Jan. 6, 1970 M. H. SONSTEGAARD 3,488,019

CARGO-GAS AIRSHIP WITH BOUNDARY LAYER CONTROL

Original Filed Nov. 25, 1966 4 Sheets-Sheet 1

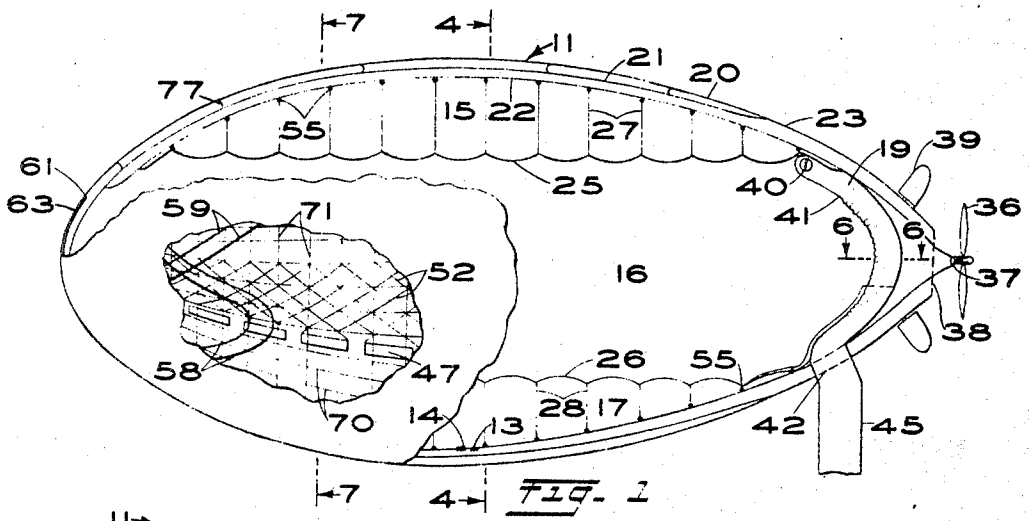


Fig. 1

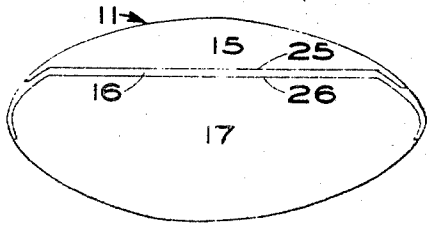


Fig. 2

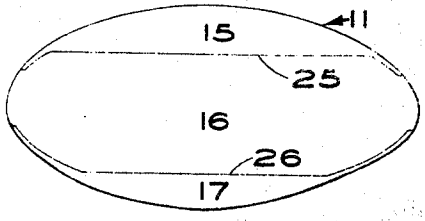


Fig. 3

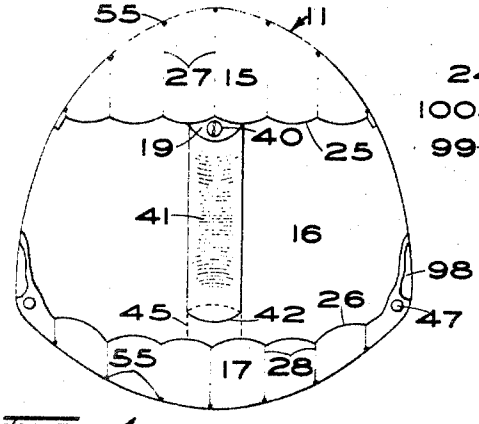


Fig. 4

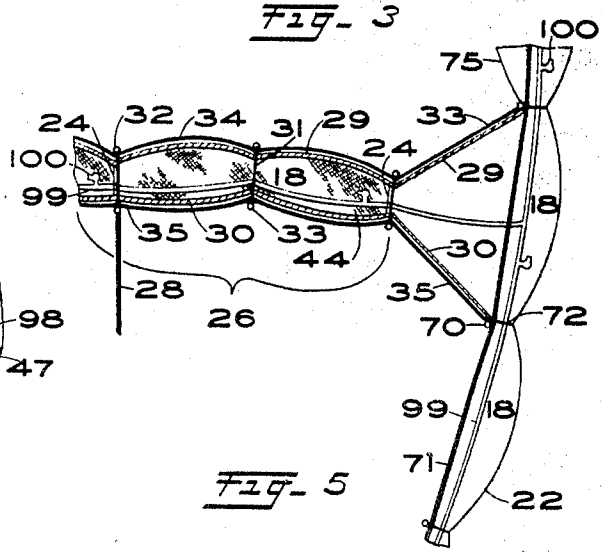


Fig. 5

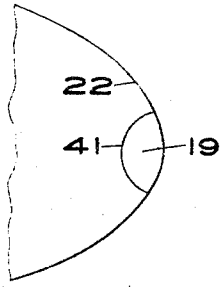


Fig. 6

INVENTOR.
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CARGO-GAS AIRSHIP WITH BOUNDARY LAYER CONTROL

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Fig-7

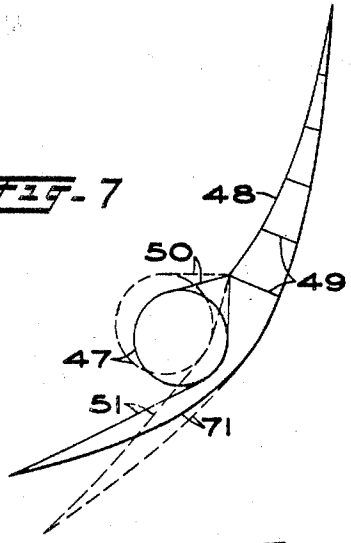
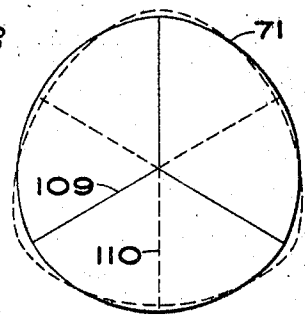


Fig-8



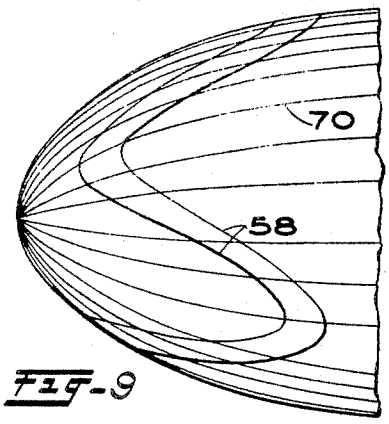


Fig-9

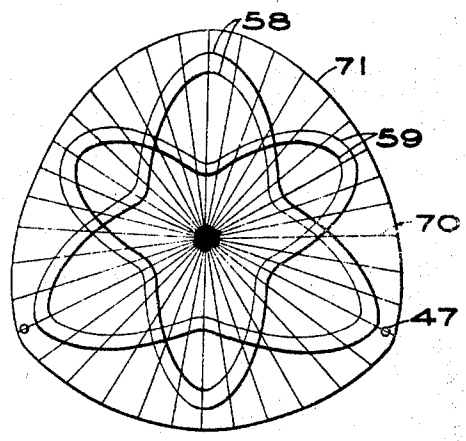


Fig-10

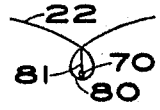


Fig-12

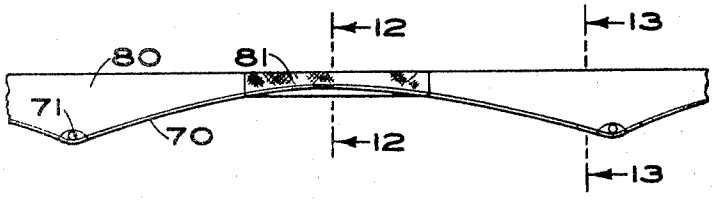


Fig-11

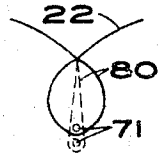


Fig-13

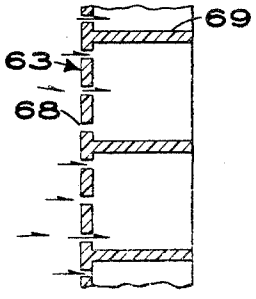


Fig-14

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CARGO-GAS AIRSHIP WITH BOUNDARY LAYER CONTROL

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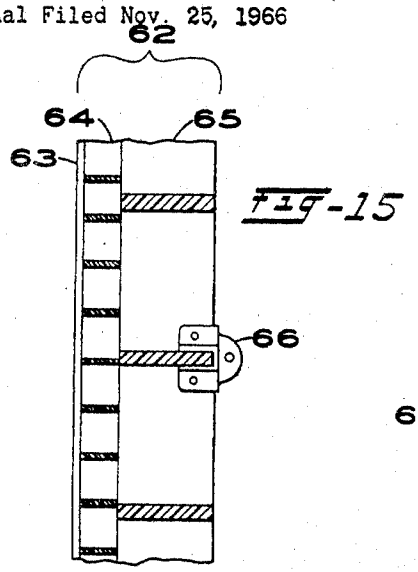


Fig-15

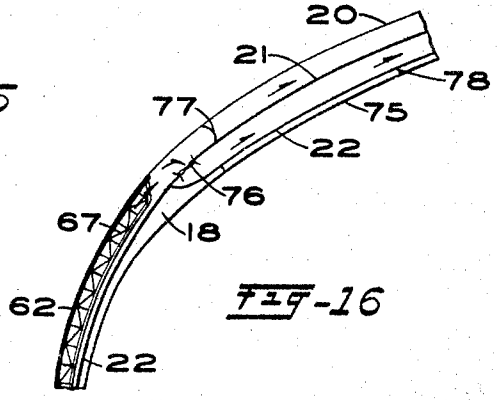


Fig-16

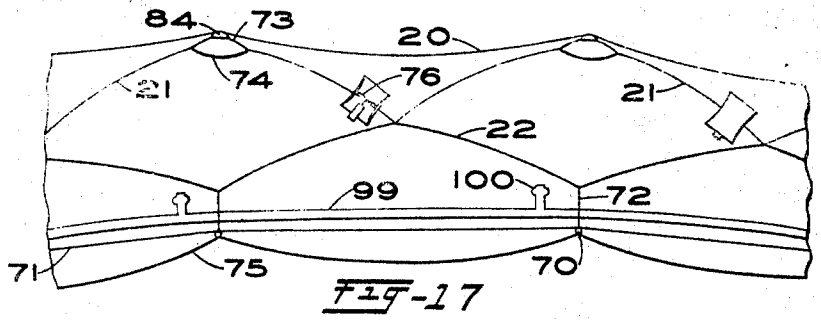


Fig-17

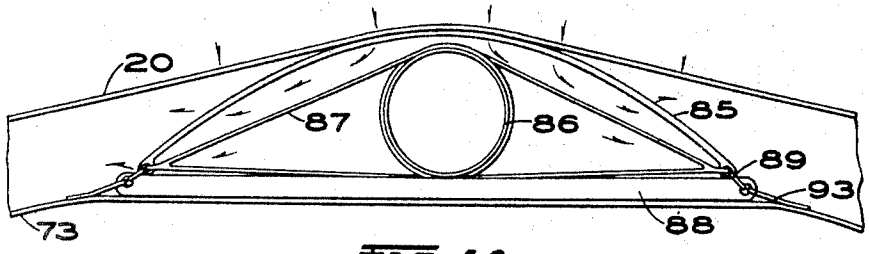


Fig-18

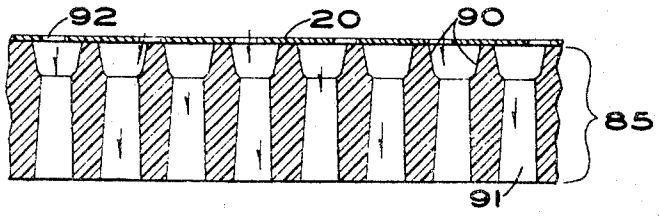


Fig-19

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CARGO-GAS AIRSHIP WITH BOUNDARY LAYER CONTROL

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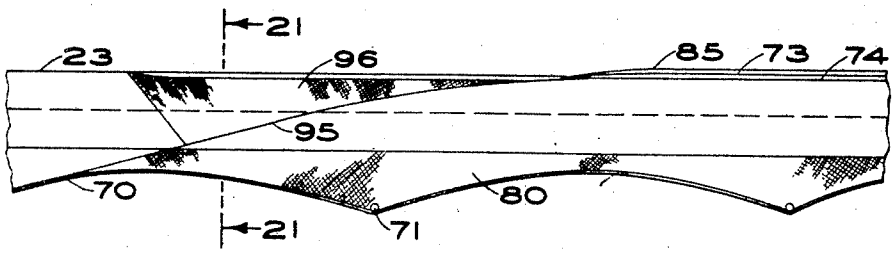


Fig-20

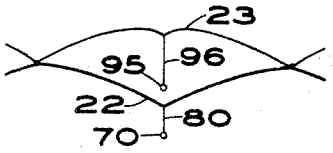


Fig-21

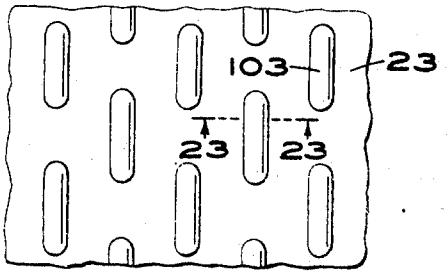


Fig-22

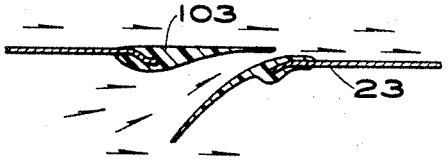


Fig-23

INVENTOR.
Miles H. Sonstegaard

United States Patent Office 3,488,019
Patented Jan. 6, 1970

3,488,019

CARGO-GAS AIRSHIP WITH BOUNDARY LAYER CONTROL

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(95 S. Hill Ave., Fayetteville, Ark. 72701)

Continuation of application Ser. No. 596,941, Nov. 25, 1966. This application Aug. 8, 1968, Ser. No. 754,093
Int. Cl. B64b 1/58
U.S. Cl. 244—30 17 Claims

ABSTRACT OF THE DISCLOSURE

A nonrigid airship with a cable framework is provided with a fire shield that allows preferential leakage, and conservation during ascent, of the shield gas. Interior, side-wall placement of ballast tanks provides space for movement of cable-controlled diaphragms, which control the position of cargo gas. Bow and amidship suction, stern blowing, and placement of ballast tanks along streamlines reduce drag. A mooring connection sternward of the necessarily smooth suction area loads and unloads gas but requires stern-into-the-wind mooring; the necessary reverse flight is achieved by a reversible propeller and controlled by reversible airfoils.

This application is a continuation of application Ser. No. 596,941, filed Nov. 25, 1966, now abandoned.

This invention relates to nonrigid airships and is directed particularly to airships having primary utility for the economical transportation of commercial gases. The principal object of the invention is to make feasible the operation of very large airships handling cargo of slightly to moderately buoyant gases by providing structural means for (1) control of gases and the rapid loading and unloading thereof, (2) drag reduction by means of boundary layer control, (3) suspension of liquid ballast tanks by a system compatible with the gas control and loading-unloading system and with the boundary layer control system, (4) a cable framework and attached pressure-containing membrane suitable for containing superpressure for altitude control and compatible with the boundary layer control system and the ballast tank suspension system, (5) a shield of nonflammable gas, for fire prevention and leak detection, incorporated in the pressure-containing system and in the gas control system, (6) a method of mooring compatible with the boundary layer control system, and (7) a propulsion and attitude-control system that makes feasible the mooring method.

The cargo gas comprising the middle layer of the gaseous content of the airship is separated from the lifting gas above and the ballast air below by a lifting-gas diaphragm and a cargo-gas diaphragm, respectively. The lifting-gas diaphragm is connected by upwardly extending cables, and the cargo-gas diaphragm by downwardly extending cables, to winches attached to the cable framework of the airship. These winches control the relative positions of lifting gas, cargo gas, and ballast air and thereby the attitude of the airship. During loading and unloading, a collapsible cargo-gas tube conducts cargo gas between the cargo-gas chamber and a mooring connection on the underside of the airship.

The boundary layer control system establishes a laminar boundary layer over the front and central portion of the airship by means of distributed suction and prevents boundary layer separation by means of distributed blowing in the region of the stern.

Ballast tanks are positioned within the space enclosed by the cable framework in two rows, one on either side of the airship, each row following a steamline. These tanks

are suspended directly from the side walls of the airship so as to avoid interference with the operation of the lifting-gas and cargo-gas diaphragms, as would result from use of conventional load-supporting cables attached to the top of the airship. The tank suspension structure limits the minimum radius of curvature in the cross-sectional shape of the airship envelope to a length compatible with the functioning of the laminar boundary layer control system.

The pressure-containing membrane is attached to the cable framework by catenary curtains having greater tensile strength in the transverse direction than in the longitudinal direction. The air-handling tubes of the boundary layer control system are integral with the pressure-containing membrane. The longitudinal and hoop cables of the nonrigid framework are reinforced in the regions of the bow and the stern by tension-distribution cables that distribute concentrated longitudinal tensions resulting from the full-load and the empty conditions of the ballast tanks and from the method used for suspending these tanks.

There is incorporated in the cargo-gas diaphragm, and in the portion of the airship envelope extending upward from this diaphragm, a layer of non-flamable gas maintained at a positive gauge pressure with respect to the contained cargo gas and lifting gas; hence, any leaks will normally be of nonflammable gas. The nonflammable gas layer is compartmentalized, each compartment having gas metered to it so that any appreciable leak will be detected and its approximate location indicated.

The mooring connection on the underside of the airship is located toward the stern, near the rear extremity of the area of distributed suction, so that the aerodynamic roughness of this cargo-gas-handling mooring connection will not initiate turbulence over a significant portion of the area designed for laminar boundary layer flow. To allow the moored airship to weathervane with changes in wind direction, the airship is moored with the stern heading into the wind.

A universally-mounted, reversible-pitch propeller located at the stern and fully reversible control airfoils mounted in the conventional location are provided to allow controlled reverse flight at sufficient airspeeds to make feasible stern-into-wind mooring.

To my knowledge, airships have not been used for transporting gases other than the necessary lifting gases and gases used as fuel for the propulsion engines of the airship itself. The German rigid airship, Graf Zeppelin, carried the major portion of its fuel in the form of a mixture having a specific gravity near unity, referred to air. At takeoff the fuel-gas bags filled the lower third of the airship, while the lifting-gas bags filled the upper two thirds. Various other airships having fuel gas compartments are known, none of which contemplates commercial transportation of gas.

An airship used for hauling commercial gases at a profit would, over most trade routes, need to be very large—on the order of tens of thousands or even hundreds of thousands of tons displacement. Means used in the past for loading gaseous fuel would not provide sufficiently high flow rates for loading and unloading very large cargoes of gases within a reasonable length of time. The present invention solves this problem by providing a very large cargo gas tube for loading and unloading gaseous cargo. This tube is integral with other necessary parts of the airship so as to be of relatively low cost and weight and operable at cargo terminals located at various altitudes; it is collapsible so as to minimize its parasitic volume requirement.

The very large volume and high density (compared with lifting gas) of cargo gas carried in an airship in the commercial gas trade makes problems of surging very difficult and costly to overcome using means old in

the art, such as cylindrical gas bags with bulkheads. The present invention solves this problem, along with the related problem of attitude control, by a system of horizontal diaphragms controlled by vertical cables wound on remotely controlled winches.

Prior art in airship construction requires relatively high specific horsepower for breasting unavoidable headwinds winds and maintaining reasonable average ground speeds. An airship carrying such low value freight as commercial gases needs to operate with relatively low specific power; drag reducing techniques are therefore especially desirable in this application of the airship. In the present invention, drag is reduced by provision of a smooth contour in the longitudinal direction, distributed suction over the forward and central portions of the airship, and distributed blowing in the region of the stern. Prior art discloses a rigid tube or manifold for conducting boundary air from suction chambers to the point of discharge. In a very large airship such a tube or manifold would be excessively heavy and costly. The present invention provides nonrigid, inflatable tubes, integral with the airship envelope, to carry boundary air from suction chambers to the region of discharge.

Prior construction depend on streaming, sometimes in conjunction with a rear-mounted propeller, to keep the line of boundary layer separation near the rearmost extremity of the airship. The present invention makes feasible a more compact, rounded stern, which reduces the overall surface-to-volume ratio and the bending moments caused by cross-currents; boundary layer separation and consequent energy loss in large-scale turbulence in the wake are prevented by distributed blowing over a large, nonrigid surface in the region of the stern.

A load suspension problem in nonrigid airships without transverse bulkheads is that suspension wires, such as those disclosed in the prior art, would extend through the space in which the lifting-gas and cargo-gas diaphragms move during normal operation of the airship. The present invention overcomes this problem with a compact suspension system whereby each row of ballast tanks is suspended from the airship wall to which it is adjacent.

This system of suspension causes a considerable change to take place in the cross-sectional shape of the airship while the ballast tanks are being loaded or unloaded. Structural problems associated with this change of shape are minimized by choice of design shape at half load and by certain features of the nonrigid cable framework.

Prior art discloses an airship with a nonrigid framework and the use in an airship of an inert gas layer surrounding flammable lifting gas for the purpose of reducing the risk of fire. Combining of these two techniques would result, however, in having the inert gas at a pressure lower than that of the lifting gas. Maintaining the inert gas layer at a lower pressure than the lifting gas allows accidental leaks of lifting gas to contaminate the inert gas, possibly to the point where the mixture becomes flammable. A simultaneous leak in the outer envelope could then create a flammable mixture in the surrounding atmosphere. If the inert gas is maintained at positive pressure with respect to both lifting gas and ambient air, all leaks are of inert gas only, so that no flammable mixture can form. Furthermore, since the volume of the inert gas in a practical airship would be small compared with the volume of flammable gases, leaks would be more quickly detected if all leaks were of inert gas.

Prior art does disclose means for maintaining a protective layer of inert gas at a positive gauge pressure with respect to the lifting gas, but the means disclosed does not provide for retaining lifting gas during ascent. These means would therefore be impractical for an airship engaged in repeated vertical maneuvers over a long route.

The present invention solves the problems of integrating a nonrigid cable framework with a shield of inert gas maintained at positive pressure with respect to the lifting gas and cargo gas and of retaining inert gas during ascent of the airship; it also provides means for locating approximately any appreciable leaks of inert gas from the shield gas layer so that leaks can be pinpointed quickly and repairs made.

In order to maintain static stability in an airship, concentrated loads such as solid or liquid ballast, fuel, and freight must ordinarily be located below the center of buoyancy. The most efficient way to support such loads from a bag reinforced by a network of tension members is by the shortest tension members. This tends to minimize the weight and original cost of cables. In an elongated airship the transverse, or hoop, members are the shortest and therefore should carry most of the suspended load. Placement of the major load on the hoop cables requires a change in the shape of the airship as it is being loaded with high-density weights and with buoyant gas. Operators of conventional nonrigid airships do not face a major problem here, both the mass of the lifting gas and of the high-density load being relatively constant; at a landing field the major shifts are between cargo and ballast or between one cargo and another. An airship transporting buoyant cargo gas, however, must increase its high density ballast as it takes on buoyant cargo gas and discharges an equal volume of ballast air. For this application, the flexible network of prior art comprising the nonrigid airship framework is not suitable. The first problem is that the diagonal, or helicoid, tension members take a considerable portion of the load as they resist the change in shape that would allow the hoop members to carry a very large portion of the load. The longitudinal members also resist this change in shape, but adjusting the effective lengths of critical longitudinal members is easier than adjusting the lengths of the diagonal members.

The present invention allows the hoop members to carry a large portion of the concentrated weight by omitting the diagonal members from the nonrigid framework, adding special tension-distribution cables in the regions of the bow and the stern, and providing for varying the effective lengths of certain critical longitudinal cables during loading and unloading of the airship.

Airships have been moored by the bow to a high mast or by a mooring connection disposed on the underside of the airship somewhat forward of the center to a short, portable mast.

The laminar boundary control system comprising part of the present invention requires that the suction surface extending from the frontmost point of the airship to a line of latitude located well toward the stern be aerodynamically smooth. The practical difficulties of making the mooring connection aerodynamically smooth dictate that the mooring connection should not be located any appreciable distance forward of the rear edge of the suction area. The mooring connection is therefore sufficiently close to the stern to cause the airship to weathervane with its stern into the wind when moored. Attaching the airship to the mooring mast by a stern connection while the airship was headed into the wind would neutralize the aerodynamic steering mechanism and allow the airship to weathervane about 180 degrees to an aerodynamically stable position. The strength required by the airship and mooring mast to withstand such a maneuver would be costly to achieve. The present invention solves the mooring problem by providing a propulsion and control system that enables the airship to fly backwards at sufficient airspeeds to allow it to be moored with its stern facing into the wind.

The present invention may be more fully understood by reference to the following detailed description and to the accompanying drawings, which show specific embodiments and in which like reference numerals designate like parts throughout the figures thereof and wherein:

FIGURE 1 is a side elevation, partly in section, of a preferred embodiment of the invention illustrating a nonrigid airship suited to hauling slightly to moderately buoyant cargo gas and constructed in accordance with the principles of the present invention;

FIGURE 2 is a cross-sectional view taken in the vertical

longitudinal median plane of the airship, showing the airship ballasted with air and carrying very little cargo gas;

FIGURE 3 shows the same view as FIGURE 2 except that the airship is loaded with cargo gas and contains only a small amount of ballast air;

FIGURE 4 is a front view, partly in cross section, on line **4—4** of FIGURE 1;

FIGURE 5 is a cross-sectional view of a small portion of the port wall and the adjoining cargo-gas diaphragm of the airship taken on line **4—4** of FIGURE 1 showing the cargo-gas diaphragm in the position it takes when the airship is about half-loaded with cargo-gas;

FIGURE 6 is a top plan cross-sectional view of a portion of the stern of the airship taken on line **6—6** of FIGURE 1;

FIGURE 7 is a cross-sectional view of a portion of the nonrigid framework of the starboard wall of the airship, and of the attached ballast tank suspension system, taken on line **7—7** of FIGURE 1;

FIGURE 8 is a front view of the airship showing the variation in cross-sectional shape resulting from a change from the unloaded to the loaded condition of the ballast tanks and cargo-gas chamber;

FIGURE 9 is a side view of the bow portion of the airship framework, showing the full-load tension distribution cables and the longitudinal cables;

FIGURE 10 is a front view of selected elements of the nonrigid framework of the airship, showing the tension distribution cables;

FIGURE 11 is a side view of a portion of the envelope complex near the top of the airship;

FIGURE 12 is a cross-sectional view taken on line **12—12** of FIGURE 11;

FIGURE 13 is a cross-sectional view taken on line **13—13** of FIGURE 11;

FIGURE 14 is a cross-sectional view of a very small portion of the perforated outer shell of the laminated bow shell of the airship;

FIGURE 15 is a cross-sectional view of a small portion of the laminated bow shell of the airship;

FIGURE 16 is a side elevation, in section, of the upper half of the bow portion of the envelope complex;

FIGURE 17 is a cross-sectional view of a portion of the envelope complex at the top of the airship;

FIGURE 18 is a cross-sectional view of a rigidizable support shown in the rigid position as it supports the perforated membrane that forms the outer cover of the amidships region in the preferred embodiment of the airship;

FIGURE 19 is a cross-sectional view of a very small portion of the perforated support member of the rigidizible support;

FIGURE 20 is a side view, partly in section, of a portion of the envelope complex in the region where the suction section adjoins the blowing section;

FIGURE 21 is a cross-sectional view taken on the line **21—21** of FIGURE 20;

FIGURE 22 is a view from the outside of the airship of the blowing membrane that covers the stern portion of the airship in the preferred embodiment;

FIGURE 23 is a sectional view of the blowing membrane taken, in a plane perpendicular to the surface of the membrane and parallel with the flow of air, on line **23—23** of FIGURE 22.

FIGURES 1–4 show the lifting gas **15** in the upper part of the airship **11**, the cargo gas **16** forming a middle layer; and the ballast air **17** in the lower part of the airship. The lifting gas **15** is separated from the cargo gas **16** by the substantially horizontal lifting-gas diaphragm **25**. The cargo gas **16** is separated from the ballast air **17** by the substantially horizontal cargo-gas diaphragm **26**. As the airship ascends, the lifting gas **15** expands, pushing the lifting-gas diaphragm **25** downward. This downward movement of the lifting-gas diaphragm **25**, along with the concurrent expansion of the cargo gas **16**, displaces the ballast air **17**, which is discharged through the air release valve **13**. When the ballast air **17** is substantially discharged, the airship is at pressure height.

It is contemplated that in the most common application the lifting gas **15** will consist largely of hydrogen and the cargo gas **16** will be a mixture of flammable hydrocarbon gases and vapors. In such an application the lifting-gas diaphragm may consist of any suitable solid material or combination of solid materials, while the cargo-gas diaphragm **26** consists of two vertically spaced membranes separated by a layer of nonflammable shield gas **18**.

The preferred construction of the cargo-gas diaphragm is shown in FIGURE 5. The upper diaphragm membrane **29** is attached to an upper network of laterally spaced upper longitudinal diaphragm cables **32** and longitudinally spaced upper transverse diaphragm cables **34**, the cables being suitably joined at each point of intersection. The lower diaphragm membrane **30** is attached to a nether network of laterally spaced lower longitudinal diaphragm cables **33** and longitudinally spaced lower transverse diaphragm cables **35**, the cables being joined by suitable means at each point of intersection. The upper cable network is held in spaced relationship to the nether cable network by spacer lines **31**, each spacer line being fastened at its upper extremity to an intersection point of the upper cable network and at its lower extremity to the corresponding intersection point of the nether cable network, and sealed with a gas-tight seal where it passes through a diaphragm membrance. The spacer lines limit the maximum distance between the upper and lower cable networks, while the shield gas **18**, a gas or mixture of gases that is nonflammable in air and not highly reactive toward the cargo gas or the lifting gas, holds the upper and lower diaphragm membranes apart because of its positive gauge pressure with respect to the cargo gas above and the ballast air below. The pressure is maintained by suitable pumps supplying shield gas to each compartment of the cargo-gas diaphragm via a flexible shield-gas tube **99**, the gas being stored in shield-gas ballonets **98** (see FIGURE 4). The shield-gas ballonets receive shield gas from the shield-gas compartments of the cargo-gas diaphragm as the airship ascends and the shield gas expands. During descent, shield gas flows from the ballonets to the cargo-gas diaphragm, the diaphragm being so constructed as to hold a relatively constant volume of shield gas. The shield-gas ballonets also accommodate a reserve supply of shield gas that can be used to replenish gas lost by accidental leakage through the upper or lower diaphragm membrane. A telemeter **100** meters shield gas to and from each shield-gas compartment; a significant leak from a shield-gas compartment will tend to show a net flow of gas being metered to the leaking compartment.

Shield gas compartments within the cargo-gas diaphragm are formed by approximately vertical diaphragm partition membranes **24** running longitudinally and by diaphragm bulkheads **44** extending transversely and approximately vertically.

The cargo-gas diaphragm is attached to the outer wall, or envelope complex, of the airship as illustrated in FIGURE 5. In the preferred form of the invention, the nonrigid framework of the airship is comprised basically of laterally spaced longitudinal cables **70**, which converge at the bow and at the stern, and of longitudinally spaced hoop cables **71**, which pass around the outside of the longitudinal cables and hold them in so as to form an elongated envelope shaped approximately as a prolate ellipsoid of revolution. The longitudinal and hoop cables are joined by suitable means at each intersection. To each longitudinal cable is fastened, by its inner edge, a catenary curtain **72** having its greatest strength in the transverse direction. To the outer edges of the catenary curtains is fastened the pressure-containing membrane **22**, this membrane having its greatest strength in the hoop, or transverse direction. To each catenary curtain, near its

lower edge, is joined in gas tight fashion the shield-gas membrane **75**. The longitudinal chambers formed by the pressure-containing membrane, catenary curtains, and shield-gas membrane, are divided into shield-gas compartments by flexible shield-gas bulkheads **78** (see FIGURE 16). These shield-gas compartments are filled with shield gas **18**, which is supplied by the same system of shield-gas ballonets, pumps, and flexible shield-gas tubes that supplies the cargo-gas diaphragm. Each shield-gas compartment in the envelope complex is supplied with shield gas via a telemeter **100**, which meters flows to and from each compartment during descent and ascent. Significant net flows of shield gas to a shield-gas compartment indicate a leak in the compartment.

The center of buoyancy of the lifting gas is moved longitudinally and laterally by means of the lifting-gas control cables **27** (see FIGURES 1 and 4), each of which is attached at its lower end to the lifting-gas diaphragm **25** and at its upper end to a control winch **55**, each control winch being anchored to the flexible framework of the airship.

The center of gravity of the ballast air can be moved longitudinally and laterally by means of the cargo-gas control cables **28**, each of which is attached at its upper end to the cargo-gas diaphragm and at its lower end to a control winch **55** anchored to the flexible framework of the airship. In the preferred form of the invention, each control winch is electrically powered, equipped for both regenerative and friction braking, and remotely controlled.

The center of buoyancy of the cargo gas is dependent on the positions of the lifting-gas diaphragm and the cargo-gas diaphragm, these positions being controlled by the control cables, which are in turn controlled by their respective control winches. The control system that includes the diaphragms, control cables, and winches is used to control, or help control, the attitude of the airship about the longitudinal and lateral axes. The control system is also used to damp surging of the contained gases. Such surging can be caused by maneuvering of the airship or by gusty winds. Control of surging is of course related to control of the attitude of the airship.

A gas-tight pressure-containing membrane **22** surrounds the body of contained gas comprising lifting gas, cargo gas, and ballast air. To the pressure-containing membrane are attached, in a gas-tight manner, the lifting-gas diaphragm and the cargo-gas diaphragm, the line of attachment for each diaphragm being substantially horizontal when the airship is in its upright operating position.

FIGURES 1, 4 and 6 illustrate the cargo-gas tube **19**. The cargo-gas tube, which in the preferred form of the invention is located at the stern of the airship, carries cargo gas from the cargo-gas chamber to the mooring connection **42** during unloading, and from the mooring connection to the cargo-gas chamber during loading. The cargo-gas tube **19**, except for its upper portion, is formed by (1) a strip of membrane, termed the inner cargo-tube membrane **41**, disposed vertically inside the envelope complex of the airship and attached in a gas-tight manner along its long edges to the innermost membrane of the envelope complex and (2) the included portion of the innermost membrane of the envelope complex. The upper portion of the cargo-gas tube, situated above the line of attachment of the lifting-gas diaphragm to the envelope complex, is formed by the inner cargo-tube membrane **41** and the included portion of the lifting-gas diaphragm **25**, the upper portion of the inner cargo-tube membrane being attached along the long edges to the lower side of the lifting-gas diaphragm. Making the upper portion of the cargo gas tube **19** integral with the lifting-gas diaphragm **25** assures that the upper end of the lifting-gas tube will always be situated at the top of the cargo-gas chamber in a position to unload substantially all of the cargo gas at any terminal whose altitude is within the design range of unloading altitudes.

At the upper end of the cargo-gas tube **19** there is at least one unloading blower **40** capable of forcing the buoyant cargo gas downward to the mooring connection **42**. While not in use for loading and unloading cargo gas, the cargo-gas tube can be allowed to collapse, the inner cargo-gas membrane moving outward until it lies against the innermost structure of the envelope complex. The cargo-gas diaphragm **26** is attached in a gas-tight manner to the inner cargo-tube membrane where the cargo-gas diaphragm abuts the inner cargo-gas tube, although it is attached along the rest of its edge to the envelope complex.

As cargo gas is unloaded from the airship, the cargo-gas diaphragm **26** moves upward until it is stopped by the overlying lifting-gas diaphragm **25**. Since the upper end of the cargo-gas tube **19** is integral with and on the underside of the lifting-gas diaphragm, the cargo gas is accessible to the unloading blower **40** at the upper extremity of the cargo-gas tube **19**. The last portion of cargo gas to be unloaded is moved toward the unloading blower by releasing tension on the control cables in a serial fashion, release of tension beginning with those cables most distant from the unloading blower inlet and progressing to those cables nearest the inlet.

The pressure of the lifting gas downward on the lifting-gas diaphragm and the pressure of the ballast air upward on the cargo-gas diaphragm cooperate to force the two diaphragms into contact, the area of contact increasing and the boundary of this area progressing toward the unloading blower as tension on the control cables is released in the sequence described above. The cargo gas is thus forced toward the unloading blower with only a small amount of residual gas left trapped between the two diaphragms. The cargo gas trapped between the diaphragms and in the cargo-gas tube, while not susceptible of economic unloading at the gas-receiving terminal can, if it is an acceptable fuel gas, be used for propulsion fuel on the return voyage, being gathered by suitable means at the relatively low rate required by the engines.

It is necessary to pump ambient air into the ballast-air chamber while the airship is descending, increasing its gauge pressure, or unloading cargo gas. At least one ballast-air blower **14** is provided for such pumping. At least one remotely controlled air-release valve **13** is provided to vent ballast air while the airship is ascending, reducing its gauge pressure, or being loaded with cargo gas.

During loading, as during unloading, the airship is moored to a hollow mooring mast **45** (see FIGURE 1) and connected thereto in gas-tight fashion by a suitable mooring connection **42**. During the loading operation, cargo gas enters the airship from the mooring mast, flows upward through the cargo-gas tube, and enters the cargo-gas chamber by reverse flow through the unloading blower or via a by-pass valve. The cargo gas displaces the cargo-gas diaphragm downward, which in turn displaces ballast air, the displaced ballast air being vented via the air-release valve **13**.

During the unloading operation, while buoyant cargo gas is being replaced by ballast air, it is necessary to remove liquid or solid ballast from the airship in order to maintain neutral buoyancy. During loading of buoyant gas, it is necessary to load liquid or solid ballast simultaneously in order to maintain neutral buoyancy. In the preferred form of the invention, liquid ballast is carried in two rows of ballast tanks **47**, as shown in FIGURES 1 and 4. These tanks carry a payload of liquid commodities when such are available for transport in the direction of the cargo-gas movement. When a liquid payload is not available, an expendable liquid ballast, such as water, can be carried. Even flowable solids can be carried in the ballast tanks.

Each row of ballast tanks is disposed within the non-rigid framework of the airship and along a streamline so that the resulting longitudinal ridge formed on the en-

velope complex will cause a minimum of interference with air flow around the airship.

Each ballast tank **47** is suspended as shown in FIGURES 1 and 7. Two or more tank suspension loops **50** surround each ballast tank **47** and support the major part of its weight. Each tank suspension loop is fastened to the lower end of the corresponding tank suspension cable **48**, which in turn is secured to the corresponding hoop cable **71** of the nonrigid framework of the airship. The tank suspension cable **48** is made to follow somewhat the general contour of the hoop cable **71** by the suspension cable tie lines **49**. The primary effect of the suspension cable tie lines is to distribute the horizontal force exerted on the hoop cable **71** by the tank suspension cable **48** so as to prevent the formation of a longitudinally extending valley in the outer surface of the envelope complex in the region where the tank suspension cables are attached to the hoop cables; the secondary effect is to decrease the amount of space occupied by the tank suspension system. The tank guy cable **51** is attached at its upper end to the lower end of the tank suspension cable **48**, and at its lower end to the hoop cable **71**. The middle portion of the tank guy cable **51** passes on the outside of, and beneath, the ballast tank, holding it in spaced relationship to the hoop cable.

As FIGURE 4 shows, the radius of the curve followed by the hoop cable attains a local minimum in the vicinity of the ballast tanks. This minimum-radius region, or shoulder, is caused by the weight of the ballast tank, and is more pronounced when the tank is heavily loaded, as shown by the solid lines in FIGURE 7, than when the tank is empty, as shown by the broken lines in FIGURE 7. Thus the angle that the hoop cable curves through in the vicinity of the tank is less when the tank is empty than when it is loaded, and the linear distance from the junction of the tank suspension cable with the hoop cable to the junction of the tank guy cable with the hoop cable is correspondingly greater. This change in distance between the vertical extremities of the suspension system is accommodated by the rotation of the ballast tank **47** and the tank suspension loop **50** around the point of attachment of the tank suspension loop to the tank suspension cable **48**. As the tank is emptied it rotates to a higher and more inward position, thus remaining clear of the hoop cable as it moves inward and upward with the partial disappearance of the downwardly and outwardly bulging shoulder. This rotation of the tank is not caused primarily by the elastic action of the tank guy cable and the tank suspension cable in response to the lightening of the tank; rather, it is caused primarily by the partial straightening of the tank guy cable as it is forced to extend over a greater distance.

Longitudinal movement of the ballast tanks is limited by suspension brace cables **52** as shown in FIGURE 1. A suspension brace cable runs diagonally upward from its lowermost point of attachment to a ballast tank to its uppermost point of attachment to a hoop cable, which it joins at the latter's junction with a tank suspension cable. The suspension brace cable is attached at intermediate points to the inner ends of the suspension cable tie lines **49** and to the attached tank suspension cables **48** (see FIGURES 1 and 7).

The extremes in the cross-sectional shapes of the midsection of the airship are shown in FIGURE 8. The solid curved line shows the shape corresponding to the unloaded condition, the buoyant cargo gas having been displaced by ballast air and the ballast tanks having been emptied. The broken curved line shows the shape corresponding to the loaded condition, with the airship containing a full load of buoyant cargo gas and with the ballast tanks loaded.

The cross-sectional shape of the unloaded airship is almost circular, because the gauge pressure is only moderately greater at the top than at the bottom, this difference being caused by a moderate vertical depth of lifting gas, and because the ballast tanks are empty so exert a relatively small distorting effect. The cross-sectional shape of the loaded airship departs further from the circular and approaches the triangular. This further departure from a circular shape is caused by the increase in gauge-pressure differential between the bottom and the top of the airship caused by the presence of the buoyant cargo-gas, and by the balancing force exerted by the heavily laden ballast tanks. This change in cross-sectional shape is easily accommodated by the flexible hoop cables. The potential problem of change of shape in the ballast tank area is solved by the tank suspension system described above. The structural problem that remains to be discussed is the effect of the change of shape on the longitudinal cables of the flexible airship framework.

When the airship is unloaded and its cross-sectional shape consequently approaches the circular, the envelope approximates the shape of a prolate ellipsoid of revolution. The lengths of the longitudinal cables are therefore approximately equal. When the airship is loaded, so that its cross-sectional shape becomes more trianguloid, there is a tendency for the longitudinal cables located near the top of the airship and near each row of ballast tanks, i.e., those located near the points of the triangle as it were, to be stretched or overloaded; there is a corresponding tendency for the longitudinal cables furthest from the points of the triangle to be unloaded and to become slack, since their routes from bow to stern are allowed to approach more nearly to a straight line.

The problem of reducing the differences in stress as between longitudinal cables is solved by two cooperating techniques: first, selection of the range of cross-sectional shapes for which the airship is to be designed, and, second, provision for adjusting, during loading and unloading operations, the effective length of the most affected longitudinal cables.

The design cross section is a compromise between the almost circular shape shown by the solid curved line in FIGURE 8 and the decidedly trianguloid shape shown by the broken curved line in FIGURE 8. This compromise shape is that which results from the provision of longitudinal cables of such lengths that each is loaded to substantially the same fraction of its ultimate strength when the airship is loaded to one half of its design capacity with cargo gas and liquid ballast and carrying its normal gauge pressure.

This construction makes it feasible to design the cables more nearly equal in strength than if the cables were all of equal length, as they would be if the design cross section were circular. Having longitudinal cables more nearly equal in strength is useful when significant superpressure is used for altitude control, as the increment in gauge pressure above the normal design pressure places a substantially equal increment of tension on each longitudinal cable.

In FIGURE 8 the three solid radial lines, which form an inverted Y, represent the three full-load tension zones **109**, while the three broken radial lines, which form a Y, represent the three no-load tension zones **110**. A full-load tension zone is a band of longitudinal cables that are subjected to maximum stress when the airship is in the fully loaded condition and to minimum stress when the airship is in the unloaded condition. A no-load tension zone is a band of longitudinal cables that are subjected to maximum stress when the airship is in the unloaded condition and to minimum stress when the airship is in the fully loaded condition.

In the unloaded condition the cross section is more nearly circular than is the design cross section, yet the distribution of stresses among the longitudinal cables is such as to minimize the degree of departure from the somewhat trianguloid design cross section, the cables of maximum stress forming a Y. In the loaded condition the distribution of stresses among the longitudinal cables is reversed, the cables of maximum stress forming an

inverted Y, the stress distribution again being such as to minimize the degree of departure from the somewhat trianguloid design cross section.

Because the longitudinal cables converge to a point at the bow and at the stern, a greater-than-average stress in a group of cables tends to be concentrated within a smaller circumferential distance as the bow or stern is approached. In order to avoid the formation of valleys along the three groups of the most highly stressed longitudinal cables and complementary bulging ridges in the areas of the least stressed longitudinal cables, it is necessary to distribute the longitudinal stresses in the bow and stern areas. In the present invention this is accomplished with tension distribution cables.

FIGURE 9 shows the longitudinal cables **70** and the two full-load tension distribution cables **58** in the bow region of the airship. FIGURE 10 shows these components and, in addition, shows two no-load tension distribution cables **59**. Each tension distribution cable forms a closed loop having three outwardly and backwardly extending lobes about 120 degrees apart and three inwardly and forwardly extending lobes also about 120 degrees apart but offset about 60 degrees from the backwardly extending lobes. A tension distribution cable is securely fastened by suitable means to each longitudinal cable. When the airship is loaded, the full-load tension distribution cables **58** are stressed and the no-load tension distribution cables **59** are relatively slack, so that in the bow region some of the tension is distributed from the longitudinal cables in the full-load tension zones to the longitudinal cables in the no-load tension zones. When the airship is in the unloaded condition the no-load tension distribution cables **59** are stressed and the full-load distribution cables **58** are relatively slack, so that in the bow region some of the tension is distributed from the longitudinal cables in the no-load tension zones to the longitudinal cables in the full-load tension zones.

The position of the full-load tension distribution cables and of the no-load tension distribution cables at the stern of the airship is substantially symmetrical, with respect to the median vertical transverse plane, with the position of the corresponding tension distribution cables at the bow. The functions of the tension distribution cables at the stern are analogous and complementary to those of the tension distribution cables at the bow.

The effective lengths of the longitudinal cables **70** located in the full-load tension zones **109** or in the no-load tension zones **110** are adjusted by means of inflating and deflating inflatable catenary curtains. The longitudinal cables in the tension zones are fitted throughout the amidships region of the airship with inflatable catenary curtains **80**, as illustrated in FIGURES 11–13. When the effective length of a cable is to be reduced, the pressure in the inflatable catenary curtain is decreased, as illustrated in FIGURE 13. The deflation allows the curtain walls to straighten and thus increases the effective depth of the catenary curtain, the increase in depth being greatest in the region of a hoop cable and nonexistent in the region of the noninflatable catenary section **81**, which is centered between each pair of hoop cables. The greater increase in depth in the regions of the hoop cables allows the catenary curves in the longitudinal cable to become more pronounced and thereby shortens the effective length of the longitudinal cable. The portion of the inflatable catenary curtain lying in the region of the noninflatable catenary section transfers no force to the longitudinal cable, as FIGURE 12 shows, but serves only to accommodate longitudinal gas movements associated with inflation and deflation of the load bearing portions of the catenary curtain.

The effective length of a cable is increased by inflating the inflatable catenary curtain, as shown in FIGURE 13. This inflattion reduces the effective depth of the catenary curtains and thereby increases the effective cable length.

During loading, the inflatable catenary curtains in the full-load tension zones are inflated, while the inflatable catenary curtains in the no-load tension zones are deflated. During unloading, the inflatable catenary curtains in the full-load tension zones are deflated, and the inflatable catenary curtains in the no-load tension zones are inflated. Shield gas is used for inflating the catenary curtains, and a single compressor may be used for pumping gas from one set of inflatable catenary curtains to the complementary set during loading and unloading operations.

In certain applications the preferred form of the present invention includes a boundary layer control system. The boundary layer control system involves the use of distributed suction on the forward and middle portions of the airship and distributed blowing on the rear portion of the airship. The distributed suction is designed to maintain a laminar boundary layer over the forward and middle portions of the airship, at least during favorable weather. The distributed blowing is designed to prevent boundary layer separation in the region of the stern.

The gross features of the boundary layer control system, shown in FIGURE 1, comprise a rigid perforated outer shell **63** which covers the bow of the airship, a perforated membrane **20**, which covers the middle portion of the airship, a blowing membrane **23**, which covers the stern portion of the airship, and an adjustable annular jet **38**, which exhausts boundary layer air not vented through the blowing membrane.

The perforated outer shell **63** is smooth and provided with small, closely spaced perforations. This perforated outer shell takes the shape of a smoothly rounded surface of revolution in its central portion, but toward its outer edge it graduates into a smooth, undulating surface, each undulation having an axis made up of a radial component and a longitudinal component. The central, nonundulating portion of the perforated outer shell is large enough to contain the stagnation point well within its outer limit during normal cruising conditions, even though the stagnation point ordinarily moves around in response to yawing, pitching, and wind gusts. As the ambient air flows radially outward from the stagnation point, a boundary layer is established. The velocity, with respect to the local airship surface, of the free air stream outside the boundary layer increases with distance from the stagnation point, reaching a maximum in the vicinity of the maximum circumference of the airship. The distributed suction applied to the boundary layer by the perforated outer shell gives the boundary layer a relatively stable form of velocity distribution known as the asymtotic distribution. Although the suction also stabilizes the boundary layer by preventing it from becoming too thick, the suction is controlled to allow the boundary layer thickness to grow almost to the maximum thickness consistent with laminar flow. By the time a parcel of ambient air reaches the undulating portion of the perforated outer shell, the thickness and velocity distribution of the boundary layer are such that the tolerance of the laminary boundary layer to surface roughness and waviness is near the maximum possible for the free stream velocity involved. Tolerance to waviness is desirable because effective waviness is met when the free stream crosses some of the perforated outer shell undulations diagonally, as it must when the stagnation point is not in the center of the perforated outer shell. Tolerance to surface roughness is desirable where the air stream crosses the bow joint **61** between the rigid perforated outer shell and the nonrigid perforated membrane. The diameter of the perforated outer shell is made as small as feasible in order to minimize the distance from the stagnation point to the bow joint **61** and threeby to minimize, for a given airspeed, the free stream velocity in the vicinity of the bow joint. The bow joint presents a roughness problem, and tolerance to roughness decreases with free stream velocity. Placing the bow joint relatively close to the stagnation point allows this potentially rough region to be crossed before the free air stream reaches a high velocity.

It is desirable to avoid exceeding the tolerance of the laminar boundary layer to a combination of waviness, roughness, and free air velocity, because if this tolerance is exceeded, flow in the boundary layer becomes turbulent and the turbulence is propagated downstream in a widening, wedge-shaped pattern. The further forward on the airship a source of turbulence is located, the greater will be the area over which a turbulent boundary layer will be substituted for a laminar boundary layer. As is well known, the skin drag caused by a turbulent boundary layer is significantly greater than the skin drag caused by a laminar boundary layer.

The perforated outer shell **63**, shown in FIGURE 14, is made of rigid or semirigid material and is in the form of a perforated, uniform sheet with integrally formed reinforcing ribs **69** shaped in a gridiron pattern. The spacing between the outer shell perforations **68** is substantially uniform and is greater than the width of a reinforcing rib. The perforated outer shell **63** is supported as shown in FIGURES 15 and 16. The reinforcing ribs of the perforated outer shell are glued, welded, or in a similar manner secured to the primary shell grid **64**, the ribs of which are of a thickness sufficiently less than the spacing between the integral reinforcing ribs of the perforated outer shell to enable boundary air to flow freely inward from each rectangular cell of the perforated outer shell, regardless of how the outer shell and the primary shell grid may register on one another.

The primary shell grid **64** is glued, welded, or otherwise suitably secured to the secondary shell grid **65**, which supports the primary shell grid. The ribs of the secondary shell grid are of a thickness sufficiently less than the spacing between the ribs of the primary shell grid to allow boundary air to flow freely inward from each cell of the primary shell grid no matter how the two grids register. The secondary shell grid is provided with suitably spaced shell mounting brackets **66**. The perforated outer shell, primary shell grid, and secondary shell grid together make up the laminated bow shell **62**, which, as FIGURE 16 shows, is secured to the rigid bow framework **67**, the shell mounting brackets being used for this purpose. The rigid bow framework is preferably made of light metal structural members joined by welding or other suitable means to form a structure strong enough to give overall rigidity to the laminated bow shell.

The rigid bow shell is secured to the nonrigid framework of the airship. The space between the laminated bow shell and the pressure-containing membrane, which is occupied by the rigid bow framework, serves as a suction chamber to receive boundary layer air drawn in through the perforated outer shell. This boundary air is in turn drawn outward and sternward into the frontmost suction chambers of the nonrigid suction section of the airship, which extends from the perforated outer shell sternward to the blowing membrane.

The perforated membranes **20** (see FIGURES 1, 16–19) is attached at its forward edge to the edge of the perforated outer shell and at its sternmost edge by the blowing membrane. The perforated membrane is supported by radially spaced and longitudinally extending rigidizible supports **84**, as shown in FIGURE 17. Each rigidizible support is secured to and supported by the outer support membrane **73**, which, along with the inner support membrane **74**, form an inflated support tube integral with the air-tube membrane **21**. Each longitudinal edge of an air-tube membrane **21** is joined in a gas-tight fashion to the pressure-containing membrane **22** along a longitudinal line running midway between two catenary curtains **72**. A series of suction chambers is formed between the perforated membrane and the air-tube membrane, adjoining suction chambers being separated from one another by a transverse suction-chamber bulkhead **77**, the latter being attached along its outer edge to the perforated membrane and along its inner edge to the air-tube membrane, as indicated in FIGURE 16.

Longitudinally extending air tubes are formed between the air-tube membrane **21** and the pressure-containing membrane **22**. Installed in the air-tube membrane are boundary air blowers **76**, the blowers being longitudinally spaced so as to provide at least one blower for each intersection of an air tube with a suction chamber. The boundary air blowers, preferably electrically powered and remotely controlled, withdraw air from the suction chambers and force it into the air tubes. Thus boundary air is drawn through the perforated membrance into the suction chambers and then forced by the boundary air blowers into the air tubes. In the air tubes the boundary air moves sternward. When the air reaches the blowing membrane, part of the air escapes through the blowing memberane, which form the outer wall of the air tubes in the reigon of the stern. The boundary air that does not escape through the blowing membrane is ejected through the adjustable annular jet.

The contour of the undulating edge of the perforated outer shell approximates the contour of the perforated membrane shown in FIGURE 17, the forward edge of the membrane being tapered and cemented, as smoothly as feasible, to the outer surface of the perforated outer shell just forward of the edge of the shell.

The rigidizible support **84**, as shown in FIGURE 18, consists of a perforated supported member **85** fastened to longitudinally spaced rigidizer cross bars **88**, which are secured to the outer support membrane **73** by the attachment straps **93**. The perforated support member **85**, which is somewhat elastic, is, in the rigid condition, held in the shape of a transverse arch by the rigidizer loops **87**, which are put in tension by their inflation of the rigidizer tube **86**. The inward movement of each edge of the perforated support member **85** is limited by the hold-down thongs **89**, which attach the perforated support member to the rigidizer cross bars **88**. The perforated support member supports the perforated membrane **20**, which is cemented or otherwise attached to the perforated support member. The perforated support member limits waviness in the perforated membrane so that a laminar boundary layer can be maintained at a relatively high free-stream velocity, and provides a gently rounded support surface along the individual longitudinal line of support so that cross flow components resulting from yawing or pitching will not initiate turbulence, as they would in passing over a sharp ridge.

As shown in FIGURE 19, the perforated support member has longitudinal ridges **90**, to the flat tops of which the perforated membrane **20** is cemented. The width of a longitudinal ridge at its top is appreciably less than the diameter of an outer-cover perforation **92**; therefore, where a perforation registers on a ridge, the perforation is not completely closed thereby. The space between adjoining right tops, moreover, is appreciably wider than the ridge top. Therefore, most of the outer-cover perforations in the general area of contact between the perforated support member and the perforated membrane suffer little or no interference from the ridge tops, so that the inward flow density of boundary air is only slightly less in the general area of contact than in the unsupported portions of the perforated membrane. In the valley between an adjacent pair of longitudinal ridges is a longitudinal row of support perforations **91**. Boundary air passes inward through the outer-cover perforations and then through the support perforations, and finally out of the rigidizible support structure via leaks near the cross bars and by reverse flow through support perforations near the edges of the perforated support members, as shown by the arrows in FIGURE 18.

The rigidizible support is made nonrigid by deflation of the rigidizer tube; this unarches the perforated support member, which can then be flexed or rolled up. Such flexibility of the rigidizible support allows the uninflated airship to be constructed, handled, and stored as a nonrigid airship without breaking the rigidizible supports.

Directly outward from each longitudinal cable **70** there is a rigidizable support **84**, as illustrated in FIGURE 17. Since the effective length of a cable varies with various conditions, such as whether airship is loaded or unloaded, or operating with or without superpressure, it is necessary for the perforated support member of the rigidizible support to vary in length also. Variations in the length of a perforated support member **85** are made to match variations in the effective length of the corresponding longitudinal cable **70** by anchoring the rear extremity of the perforated support member to the longitudinal cable by means of anchor cable **95**, as shown in FIGURES 20 and 21. The preforated support member is sufficiently elastic so that it will stretch to accommodate to changes in the effective length of the longitudinal cable. The anchor cable is supported in a gentle curve by the support membrane **96**, the anchor cable thereby exerting tension on the perforated support member in a direction that is almost tangent to the outer surface of the airship, thus avoiding a sizable inward component of force that would collapse the air tube and allow the perforated membrane to rest on the air-tube membrane. The support membrance **96** is attached along its upper edge to the blowing membrane **23**, and is supported thereby.

The blowing membrane **23**, which forms the outer wall of the air tubes in the stern portion of the airship, is fitted with slot-like, sternward facing blowing nozzles **103**, as illustrated in FIGURES 22 and 23. Boundary air, pumped into the air tubes by the boundary air blowers and forced sternward, begins to escape into the atmosphere when it reaches the blowing membrane. The blowing nozzles acceleratee air from the air tubes and blow it sternward along the surface of the blowing membrane. As the sternward moving air stream from a frontmost blowing nozzle develops a boundary layer adjacent to the blowing membrane and loses velocity relative to the blowing membrane, the sternward-moving air stream is displaced outward by the air stream from the next blowing nozzle. Exchange of momentum takes place between the adjacent air streams, the second air stream imparting to the first, or outside air stream, sufficient momentum to accelerate it to the local free stream velocity. Each succeeding nozzle supplies a jet of air that displaces the air from the preceding nozzle and accelerates it to the free stream velocity. In this manner the build-up of a thick, slow moving boundary layer on the stern area of the airship is prevented, and the high pressure air near the stern cannot form a reverse flow along the blowing membrane and thereby cause boundary layer separation and large scale turbulence.

The air that is not ejected through the blowing nozzles is ejected through the adjustable annular jet **38** located at the sternmost extremity of the blowing membrane. During high speed operation, when the air flow through, and pressure drop across, the blowing nozzles must be relatively high, the cross-sectional area of the adjustable annular jet is small. During low speed operation, when air flow through, and pressure drop across, the blowing nozzles are relatively small, the annular jet is opened to a larger cross-sectional area to obtain greater thrust for helping to accelerate the airship.

The mooring connection is located sternward of the rear edge of the perforated membrane because of the difficulty of building into the mooring connection sufficient surface smoothness to maintain a laminar boundary layer on the perforated membrane if the mooring connection is inthe area covered by the perforated membrane.

Location of the mooring connection near the stern presents a mooring problem because of the tendency of the airsip to weathervane into a stern-into-the-wind position when moored in the usual bow-into-the-wind position. This problem is solved by providing propulsion and control means that allow the airship to back into the wind while approaching and leaving the mooring mast.

A reversible-pitch propeller **36** on a universal propeller mount **37** at the stern of the airship, as shown in FIGURE 1, provides propulsive thrust for both backward and forward movement. The universal mount allows the propeller to be used effectively for steering at low speeds, either in the forward or the reverse direction. Each reversible control-airfoil **39** is mounted on a fully rotatable axis, with the greater part of the area on the trailing side of the axis. The airfoils are used for turning the airship and for stabilizing it during high-speed forward operation. In reverse operation for mooring, the airfoils are rotated 180 degrees from the normal position so that the leading edge of each airfoil faces the stern. In this general position they are used to stabilize and steer the airship while it is backing into the wind.

I claim:

1. In a nonrigid airship, a nonrigid framework comprising longitudinal cables converging at the bow and at the stern and longitudinally spaced hoop cables intersecting said longitudinal cables and fastened thereto at each point of intersection, a pressure-containing membrane enveloping said framework, means including a plurality of catenary curtains securing the pressure-containing membrane to said longitudinal cables, a shield-gas membrane disposed within the nonrigid framework coextensive with at least a portion of said framework, said shield-gas membrane being fastened to the inner edges of said catenary curtains and cooperating therewith and with the pressure-containing membrane to constitute a plurality of longitudinally extending gas-tight compartments, shield-gas bulkheads partitioning said compartments to form a plurality of shield-gas compartments, and a nonflammable shield gas within said shield-gas compartments at a positive gauge pressure with respect to the flammable gases contained within the airship.

2. The construction in accordance with claim **1**, wherein there is provided at least one shield-gas ballonet, flexible shield-gas tubes connecting said shield-gas compartments to said shield-gas ballonet, means for moving said nonflammable gas from said ballonet to said shield-gas compartments for maintaining a predetermined pressure relationship between said flammable and nonflammable gas volumes, and a telemeter for measuring the quantity of gas moving to and from each shield-gas compartment.

3. The structure in accordance with claim **2**, wherein means are provided for reducing air resistance in flight through the establishment and maintenance of a laminar boundary layer on the bow and intermediate portion of the outer envelope and delaying boundary layer separation adjacent to the stern, said means including a rigid bow section, a nonrigid stern bowing section, and a nonrigid intermediate suction section extending from said bow section to said stern section;

said rigid bow section comprising a perforated outer shell having a central portion in the shape of a surface of revolution merging with an undulating outer edge, means including a plurality of associated grid members within said shell for securing said shell to the cables of the nonrigid framework and forwardly with respect to the pressure-containing membrane to provide a bow suction chamber into which boundary air may be drawn;

said nonrigid intermediate suction section including a perforated membrane joined at its forward end to the undulating outer edge of said perforated outer shell; a plurality of rigidizable supports extending longitudinally from said undulating outer edges to said stern blowing section and supporting said perforated membrane, each rigidizable support comprising a perforated support member and a plurality of rigidizer cross bars joined thereto, a plurality of rigidizer loops maintaining the perforated support member when rigidized in the shape of a transverse arch, a longitudinally extending rigidizer tube, each rigidizer loop being fastened to an outer edge of said perforated support member and extending

around a rigidizer tube; a plurality of longitudinally extending pressure tubes, each pressure tube being inflated and integral with an air tube membrane, a plurality of longitudinally extending air tubes, each formed by an air-tube membrane and the included portion of the pressure-containing membrane, each air-tube membrane being secured along its longitudinal edges to the pressure-containing membrane, each assocaited pressure tube supporting a rigidizable support; a plurality of suction-chamber bulkheads, each bulkhead being disposed so as to partition the suction chamber into a plurality of sections; at least one boundary air blower in each section, said blower being positioned in the air-tube membrane and adapted to move air from the suction chamber to an air tube, the frontmost suction chamber being connected to the bow suction chamber for exhausting boundary air therefrom for discharge through the air tubes to said nonrigid stern blowing section;

said nonrigid stern blowing section including a sternward extension of said air tubes, the outer membrane of each tube being provided with a plurality of spaced and sternwardly directed blowing nozzles, rearwardly positioned annular jet means adapted for receiving air from said air tubes, and means for adjusting the transverse vertical cross section of said annular jet.

4. The airship of claim 3, wherein a plurality of rows of ballast tanks are disposed within and adjacent to the envelope complex, each row following a streamline near the elevation of and below the principal longitudinal axis of the airship; the perforated support members in the nonrigid intermediate suction section are formed of an elastic material, an anchor cable connecting the rear extremity of each perforated support member in each full-load tension zone and each no-load tension zone to the longitudinal cable associated with said perforated support member, each anchor cable being supported by a support membrane fastened to the center of the blowing membrane of the associated air tube, inflatable catenary curtains connecting longitudinal cables in the full-load and no-load tension zones to the pressure-containing membrane; and means are provided for inflating the inflatable catenary curtains in the zones of maximum stretch and for deflating the inflatable catenary curtains in the zones of minimum stretch, the zones of maximum and minimum stretch alternating respectively in response to the loaded and unloaded condition of said ballast tanks.

5. In a nonrigid airship having a longitudinally extending envelope of modified circular cross-section, a flexible envelope structure devoid of structural members capable of withstanding substantial compressive stresses and means for providing unobstructed space for movable diaphragms, carrying flowable freight and ballast, and reducing air resistance, said means including at least one pair of rows of ballast tanks, each row being disposed within and close to said envelope structure, each pair of rows being disposed adjacent symmetrical longitudinal streamlines of the envelope structure, each row of ballast tanks following the contour of its respective streamline, each ballast tank being suspended in abutting relationship with said flexible envelope structure.

6. The airship of claim 5 wherein means are provided for reducing the required structural material, said means including in the envelope structure a nonrigid framework of circumferentially spaced longitudinally extending cables converging at the bow and stern and longitudinally spaced hoop cables intersecting the longitudinal cables and joined thereto at each intersection, the individual lengths of said longitudinal cables being such that each longitudinal cable is loaded to substantially the same fraction of its ultimate strength when the airship is loaded to one half of its design capacity with cargo gas and liquid ballast and carrying its normal gauge pressure.

7. In a nonrigid airship having a longitudinally extending envelope of modified circular cross-section, means for providing unobstructed space for movable diaphragms, carrying flowable freight and ballast, and reducing air resistance, said means including at least one pair of rows of ballast tanks, each row being disposed within and close to said envelope, each pair of rows being matched with a pair of bilaterally symmetrical steamlines, each row of ballast tanks following the contour of its respective streamline, and wherein the envelope structure includes a nonrigid framework of circumferentially spaced longitudinally extending cables converging at the bow and stern and longitudinally spaced hoop cables intersecting the longitudinal cables and joined thereto at each intersection, and a ballast-tank suspension system, said system including

a tank suspension cable attached at its upper end to a hoop cable and tie line means holding said suspension cable in conformity with the general contour of the hoop cable,

a tank suspension loop at the lower end of said suspension cable and extending around a tank for attaching said tank to said tank suspension cable,

a tank guy line attahced at its upper end to the lower end of said tank suspension cable and at its lower end to the hoop cable, and intermediate portion of said guy line passing around and holding said tank in spaced relationship with the hoop cable, and

a suspension brace cable running diagonally upward from the tank to a hoop cable and attached at its upper end to an associated hoop cable at the point of attachement of a tank suspension cable thereto, said brace cable being fastened along its length to said tie line means.

8. In a nonrigid airship having a longitudinally extending envelope of modified circular cross-section, means for providing unobstructed space for movable diaphragms, carrying flowable freight and ballast, and reducing air resistance, said means including at least one pair of rows of ballast tanks, each row being disposed within and close to said envelope, each pair of rows being matched with a pair of bilaterally symmetrical streamlines, each row of ballast tanks following the contour of its respective streamline, and wherein the envelope structure includes a nonrigid framework of circumferentially spaced longitudinally extending cables converging at the bow and stern and longitudinally spaced hoop cables intersecting the longitudinal cables and joined thereto at each intersection; two sets of full-load tension distribution cables, a forward set near the bow and rear set near the stern, and two sets of no-load tension distribution cables, a forward set near the bow and a rear set near the stern, each set of tension distribution cables comprising one or more tension distribution cables, each forward tension distributon cable forming a closed loop extending toward the maximum circumference of the envelope in three places to form three rearwardly extending lobes about 120 degrees apart and extending toward the bow in three places to form three forwardly extending lobes displaced about 60 degrees from said rearwardly extending lobes, each rearward tension distribution cable forming a closed loop extending toward the maximum circumference of the envelope in three places to form three forwardly extending lobes about 120 degrees apart and extending toward the stern in three places to form three rearwardly extending lobes displaced about 60 degrees from said forwardly extending lobes; and fastening means for securing each intersection of a longtudinal cable with a tension distribution cable.

9. In a nonrigid airship having a longitudinally extending envelope of modified circular cross-section, means for providing unobstructed space for movable diaphragms, carrying flowable freight and ballast, and reducing air resistance, said means including at least one pair of rows

of ballast tanks, each row being disposed within and close to said envelope, each pair of rows being matched with a pair of bilaterally symmetrical streamlines, each row of ballast tanks following the contour of its respective streamline, and wherein means are provided for controlling the position of distinct volumes of lifting gas, cargo gas, and ballast air and rapid loading and unloading of cargo gas, said means consisting of complete structure including:

a lifting-gas diaphragm separating lifting gas above from cargo gas below, said diaphragm being attached around its periphery to the envelope structure of the airship in a as-tight manner;

a cargo-gas diaphragm separating cargo gas above from ballast air below, said diaphragm being attached in gas-tight fashion around its periphery to the envelope structure except that, where an inner cargo-tube membrane intervenes, said diaphragm is attached thereto;

a cargo-gas tube comprising a collapsible inner cargo-tube membrane, an included portion of the lifting-gas diaphragm, and an included portion of the envelope structure, the vertically extending edges of said inner cargo-tube membrane being fastened in gas-tight fashion to the underside of said lifting-gas diaphragm and to the inside of said envelope structure, the lower end of said cargo-gas tube being connected to a mooring connection;

an unloading blower disposed at the upper extremity of said cargo-gas tube so as to withdraw cargo gas from the cargo-gas chamber and force it downward to the mooring connection;

lifting-gas control cables, each cable being secured at its lower end to the lifting-gas diaphragm and at its upper end to a control winch secured to the envelope structure; and

cargo-gas control cables, each cable being secured at its upper end to the cargo-gas diaphragm and at its lower end to a control winch secured to the envelope structure.

10. In a nonrigid airship having a longitudinally extending envelope of modified circular cross-section, means for providing unobstructed space for movable diaphragms, carrying flowable freight and ballast, and reducing air resistance, said means including at least one pair of rows of ballast tanks, each row being disposed within and close to said envelope, each pair of rows being matched with a pair of bilaterally symmetrical streamlines, each row of ballast tanks following the contour of its respective streamline, wherein means are provided for controlling the position of distinct volumes of lifting gas, cargo gas, and ballast air and rapid loading and unloading of cargo gas, said means consisting of a composite structure including

a lifting-gas diaphragm separating lifting gas above from cargo gas below, said diaphragm being attached around its periphery to the envelope structure of the airship in a gas-tight manner,

a cargo-gas diaphragm separating cargo gas above from ballast air below, said diaphragm being attached in gas-tight fashion around its periphery to the envelope structure except that, where an inner cargo-tube membrane intervenes, said diaphragm is attached thereto,

a cargo-gas tube comprising a collapsible inner cargo-tube membrane, an included portion of the lifting-gas diaphragm, and an included portion of the envelope structure, the vertically extending edge of said inner cargo-tube membrane being fastened in gas-tight fashion to the underside of said lifting-gas diaphragm and to the inside of said envelope structure, the lower end of said cargo-gas tube being connected to a mooring connection,

an unloading blower disposed at the upper extremity of said cargo-gas tube so as to withdraw cargo gas from the cargo-gas chamber and force it downward to the mooring connection,

lifting-gas cables, each cable being secured at its lower end to the lifting-gas diaphragm and at it uppers end to a control winch secured to the envelope structure, and

cargo-gas control cables, each cable being secured at its upper end to the cargo-gas diaphragm and at its lower end to a control winch secured to the envelope structure, and

wherein means are provided for reducing the risk of accidental mixing of cargo gas with ballast air and detecting and locating leaks in the cargo-gas diaphragm, said means including:

a layer of nonflammable shield gas incorporated in the cargo-gas diaphragm, said diaphragm comprising a structure including an upper diaphragm membrane separating said shield gas from said cargo gas, a lower diaphragm membrane separating said shield gas from said ballast air, spacer line means for limiting the maximum distance between said upper diaphragm membrane and said lower diaphragm membrane, and longitudinal diaphragm partition membranes and transverse diaphragm bulkheads disposed between and connecting said upper diaphragm membrane with said lower diaphragm membrane so as to divide into distinct gas-tight compartments the space occupied by the shield gas;

at least one shield-gas ballonet capable of receiving shield gas from said cargo-gas diaphragm when said shield gas expands and containing a reserve supply of shield gas for use as make-up for leakage;

a plurality of flexible shield-gas tubes, each tube connecting at least one gas-tight compartment in said cargo-gas diaphragm with a shield-gas ballonet;

pump and valve means for maintaining the shield gas in the cargo-gas diaphragm at a positive gauge pressure with respect to said cargo gas and said ballast air; and

metering and recording means for indicating cumulative net flows of shield gas to each gas-tight compartment in said cargo-gas diaphragm.

11. In a nonrigid airship, means for reducing air resistance in flight through the establishment of a laminar boundary layer on the bow and intermediate portion of the outer envelope and delaying boundary layer separation adjacent to the stern, said means including a rigid-bow section, a nonrigid stern blowing section, and a nonrigid intermediate suction section extending from said bow section to said stern section,

said rigid bow section comprising a perforated outer shell having a central portion in the shape of a surface of revolution merging with an undulating outer edge, means including a plurality of associated grid members within said shell for securing said shell to the pressure-containing structure of the airship and forwardly with respect to said pressure-containing structure to provide a bow suction chamber into which boundary air may be drawn,

said nonrigid intermediate suction section including a perforated membrane joined at its forward end to the undulating outer edge of said perforated outer shell; a plurality of rigidizable supports extending longitudinally from said undulating outer edge to said stern blowing section and supporting said perforated membrane, each rigidizable support comprising a perforated support member and a plurality of rigidizer cross bars joined thereto, a plurality of rigidizer loops maintaining the perforated support member when rigidized in the shape of a transverse arch, a longitudinally extending rigidizer tube, each rigidizer loop being fastened to an outer edge of said perforated support member and extending around a rigidizer tube; a plurality of longitudinally extending pressure tubes, each pressure tube being

inflated and integral with an air-tube membrane; a plurality of longitudinally extending air tubes, each formed by an air-tube membrane and the included portion of the pressure-containing structure of the airship, each air-tube membrane being secured along its longitudinal edges to said pressure-containing structure, each associated pressure tube supporting a rigidizable support; a plurality of suction-chamber bulkheads, each bulkhead being disposed so as to partition the suction chamber into a plurality of sections; at least one boundary air blower in each section, said blowers being positioned in the air-tube membrane and adapted to move air from the suction chamber to an air tube, the frontmost suction chambers being connected to the bow suction chamber for exhausting boundary air therefrom for discharge through the air tubes to said nonrigid stern blowing section;

said nonrigid stern blowing section including a sternward extension of said air tubes, the outer membrane of each tube being provided with a plurality of spaced and sternwardly directed blowing nozzles, rearwardly positioned annular jet means adapted for receiving air from said air tubes, and means for adjusting the transverse vertical cross section of said annular jet.

12. In an airship, means for transporting gaseous cargo in bulk, means for establishing and maintaining a laminar boundary layer on the bow and intermediate portions of said airship, and means for loading and unloading cargo gas and mooring and unmooring said airship by stern-into-the-wind flight, said means including:

a mooring connection suited for use with a fixed mooring mast and located on the underside of said airship and far enough sternward so as not to interfere substantially with said laminar boundary layer and so as to cause said airship to weathervane with the stern facing the wind, and

a reversible-pitch propeller on a universal propeller mount located at the stern of the airship.

13. The airship of claim 12 wherein at least one reversible control-airfoil is mounted near the stern, said airfoil being capable of being rotated 180 degrees from the normal forward-flight position and of thein stabilizing and steering the airship while said airship is backing into the wind.

14. In a nonrigid airship having a longitudinally extending envelope, means for controlling the position of distinct volumes of lifting gas, cargo gas, and ballast air, said means consisting of a composite structure including:

a lifting-gas diaphragm separating lifting gas above from cargo gas below, said diaphragm being attached around its periphery to the envelope structure of the airship in a gas-tight manner;

a cargo-gas diaphragm separating cargo gas above from ballast air below, said diaphragm being attached in a gas-tight manner around its periphery to the envelope structure except that, where an inner cargo-tube membrane intervenes, said diaphragm is attached thereto; and

a plurality of lifting-gas control cables disposed in an approximately vertical position within the envelope and secured at their lower ends to the lifting-gas diaphragm and at their upper ends to the envelope structure, and means for varying the effective lengths of said cables.

15. The airship of claim 14 wherein means are provided for the rapid loading and unloading of cargo gas, said means including:

a cargo-gas tube comprising a collapsible inner cargo-tube membrane, an included portion of the lifting-gas diaphragm, and an included portion of the envelope structure, the vertically extending edges of said inner cargo-tube membrane being fastened in a gas-tight manner to the underside of said lifting-gas diaphragm and to the inside of said envelope structure, the lower end of said cargo-gas tube being connected to a mooring connection; and

an unloading blower disposed at the upper extremity of said cargo-gas tube so as to withdraw cargo gas from the cargo-gas chamber and force it downward to the mooring connection.

16. In a nonrigid airship, means for establishing a laminar boundary layer over the bow and middle portions of the envelope, said means including:

a rigid perforated outer shell at the bow, said shell having a smoothly rounded central portion,

a nonrigid perforated membrane supported by a plurality of longitudinally extending perforated support members and extending sternwardly from said rigid perforated outer shell,

a plurality of inflatable air tubes disposed to carry boundary air to the sternward extremity of said nonrigid perforated membrane, and

a plurality of boundary air blowers disposed to draw boundary air inward through said rigid perforated outer shell and said nonrigid perforated membrane and force it into said inflatable air tubes.

17. In an airship having a cargo-gas diaphragm separating cargo gas from ballast air, means for reducing the risk of accidental mixing of said cargo gas and ballast air, said means including:

a layer of nonflammable shield gas incorporated in the cargo-gas diaphragm, said diaphragm comprising a structure including an upper diaphragm membrane separating said shield gas from said cargo gas, a lower diaphragm membrane separating said shield gas from said ballast air, spacer line means for limiting the maximum distance between said upper diaphragm membrane and said lower diaphragm membrane, and longitudinal diaphragm partition membranes and transverse diaphragm bulkheads disposed between and connecting said upper diaphragm membran with said lower diaphragm membrane so as to divide into distinct gas-tight compartments the space occupied by the shield gas;

at least one shield-gas ballonet capable of receiving shield gas from said cargo-gas diaphragm when said shield gas expands and containing a reserve supply of shield gas for use as make-up for leakage;

a plurality of flexible shield-gas tubes, each tube connecting at least one gas-tight compartment in said cargo-gas diaphragm with a shield-gas ballonet; and

pump and valve means for maintaining the shield gas in the cargo-gas diaphragm at a positive gauge pressure with respect to said cargo gas and said ballast air.

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