyldiethoxysilane, trimethylalkoxysilanes, e.g., trimethylbutoxysilane, 3,3,3-trifluoropropylmethyldichlorosilane, symdiphenyltetramethyldisiloxane, trivinyltrimethylcyclotrisiloxane, hexaethyldisiloxane, pentylmethyldichlorosilane, divinyldipropoxysilane, vinyldimethylchlorosilane, vinylmethyldichlorosilane, vinyldimethylmethoxysilane, trimethylchlorosilane, hexamethyldisiloxane, hexenylmethyldichlorosilane, hexenyldimethylchlorosilane, dimethylchlorosilane, dimethyldichorosilane, mercaptopropylmethyldimethoxysilane, bis{3-(triethoxysilyl) propyl}tetrasulfide, hexamethyldisilazane and combinations thereof.

[0059] The aerogel can be in granular, pellet, bead, powder, or other particulate form and in any particle size suitable for an intended application. For instance, the particles can be within the range of from about 0.01 microns (μm) to about 10.0 millimeters (mm) and preferably have a mean particle size in the range of 0.3 to 4.0 mm.

[0060] Examples of commercially available aerogel materials in particulate form are those supplied under the tradename of Nanogel® by Cabot Corporation, Billerica, Massachusetts. Nanogel® granules have high surface area, are greater than about 90% porous and are available in a particle size ranging, for instance, from about 8 μm to about 10 mm.

[0061] Aerogel also can be produced in monolithic shape, for instance as a rigid, semi-rigid, semi-flexible or flexible structure, e.g., mat shaped composites that include fibers. Flexible or semi-flexible monoliths are preferred for use in the insert described herein.

[0062] Whether in particulate or monolithic shape, the aerogel can include one or more additives such as fibers, opacifiers, color pigments, dyes and mixtures thereof. For instance, a silica aerogel can be prepared to contain additives such fibers and/or one or more metals or compounds thereof. Specific examples include aluminum, tin, titanium, zirconium or other non-siliceous metals, and oxides thereof Non-limiting examples of opacifiers include carbon black, titanium dioxide, zirconium silicate, and mixtures thereof. Additives can be provided in any suitable amounts, e.g., depending on desired properties and/or specific application.

[0063] Composite materials that include fibers and aerogel (e.g., fiber-reinforced aerogels) and, optionally, at least one binder also can be employed. The fibers can have any suitable structure. For example, the fibers can have no structure (e.g., unassociated fibers). The fibers can have a matrix structure or similar mat-like structure which can be patterned or irregular and random. Preferred composites of materials comprising fibers include composites formed from aerogels and fibers wherein the fibers have the form of a lofty fibrous structure, batting or a form resembling a steel wool pad. Examples of materials suitable for use in the preparation of the lofty fibrous structure include fiberglass, organic polymeric fibers, silica fibers, quartz fibers, organic resin-based fibers, carbon fibers, and the like. The material having a lofty fibrous structure can be used by itself or in combination with a second, open-cell material, e.g., an aerogel material. For instance, a blanket can have a silica aerogel dispersed within a material having a lofty fibrous structure.

[0064] Other composite materials suitable in forming the insert layer include at least one aerogel and at least one syntactic foam. The aerogel can be coated to prevent intrusion of the polymer into the pores of the aerogel, as described, for instance in International Publication No. WO 2007047970, with the title Aerogel Based Composites, the teachings of which are incorporated herein by reference in their entirety.

[0065] In one specific example, the insert is or includes a cracked aerogel monolith such as described in U.S. Pat. No. 5,789,075, issued on Aug. 4, 1998 to Frank et al., the teachings of which are incorporated herein by reference in their entirety. Preferably, the cracks enclose aerogel fragments that are connected by fibers. Aerogel fragments can have an average volume of 0.001 mm^3 to 1 cm^3. In one composite, the aerogel fragments have an average volume of 0.1 mm^3 to 30 mm^3.

[0066] In another specific example, the insert is a composite that includes aerogel material, a binder and at least one fiber material as described, for instance, in U.S. Pat. No. 6,887,563, issued on May 3, 2005 to Frank et al., the teachings of which are incorporated herein by reference in their entirety.

[0067] Other specific examples of aerogel-based inserts are fiber-web/aerogel composites that include bicomponent fibers as disclosed in U.S. Pat. No. 5,786,059 issued on Jul. 28, 1998 to Frank et al., the teachings of which are incorporated herein by reference in their entirety. Such composites use at least one layer of fiber web and aerogel particles, wherein the fiber web comprises at least one bicomponent fiber material, the bicomponent fiber material having lower and higher melting regions and the fibers of the web being bonded not only to the aerogel particles but also to each other by the lower melting regions of the fiber material. In some applications, the bicomponent fibers are manufactured fibers which are composed of two firmly interconnected polymers of different chemical and/or physical constructions and which have regions having different melting points, i.e. lower and higher melting regions.

[0068] As described in the above-referenced patent, the bicomponent fibers can have a core-sheath structure. The core of the fiber is a polymer, preferably a thermoplastic polymer, whose melting point is higher than that of the thermoplastic polymer which forms the sheath. The bicomponent fibers are preferably polyester/copolyester bicomponent fibers. It is also possible to use bicomponent fiber variations composed of polyester/polyolefin, e.g. polyester/polyethylene, or polyester/copolyolefin or bicomponent fibers having an elastic sheath polymer. Side-by-side bicomponent fibers also can be employed.

[0069] The fiber web may further comprise at least one simple fiber material which becomes bonded to the lower melting regions of the bicomponent fibers in the course of thermal consolidation. The simple fibers are organic polymer fibers, for example polyester, polyolefin and/or polyamide fibers, preferably polyester fibers. The fibers can be round, trilobal, pentalobal, octalobal, ribbony, like a Christmas tree, dumbbell-shaped or otherwise star-shaped in cross section. It is similarly possible to use hollow fibers. The melting point of these simple fibers should be above that of the lower melting regions of the bicomponent fibers.

[0070] In further specific examples, the insert layer is in the form of an aerogel sheet or blanket. The sheet or blanket can include, for instance, aerogel particles dispersed in fibers. In other cases, the sheet or blanket includes fibrous batting with continuous aerogel throughout. Sheets or blankets can be produced, for instance, from wet gel structures as described in U.S Patent application Publication Nos. 2005/0046086 A1, published on Mar. 3, 2005 and 2005/0167891 A1, published on Aug. 4, 2005, both to Lee et al., the teachings of which are incorporated herein by reference in their entirety.

[0071] The insert also can consist of, consist essentially of or can include a porous material other than an aerogel. In specific examples, the material is a microporous or, preferably, a nanoporous oxide of a metal such as silicon, aluminum, zirconium, titanium, hafnium, vanadium, yttrium and others, and/or mixtures thereof. As used herein, the term “microporous” refers to materials having pores that are about 1 micron and larger; the term “nanoporous” refers to materials having pores that are smaller than about 1 micron, preferably less than about 0.1 microns. Pore size can be determined by methods known in the art, such as mercury intrusion porosimetry, or microscopy. Preferably the pores are interconnected giving rise to open type porosity.

[0072] Combinations of insulating materials such as described above also can be employed. For instance, the insert can include different types of aerogel, e.g., in particulate and/or monolithic form.

[0073] Aerogels also can be combined with a non-aerogel material, for example with one or more conventional insulators such as gas, e.g., argon, air, carbon dioxide, vacuum; perlite; fiber glass; silica; aluminoasilicates; plastics; or others known in the construction industry. If translucency is important, aerogel material can be combined with transparent or translucent non-aerogel material, for instance, glass microbeads or microspheres, such as those commercially available from 3M Corporation.

[0074] The non-aerogel material can have a particle size suitable for the application. For instance, a suitable particle size of the non-aerogel material can be within the range of from about 0.05 mm and about 4 mm.

[0075] Aerogel and non-aerogel materials can be blended in any proportion suitable to the application. Cost requirements, insulating properties, light transmission, function of the composite within the overall construction are some of the factors that can be considered. Generally, the non-aerogel material can be present in the mixture in an amount anywhere from 0% to 99%. For instance, aerogel and non-aerogel materials can be blended in 20:80 to 80:20 ratios, e.g., 60:40, 50:50 or 40:60. Other ratios can be used.

[0076] Optionally, the material employed to form the insert layer or insert, e.g., loose aerogel particles or another granular material, can be enclosed in a film or casing made of one or more polymers such as nylon, polycarbonate, metal sheets, or other suitable materials, forming a pillow, mat, bag, and the like. The material also can be present in layers.

[0077] The insert layer is sized and shaped to meet construction and design specifications. In illustrative examples, the insert has a thickness of about 0.125 inches or greater. Preferably, the insert has a thickness within the range of from about 25 mm to about 200 mm.

[0078] In one aspect of the invention, the insert layer has a density less than about 0.5 g/cm^3, preferably less than about 0.3 g/cm^3 and more preferably less than about 0.1 g/cm^3. In another aspect of the invention, the insert has a void volume fraction of at least 10% and preferably at least 50%. In specific examples, the insert has a void volume % of at least 90%.

[0079] In preferred implementations, the insert has a light transmission greater than 0% and preferably is translucent. As used herein, the term “translucent” refers to a light transmittance (% T) of at least 0.5% when measured at visible light wavelengths. Preferably, the insert material has a % T of at least 10% for a 0.25 inch thickness. As one example, an insert made of Nanogel® material and having a thickness of 25 mm has a visible light transmission of about 53%, while an insert made of Nanogel®, having a thickness of 50 mm, has a visible light transmission of about 26%. In further aspects of the invention, the insulating material eliminates glare, allowing a soft, deep distribution of daylight. Light transmission through a Nanogel® insulator, for example, can be referred to as diffused.

[0080] An insert layer that is an insulator is preferred. As used herein, the term “insulating” or “insulator” refers to thermal, acoustic or electric insulating properties. In preferred implementations, the insert combines two or more types of insulating properties.

[0081] In one example the insert is a thermal insulator. In many implementations, the insert has an R-value of at least 2, more preferably between 3 and 38. “R value” is a parameter well known in describing construction materials and is a measure of thermal resistance to heat flow.

[0082] In another example the insert layer has a substantially constant thermal conductivity (k-value), within the range of from about 12 to about 30 (mW)/m·K at 37° C. and 1 atmosphere of pressure. Also preferred are inserts for which the thermal conductivity or k-value of the insert remains constant, or preferably decreases with load or compression.

[0083] In a further example, the insert is an acoustic insulator. Nanogel® aerogel particles, for instance, slow down the speed of sound through the structure, reducing noise, in particular in the low to mid frequency range from 40 to 500 Hz.

[0084] In yet another example the insert is an electrical insulator.

[0085] Hydrophobic inserts are preferred. More preferred are water and mold resistant inserts. Suitable inserts may also have fire resistant or fire-proof properties.

[0086] The insert layer can be resilient and/or compressible. In some implementations of the invention, the insert material has elastic compressibility, wherein application of a pressure to a bulk amount of the compressible material results in a reduction of the volume occupied by the compressible material, and wherein after release of the pressure the volume of the compressible material increases and preferably returns to substantially the same value as before application of the pressure. Thus elastic response to compression or “compressive spring back” results in recovery of insert thickness, preferably of the full insert thickness, when compression is removed.

[0087] In one example the insert is compressible and has a compressive spring back force that allows the material to be firmly held in place between the layers. The insert may be able to withstand pressures of 1 psi, or preferably 10 psi, or more preferably 100 psi, or still more preferably 1000 psi, without permanent damage or destruction. The insert may experience volumetric compression to a second volume that is, e.g., 5% to 80% less than its initial volume when put under compressive load. The insert may then spring back to a final volume that is substantially greater than the second volume as the load is decreased. This behavior allows for systems wherein the insert substantially fills the volume between the layers even if that volume is changing due to wind load, creep, mechanical compression or other outside forces.

[0088] Incorporating a material such as described above in a structure or composite suitable for architectural membrane applications can be conducted during the manufacture of the composite. Existing assemblies also can be refurbished or retrofitted to include a material such as aerogel, either in situ or off-site. For instance, an existing architectural membrane can be lined with a monolithic aerogel blanket, optionally supported by a layer such as the first or second layer described above, or by other means. Air-supported cushions or pillows also can be designed or retrofitted to include aerogel or other materials described herein.

[0089] Several approaches can be employed to produce architectural membrane structures. In one example a monolithic structure, e.g., an aerogel blanket, is incorporated into the structure or composite by stacking or layering. For instance, a monolithic insert can be disposed over a bottom layer then covered with a top layer. Material, e.g., lose granules, retained in a sheath or casing can be incorporated in a similar fashion.

[0090] To produce the composite, a material, e.g., aerogel in monolithic or granular form, or as part of a composite, also can be provided in a gap space formed between the first and second layers described above. Assemblies that have multiple layers can contain the material in one, more than one, or all of the gap spaces. Particulate material, e.g., aerogel can be added to one gap space, while monolithic material, e.g., an aerogel blanket, can be provided to another.

[0091] In one example, the structure is produced by placing particulate material as the insert between the layers, e.g., introducing particulate material in the space defined by the two outer layers, then using a mechanism to tightly enclose the material between the layers. Processes that can be used to make the enclosure include mechanical compression, layer tensioning, vacuum sealing, or other approaches. When the insert material is compressible and springy, it will be held tightly in place without bunching, flowing, or significant break-down. The level of volumetric compression under 1 atmosphere of pressure could be 10% or more, preferably 25% or more, or still more preferably 40% or more when compared to initial bulk density.

[0092] In specific implementations the compression of the material is sufficient to accommodate, overcome or sustain a volume change in a gap space in cases when the volume change is caused by wind, creep, mechanical force or any combination thereof.

[0093] In another example, aerogels or another suitable material is incorporated within the architectural membrane structure by techniques disclosed, for instance in U.S. Pat. No. 6,598,283 B2, issued to Rouanet et al. on Jul. 29, 2003, the teachings of which are incorporated herein by reference in their entirety. U.S. Pat. No. 6,598,283 B2 describes, for instance, a method which includes providing a sealed first container comprising aerogel particles under a first air pressure that is less than atmospheric pressure. The unrestrained volume of the aerogel particles at the first air pressure is less than the unrestrained volume of the aerogel particles under a second air pressure that is greater than the first air pressure. The sealed first container is placed within a second container, e.g., the space between the outer layers and the sealed first container is breached to equalize the air pressure between the first and second containers at the second air pressure and to increase the volume of the aerogel particles, thereby forming the insulation article.

[0094] Techniques described in U. S. Patent Application Publication No. 2006/0272727 A1, to Dinon et al., published on Dec. 7, 2006 also can be adapted to incorporate insert material into the structures disclosed herein. U.S. Patent Application Publication No. 2006/0272727 discloses an insulated pipe-in-pipe assembly comprising (a) at least one inner pipe, (b) an outer pipe disposed around the at least one inner pipe so as to create an annular space between the outer and inner pipes, (c) porous, resilient, compressible material disposed in the annular space, and (d) a remnant of a container that previously was positioned in the annular space and previously held the compressible material in a volume less than the volume of the compressible material in the annular space. A method for making such an insulated pipe-in-pipe assembly also is described.

[0095] In specific examples, loose granular material is used in conjunction with a binder material between the layers. The layers can either tightly enclose the material, as described above, or can loosely enclose the material. In loose enclosures, the layers can be held apart by air in a pillow-like form. In this case, the insert material can completely fill the inner pillow region or could partially fill the region, being affixed to one or more of the outer layers by an optional binder.

[0096] Other suitable approaches can be employed to incorporate granular materials in air-supported structures, e.g., pillows or cushions. Furthermore, air-supported cushion or pillow structures can be formed utilizing monolithic and/or composite materials, e.g., aerogel blankets and the like.

[0097] To reduce or minimize settling and the formation of voids, the space or gap volume between the outer layers can be "overfilled" or "overpacked". Overpacked systems can have a density at least as high as the tap density. For aerogel particles, overfilling is to a density higher than the tap density. In systems filled with aerogel particles that are very light compared to a relatively heavy frame, the density can be considerably greater than the tap density, for instance about 105 to about 115%-120% and higher of tap density.

[0098] Optionally, moisture can be removed from the insert material prior to, during or after being added to form the architectural membrane structure.

[0099] The manufacture or fabrication process can further include adhering two or more of the first layer, insert layer and second layer (i.e., plies) to one another. Non-adhering techniques also can be employed, resulting in at least two of the plies being non-adhering. Specific approaches for joining together two or more of the plies include stitching the plies together, laminating the plies together, powder bonding the plies together, or other suitable techniques. The plies may be directly connected, or they may be indirectly connected together by intervening materials.

[0100] Suitable techniques that can be used to produce the architectural membrane structure of the invention include but are not limited to lamination, adhesives, sandwiching between two tensioned layers, sewing, riveting, blowing in loose material, wet processing into a composite form and others.

[0101] The architectural composites of the invention can be finished into panels. To finish the composite edges and/or corners of the composite structure can be sealed or clamped together. Edge conditions for panels utilizing composites of the invention are illustrated in FIG. **2** and FIG. **3**. Also shown in FIG. **2** and FIG. **3** are fastening systems or devices that can be employed in combination with the composites of the invention.

[0102] Shown in FIG. **2**, for instance, is a fastening device that includes edge bars **40** for securing panel **42**. Panel **42** includes a composite such as described above, having insert **16** and optionally sealed outer layers **12** and **14**. The panel is provided with roped or beaded edges **52**. Edge bars **40** grip the layers and can be fasten to supporting or perimeter components.

[0103] Another approach for fastening a composite such as described above is illustrated in FIG. **3**. Shown in FIG. **3** is fastening device **60** for securing panel **62** comprising a composite having insert **16**. In this example, the composite includes non-structural outer layer **64** and single reinforced fabric outer layer **66** and the panel is fastened using roped edge **72** and clip **74**.

[0104] The fastening systems depicted in FIG. **2** and FIG. **3** can be fabricated in whole or in part from aluminum or another suitable materials. Fastening means other than those depicted in FIG. **2** and FIG. **3** also can be employed.

[0105] Architectural membrane structures of the invention can have a substantially constant thickness, the thickness being, for instance, within the range of from about 0.25 inches to about 4 inches, preferably within the range of from about 0.375 inches to about 3 inches.

[0106] In preferred implementations, the structure can have a measure of thermal resistance to heat flow, referred to herein as "R" value of at least 2, preferably within the range of from about 3 to 38. A desirable R value for the overall structure or composite is a value that is greater than the R value of the outer layers in the absence of the insert.

[0107] Preferably, thermal insulating properties of the architectural membrane structure increase with load or compression. In specific implementation, the structure has a thermal conductivity (k-value) that remains constant or, preferably, decreases with load and/or compression.

[0108] In some embodiments, the architectural membrane structure has a light, e.g., visible light, transmittance (% T) greater than 0%, e.g., at least about 0.25%, preferably at least about 0.5%, e.g., within the range of from about 0.5% and about 2%, more preferably at least 2, e.g., within the range of from about 2% and 10%, and most preferably greater than about 10% and up to 80% or higher. Also preferred are composites that have high light reflectance, e.g., of at least 60%, preferably at least 70% and more preferably 80% or more. Suitable approaches for measuring light transmittance and spectral reflectance are set out in European Standard EN 410 or in ASTM E424.

[0109] Solar heat gain coefficients can be, for instance, in the range of from about 0.21 to 0.73.

[0110] The architectural structure preferably provides acoustic insulation with particular properties of sound absorption and diffusion, and with enhanced performance in the OITC rating (outdoor indoor transmission class) in the range between 40 and 400 Hz.

[0111] In preferred implementations, the architectural membrane structure includes a load bearing insulator, i.e., an insulator that retains or substantially retains one or more of its insulating properties, e.g., its thermal insulating properties, under a mechanical load.

[0112] In specific examples, the insert transfers a load between the outer layers under conditions such as wind, where one layer, e.g., membrane, resists pressures from one direction, say into the composite, and the other layer or membrane resists pressure from the same direction, say, away from the composite. These pressures may be of the order of 10 to 40 pounds per square foot (psf). The structure disclosed herein preferably also resists snow loads, where the pressures typically occur on the top layer only; these pressures may range from 20 psf to in excess of 100 psf.

[0113] In some implementations, one or both outer layer(s) is/are partially and, preferably, entirely supported by the insert.

[0114] In other examples of the invention, the architectural membrane structure disclosed herein has fire resistance properties and preferably is fire-proof. Furthermore, the structure can be water, weather and/or mold resistant.

[0115] The structure or composite can constitute an architectural element, structural element or can serve as both. As with conventional architectural membranes, the composite of the invention can be used to produce pre-assembled modules.

[0116] In some implementations, the architectural membrane structure is an air supported cushion or pillow.

[0117] In other implementations, the structure or composite of the invention is used as a tensioned structure, having a shape that is determined by tension in the composite and the geometry of the support structure. Typically, the structure includes flexible elements (e.g. composite and cables), non-flexible elements (e.g. struts, masts, beams, rings, or arches) and the anchorage (e.g. supports and foundations). Preferably, when installed, the tensioned layer is the bottom layer.

[0118] In addition to three dimensional curves, composites of the invention can be pretensioned for instance to a pretension value calculated based on expected loading during the life cycle of the architectural structure or composite. Preferably, the pretension is high enough to have a minimum of tension in both directions under any possible condition. If pretension is too low, the composite can become susceptible to vibrations caused by wind. If pretension is too high, the composite can require heavy and expensive supporting structure and/or foundation.

[0119] Shapes that can be used alone or in combination include synclastic, e.g., spheres or domes, anticlastic, e.g. saddle-like, and others. Thus composites of the invention can be erected or prefabricated as domes, conical, waveform, synclassic, anticlassic, pleated and other shapes.

[0120] Architectural membrane composites according to the inventions can be used in envelope structures such as roofs, overhangs, canopies, tents and tent-like structures, walls, artistic displays, esthetic or other structures which can be integrated in the design and construction of airports, storage facilities, hangars, arenas, activity centers, sports or gathering venues, domes, green houses, residential or commercial buildings, manufacturing facilities, museums, hotels, universities, railroad, bus or subway stations, waiting areas, theaters, opera houses, amphitheaters, passageways between buildings, connecting joints in industrial facilities and so forth.

[0121] Envelope structures that include the composites disclosed herein can be used as substitutes or in addition to envelopes that employ existing architectural membranes.

[0122] The architectural membrane structure disclosed herein can be used as cladding or can be integrated in domes and other constructions, such those described in U.S. Pat. No. 4,736,553 issued to Geiger on Apr. 12, 1988; U.S. Pat. No. 5,103,600 issued to Geiger and Campbell on Apr. 14, 1992; U.S. Pat. No. 5,261,193, issued on Nov. 16, 1993 and U.S. Pat. No. 5,430,979, issued on Jul. 11, 1995, both to Wieber et al; U.S. Pat. No. 5,502,928 issued to Terry on Apr. 2, 1996; U.S. Pat. No. 6,282,842 B1 issued to Simens on Sep. 4, 2001; and many others. It can be a substitute or can be combined with existing materials, e.g., the flexible composites described in U.S. Pat. No. 7,153,792 issued on Dec. 26, 2006 to Sahlin et al. The teachings of these patents are incorporated herein by reference in their entirety.

[0123] Shown in FIGS. **4**A and **4**B, for instance, is building **200**, including walls **202** and **204** and roof **206**. A composite such as described herein is supported by beams **208**. Alternatively or in addition to beams **208**, other means for support can be employed, e.g., cabling and/or air pressure.

[0124] Engineering approaches for integrating composites disclosed herein into various architectural designs depend on the purpose of the envelope, its function, shape, properties sought and other factors. These approaches can be the same or different from those known or being developed in relation to existing architectural membranes.

[0125] Examples are described, for instance, in U.S. Pat. No. 5,502,928 issued on Apr. 2, 1996 to Terry and U.S. Pat. No. 4,736,553 issued to Geiger on Apr. 12, 1988, the teachings of which are incorporated herein by reference in their entirety. Other examples are described in publications such as the following available from www.geigerenginners.com: (i) *Design Experience with Nonlinear Tension Based Systems: Tents, Trusses and Tensegrity* by D. Campbell, D. Chen, and P. Gossen P. E.; (ii) *Membrane Designs and Structures in the World,* edited by Kazuo Ishii; (iii) *Tensioned Fabric Membrane Roofs for "Tensegrity" Domes* by D. Campbell, et. al. These publications are incorporated herein by reference in their entirety.

[0126] While this invention has been particularly shown and described with references to preferred embodiments thereof, it will be understood by those skilled in the art that various changes in form and details may be made therein without departing from the scope of the invention encompassed by the appended claims.

What is claimed is:

1. An architectural membrane structure comprising aerogel.

2. The architectural membrane structure of claim **1**, wherein the aerogel is present in an aerogel composite, in a monolith or is in particulate form.

3. The architectural membrane structure of claim **1**, wherein aerogel is present in a blanket, mat or sheet.

4. The architectural membrane of claim **1**, wherein the aerogel is present in a fiber-web/aerogel composite.

5. The architectural membrane structure of claim **1**, wherein the structure has a substantially constant thickness.

6. The architectural membrane structure of claim **1**, wherein the structure has a first layer, a second layer and an insert layer including the aerogel between said first and second layers.

7. The architectural membrane structure of claim **6**, wherein the insert layer has a thickness of at least 0.375 inches.

8. The architectural membrane structure of claim **6**, comprising additional outer layers or interior layers that are interspersed in the insert layer.

9. The architectural membrane structure of claim **6**, wherein at least one of said first and second layers is woven.

10. The architectural membrane structure of claim **6**, wherein at least one of said first and second layers is nonwoven.

11. The architectural membrane structure of claim **6**, wherein at least one of said first and second layers includes fiberglass, polyester, polytetrafluoroethylene, metal mesh, fibrous batting or any combination thereof.

12. The architectural membrane structure of claim **6**, wherein at least one of said first and second layers is coated with polytetrafluoroethylene, vinyl, silicone, titanium dioxide or any combination thereof.

13. The architectural membrane structure of claim **6**, wherein a space defined by said first and second layers is substantially completely filled by the aerogel.

14. The architectural membrane structure of claim **6**, wherein a space defined by said first and second layers is partially filled by the aerogel.

15. The architectural membrane structure of claim **6**, wherein the first layer and the second layer have the same thickness.

16. The architectural membrane structure of claim **6**, wherein the first layer or the second layer has a thickness of at least about 0.03 inches.

17. The architectural membrane structure of claim **6**, wherein at least two of the first layer, the insert layer, and the second layer are adhered to one another.

18. The architectural membrane structure of claim **6**, wherein at least two of the first layer, the insert layer and the second layer are not adhered to one another.

19. The architectural membrane structure of claim **6**, having at least one edge or corner that is sealed or clamped.

20. The architectural membrane structure of claim **1**, having a thermal insulation R value of at least 2.

21. The architectural membrane structure of claim **1**, having a % T greater than 0%.

22. The architectural membrane structure of claim **1**, wherein the structure is a tensioned structure.

23. The architectural membrane structure of claim **22**, wherein the aerogel is disposed between a first layer and a second layer and only one of said layers is tensioned.

24. The architectural membrane structure of claim **1**, wherein the aerogel is disposed between a first layer and a second layer and transfers a load between said layers.

25. The architectural membrane structure of claim **1**, wherein the aerogel is adhered to a layer.

26. The architectural membrane structure of claim **1**, wherein when installed, the aerogel is under compression.

27. The architectural membrane structure of claim **26**, wherein the compression is sufficient to accommodate a volume change in a gap space and wherein the volume change is caused by wind, creep, mechanical force or any combination thereof.

28. The architectural membrane structure of claim **1**, wherein the aerogel has an elastic response to compression.

29. The architectural membrane structure of claim **1**, wherein the aerogel is present in a layer having a thermal conductivity value that decreases with load or compression.

30. The architectural membrane structure of claim **1**, wherein the composite has thermal insulating properties, electrical insulating properties, acoustical insulating properties or any combination thereof.

31. The architectural membrane structure of claim **1**, wherein the aerogel is present in a layer having a density no greater than 0.5 g/cm^3.

32. The architectural membrane structure of claim **1**, wherein the aerogel is present in a layer having a void volume of at least 50%.

33. An architectural or structural envelope comprising the architectural membrane structure of claim **1**.

34. The envelope of claim **33**, further comprising at least one additional element selected from the group consisting of a flexible element, a non-flexible element, and an anchorage element.

35. The envelope of claim **33**, wherein the envelope is a roof, overhang, canopy, wall, esthetic or artistic structure.

36. The envelope of claim **33**, wherein the aerogel substantially fills a space between layers when subjected to volumetric compression followed by volumetric expansion.

37. A construction comprising the envelope of claim **33**.

38. The construction of claim **37**, wherein the construction is an airport, storage facility, hangar, arena, activity center, sports venue, gathering venue, dome, green house, residential or commercial building, manufacturing facility, museum, hotel, railroad, bus or subway station, canopy, passageway or university.

39. A system comprising a fastening device and the architectural membrane structure of claim **1**.

40. An architectural membrane structure comprising a granular material.

41. The architectural membrane structure of claim **40**, having a thermal insulation R value between 3 and 38.

42. The architectural membrane structure of claim **40**, having a % T in the range of from about 0.25 to about 80%.

43. The architectural membrane structure of claim **40**, having a reflectance of at least 80%.

44. An architectural membrane structure having a thermal conductivity that remains essentially the same or decreases with load or compression.

45. An architectural membrane structure comprising a substantially load bearing insulator.

46. An architectural membrane structure comprising a first membrane layer, a second membrane layer and a nanoporous material between said layers.

47. The architectural membrane structure of claim **46**, wherein the nanoporous material is a monolith, a particulate material or a nanoporous composite.

48. The architectural membrane structure of claim **46**, further comprising a binder material between said layers.

49. A method for manufacturing an architectural membrane structure, comprising securing an aerogel material between a first and second layer.

50. The method of claim **49**, wherein at least two of the first layer, an insert layer containing the aerogel material and the second layer are adhered to one another.

51. The method of claim **49**, wherein at least two of the first layer, an insert layer containing the aerogel material and the second layer are laminated to one another.

52. The method of claim **49**, further comprising sealing or clamping at least one edge or one corner of the architectural membrane structure.

53. The method of claim **49**, wherein the aerogel material is in particulate form.

54. The method of claim **49**, wherein the aerogel material is enclosed in a space between said layers by mechanical compression, layer tensioning, vacuum sealing or any combination thereof.

55. The method of claim **49**, wherein the aerogel material is provided in at least one container placed between said layers.

56. The method of claim **55**, further comprising breaching the container.

57. The method of claim **49**, wherein the aerogel material is provided in a blanket, mat or a composite.

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