Oct. 14, 1969 M. A. BROWN 3,472,033

FLUID STORAGE APPARATUS

Filed Oct. 26, 1966 2 Sheets-Sheet 1

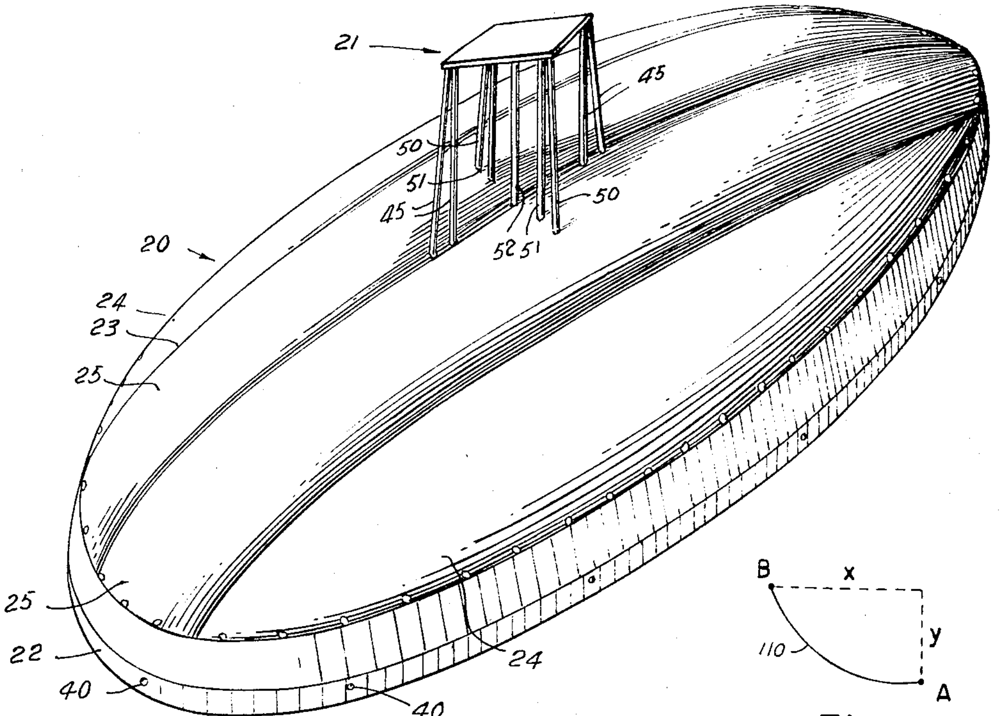

Fig. 1

Fig. 9

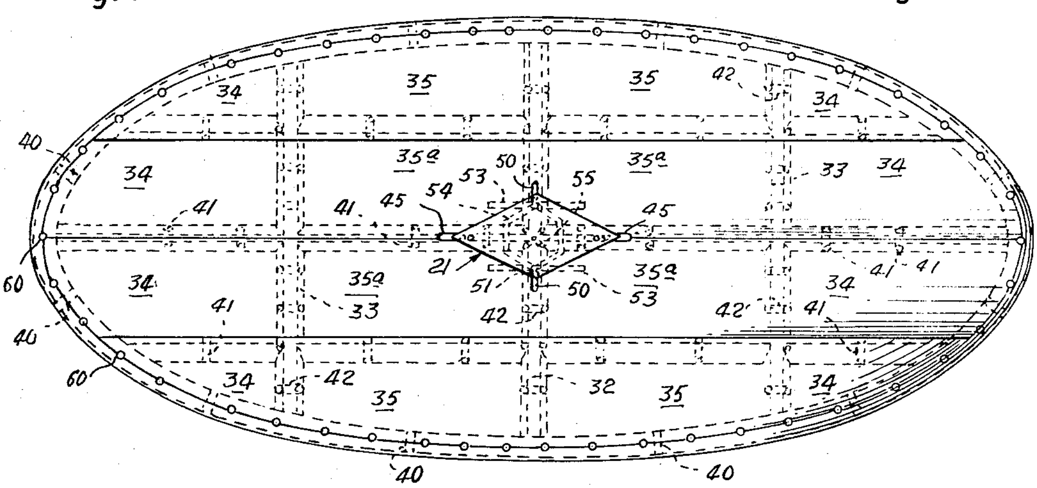

Fig. 2

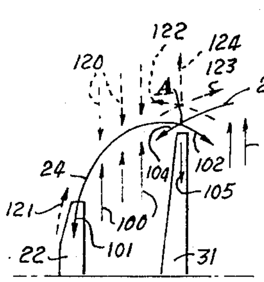

Fig. 7

INVENTOR
Morris A. Brown

BY *Hastings Ackley and Walter J. Jagmin*
ATTORNEYS

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FLUID STORAGE APPARATUS

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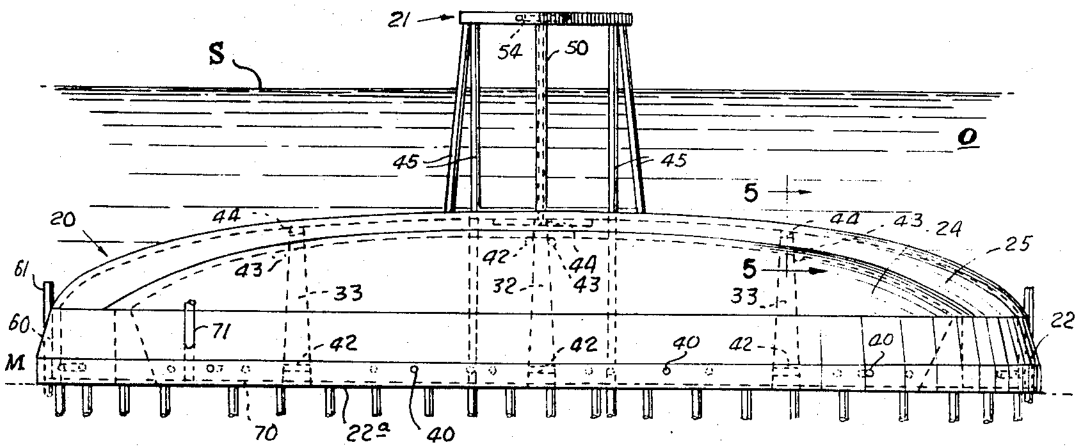

Fig.3

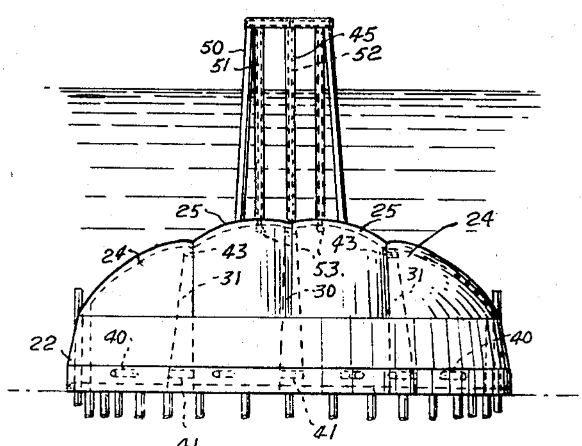

Fig. 4

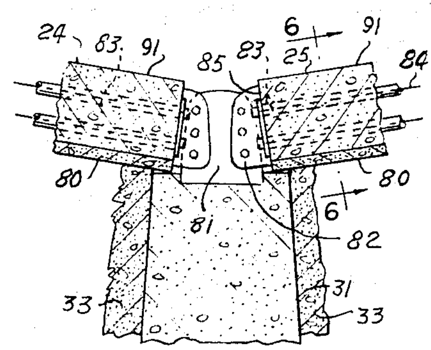

Fig. 5

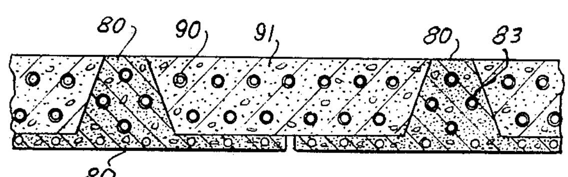

Fig. 6

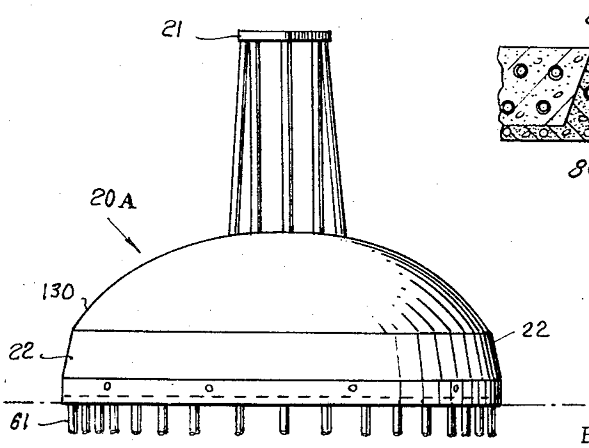

Fig.8

INVENTOR

Morris A. Brown

BY

ATTORNEYS

United States Patent Office

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FLUID STORAGE APPARATUS

Morris A. Brown, Dallas, Tex., assignor to H. J. Gruy and Associates, Incorporated, Dallas, Tex., a corporation of Texas

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ABSTRACT OF THE DISCLOSURE

A tank for storing materials at an underwater location having roof structure including curved portions defined by an inverted catenary, a conduit for introducing materials for storage into the tank and withdrawing them from the tank, and flow passages for water to flow into and out of the tank responsive to changes in the volume of the stored materials so that the tank remains full of fluid at all times.

This invention relates to storage apparatus and more particularly relates to tanks for material storage at underwater locations.

It is one object of this invention to provide new and improved storage apparatus.

It is another object of this invention to provide new and improved tanks for material storage at underwater locations.

It is a further object of the invention to provide a storage tank particularly adapted to the storage of fluids at underwater locations.

It is another object of the invention to provide an underwater storage tank which is particularly adapted to the storage of fluids having a positive buoyancy within the water medium in which the tank is immersed.

It is another object of the invention to provide a submarine type storage tank adapted to be supported at the bottom of a body of water and of sufficient weight to counteract the buoyancy of material contained within the tank when it is full.

It is a further object of the invention to provide a submarine type storage tank which utilizes a roof structure of minimum weight and thickness.

It is a further object of the invention to provide an underwater type storage tank formed of prestressed concrete and having a dome type roof structure of minimum thickness and weight.

It is a still further object of the invention to provide an underwater storage tank constructed of prestressed concrete in the form of an elliptical paraboloid.

It is another object of the invention to provide an underwater storage tank having a domed roof structure comprising concrete prestressed to the extent that it remains in compression when subjected to an upward buoyant force from stored material of less density than the surrounding water.

It is still another object of the invention to provide an underwater storage tank comprising a dome shaped prestressed concrete structure which is shaped in both lateral and longitudinal cross section in the form of an inverted catenary.

It is still a further object of the invention to provide an underwater storage tank having a prestressed concrete roof structure comprising side-by-side longitudinal panels or sections each of which has both lateral and longitudinal cross sectional shapes in the form of an inverted catenary.

It is a further object of the invention to provide an underwater prestressed concrete storage tank in the shape of an elliptical paraboloid including a peripheral elliptical beam or outer wall having a base portion provided with lower flow passage means for the entrance and exit of sea water during the filling and withdrawing of oil and a plurality of lateral and longitudinal inner partitions forming a plurality of interconnected compartments within the tank.

It is still a further object of the invention to provide an underwater prestressed concrete storage tank which weighs a sufficient amount to counteract the positive buoyancy of the maximum quantity of petroleum products storable in the tank.

It is a further object of the invention to provide an underwater storage tank in the form of an elliptical paraboloid which has a center of gravity sufficiently below its center of buoyancy that the tank is stable when floating in the water and may be towed in the upright position at which it is supported at the bottom of the water.

It is another object of the invention to provide prestressed concrete storage tank having a dome shaped roof and supported on outer and inner partition walls with a major portion of the mass of the tank residing in the walls.

It is another object of the invention to provide a dome shaped underwater storage tank having a roof structure supported on only an outer wall.

It is another object of the invention to provide an underwater storage tank including loading and unloading facilities comprising flow conductor means adapted to be lifted to the surface when in use and permitted to sink to a safe level below the surface when not in use.

It is a still further object of the invention to provide an underwater storage tank which supports its own mooring platform including facilities for providing fluid flow between a vessel tied to the platform and storage compartments within the tank.

It is another object of the invention to provide an underwater storage tank which is held against lateral movement on the floor of a body of water by vertical pilings driven through the peripheral beam or outer wall of the tank.

It is another object of the invention to provide a domed underwater tank wherein the resultant forces from its roof structure, both from weight and from buoyant material in the tank, act along lines within the bodies of the supporting outer wall and inner partitions.

It is a further object of the invention to provide an underwater storage tank having means in its peripheral beam for conducting cement grout through the lower face of the beam for grouting between the bottom of the beam and the surface on which the tank is supported.

Additional objects and advantages of the invention will be readily apparent from the reading of the following description of a device constructed in accordance with the invention, and reference to the accompanying drawings thereof, wherein:

FIGURE 1 is a perspective view of a preferred form of underwater storage tank embodying the invention;

FIGURE 2 is a top plan view of the storage tank of FIGURE 1;

FIGURE 3 is a side view in elevation of the storage tank of FIGURE 1 at operating position on the bottom of a body of water;

FIGURE 4 is an end view in elevation of the storage tank of FIGURE 3;

FIGURE 5 is a fragmentary view in section and elevation of a typical joint between roof panels of the storage tank and an internal load bearing partition at an intermediate stage in the construction of the tank;

FIGURE 6 is a fragmentary view in section illustrating the structure of the roof panels along a line **6—6** of FIGURE 5;

FIGURE 7 is a schematic force diagram illustrating the forces acting between one of the roof panels and the outer wall and an internal load bearing partition wall under conditions both when the tank is filled with surrounding water and when filled with fluid having a density less than the surrounding water;

FIGURE 8 is an end view in elevation of an alternate form of storage tank embodying the invention; and

FIGURE 9 is a schematic illustration of a catenary curve which is inverted to form the shape of a section of one of the roof panels.

Referring to the drawings, an underwater storage tank **20** embodying the invention for storage of flowable materials, such, especially, as oil and gas, at sub-sea or ocean bottom locations comprises structure having a substantially elliptical paraboloid shape open at its bottom and adapted to rest on or near the surface of the bed of the body of water. The tank is supported at a safe level below surface wave action and ship traffic and supports a platform **21** which extends above the surface S of the body of water O in which the tank is positioned for loading tankers and barges from the storage tank. The tank **20** is preferably constructed of prestressed concrete including an elliptical peripheral beam or outer wall **22** supporting a roof structure **23** which in both lateral and longitudinal section is in the general shape of an inverted catenary. The roof structure **23** is formed by a plurality of longitudinal outer panels **24** and intermediate panels **25** each of which is in the shape of an inverted catenary in lateral and longitudinal section, FIGURES 3 and 4.

The longitudinal roof panels 24 and 24 are jointly supported by the outer wall **22** and by longitudinal and transverse inner walls or partitions comprising a central longitudinal partition **30**, intermediate longitudinal partitions **31**, a central lateral partition **32**, and intermediate lateral partitions 33. The longitudinal and lateral partitions have bottom edge surfaces aligned with the bottom edge surface of the outer wall **22** and extend fully to the roof panels thereby functioning both as bearing walls and dividing partitions separating the storage tank into a plurality of end compartments **34** and intermediate compartments **35** and **35*a***. The compartments communicate with each other in both their lower and upper portions whereby they remain fluid filled with either sea water, fluids stored in the tank, or a combination of the water and stored fluids. The outer wall **22** has a plurality of generally horizontal flow passages **40** located near its bottom edge face **22*a*** to allow water surrounding the tank to flow into and out of the tank as required during the pumping in and removal of fluid products stored in the tank. As shown in FIGURE 2, all of the outer compartments bounded by the outer wall are in direct fluid communication with the surrounding water while the inner intermediate chambers **35*a*** contiguous to the central longitudinal partition **30** communicate with each other and with adjacent outer chambers through similar generally horizontal lower flow passages near the lower edge surfaces of the partitions. Specifically, the longitudinal partitions **30** and **31** have lower flow passages **41** while, similarly, the lateral partitions **32** and **33** have correspondingly positioned lower flow passages **42**. The longitudinal partitions also include upper lateral flow passages **43**, FIGURE 3, and the lateral partitions similarly are provided with upper longitudinal flow passages **44** all of which are in the upper portions of the partitions preferably adjacent to the inner surfaces of the roof panels supported by the partitions. All of the outer wall and partition flow passages, both upper and lower, are open at all times providing continuous fluid communication between the upper portions of the compartments, the lower portions of the compartments, and between the surrounding body of water and the lower portions of the outer compartments for free flow of surrounding water into and out of the lower portions of the compartments and of stored product fluids between upper portions of the compartments.

The loading platform **21** is supported on longitudinally aligned pillars or columns **45** which may be tubular members such as pipe embedded along lower end portions in the roof structure and preferably extending for rigidity purposes into the central longitudinal partition **30**. The loading platform is also supported on laterally aligned pillars **50** and flow lines **51** along with a gas flare line **52**. The flow lines **51** are connected at lower ends into longitudinally aligned oil intake manifolds **53** for withdrawing fluids stored within the tank to the loading platform through the flow lines. The intake manifolds **53** are each supported through the central lateral partition **32** opening at opposite ends into the storage chambers **35*a***. The openings of the intake manifolds into the storage chambers are covered with screening means, not shown, to prevent entry of foreign matter into the manifolds. At their upper ends the flow lines **51** are connected into a loading manifold **54** suitably supported within the loading platform and provided with fittings, not shown, for coupling loading hoses from a tanker or barge moored to the platform **21**.

The gas flare line **52** is connected at its lower end into a flow passage system **55** provided at the intersection of the lateral partition **32** and the longitudinal partition **30** communicating into top portions of the four adjacent storage chambers **35*a*** for the purpose of venting gaseous fluid from the storage tank. The gas flare line is provided with valve means, not shown, to prevent flow of gaseous fluid from the tank through the line when desired. The platform **21** has suitable facilities, not shown, for the mooring of ships and barges.

The outer wall **22** of the tank has a plurality of substantially vertical holes **60** each of which receives a pile **61** driven downwardly into the bed M supporting the tank. The piles primarily are for holding the tank against lateral movement. For purposes of simplification of the drawings, only a portion of the holes **60** and piles **61** are illustrated. The number of pile holes in the outer wall and the piles employed for anchoring the storage tank depend upon conditions prevailing at the location at which the tank is used, such as the rate and direction of the current and the character of the bed in which the piles are driven. Each of the piles **61** is driven by any suitable means through its hole **60** into the bed to the desired depth and then is cut off at any desired height above the outer wall. A walkway, if desired, around the outer wall of the tank for use by divers during inspection of the tank, may be mounted on the upper ends of the piles.

A grout line **70** comprising a conduit such as a pipe is cast in the outer wall **22** tangent to its bottom edge surface extending around the entire wall to provide a means for pumping cement grout beneath the outer wall to seal between the outer wall bottom edge and the surface supporting the tank. The grout line is either split longitudinally or provided with a plurality of perforations opening through the bottom edge surface of the wall **22** so that the grout is forced downwardly beneath the wall along its entire length. One or more riser pipes **71** are formed in the wall **22** and connected into the grout line. Suitable conduit means, such as hose or pipe, not shown, extends from the surface and is coupled to the riser pipe for forcing the cement grout into the grout line from a bare or ship at the surface. After the space between the bottom surface and the peripheral wall has been grouted the supply line to the riser is removed.

The storage tank is preferably constructed of prestressed reinforced concrete to provide a tank of minimum roof thickness while having sufficient weight to counterbalance the buoyant force of a maximum quantity of fluid such as oil and gas stored within the tank. The tank is preferably constructed in a facility such as a large dry dock from which it may be floated. A storage tank embodying the invention which holds approximately 300,000 barrels of crude oil is about 400 feet long, 180 feed wide, and 65 feet high. The initial phases of the construction of the tank are the pouring of the elliptical peripheral wall 22 and the longitudinal and lateral partitions. The fabrication of the roof structure on the outer wall and partitions follows.

To conform to the desired shape of the roof structure the top edge surfaces of both the longitudinal and lateral partitions are each formed with the curvature of an inverted catenary as illustrated in FIGURES 3 and 4. Each panel of the roof structure includes a plurality of precast inverted T-shaped beams **80**, FIGURE 6, extending laterally across the tank between adjacent supporting structures such as the outer wall and longitudinal partitions. Each beam is precast with a longitudinal curvature in the shape of the desired inverted catenary and prestressed longitudinally. Concrete is poured on and between the beams and stressed to resist the buoyant upward force of the oil stored in the tank. For example, the beams **80** defining a roof panel **24** are aligned in side-by-side parallel lateral relationship supported at opposite ends on and secured to the peripheral wall **22** and the adjacent longitudinal partition **31**. The beams forming the panels **24** extend from the outer wall inwardly to the adjacent partition **31**. Similarly the beams forming the panels **25** extend between the partition **30** and the partition **31** on each side of the central partition and at the ends of the panels are supported in part by the outer wall. A typical connection between the adjacent ends of the beams **80** forming the adjacent roof panels **24** and **25** is illustrated in FIGURE 5. A plurality of upwardly extending brackets **81** are supported on and secured to the partition **31** longitudinally spaced along the top of the partition at the desired locations of adjacent ends of the beams **80** for forming the adjacent roof panels **24** and **25**. The beams each have end brackets **82** which are suitable riveted or bolted to the bracket **81**. The beams are prestressed by suitable conventional means. For example, pipes **83** are cast in the beams to receive cables **84** connected through the pipes between plates **85** formed with the brackets **82** and supported on each end of each beam. The cables are stressed by placing them in tension and suitably securing them at opposite ends to the plates. After the beams forming each roof panel are secured as shown in FIGURE 5 between the partitions and outer wall a substantially solid roof structure is defined by the beams alone to provide a form for the pouring of the concrete to complete the roof. In view of the substantial size of the tank it generally is preferred that the fabrication of the roof be accomplished in stages and thus each roof panel is poured as a unit rather than attempting to pour the entire roof structure in one continuous operation.

After the beams **80** are secured in position on the partitions and outer wall as described above suitable concrete forms, not shown, are positioned along the top of each of the longitudinal partitions and the outer wall at the ends of the beams **80** to retain the concrete poured between the beam ends along the partition and wall tops until it has set. Pipes **90** to accommodate prestressing wires or cables are supported in spaced relation parallel to and between the beams **80** as shown in FIGURE 6 extending to plates, not shown, similar to the plates **85**, supported in alignment with the ends of the beams by form structure on the outer wall and partitions. The concrete **91** is then poured between the beams **80** to a depth sufficient to provide a smooth outer surface along the beams as shown in FIGURE 6. Wires or cables are extended through the pipes **90** and secured at opposite ends to plates **85** over the end surfaces of the concrete sections **91** and stressed to the desired value so that both the beams **80** and the intervening concrete sections **91** are equally prestressed for resisting the buoyant effect of oil stored within the tank. After pouring the concrete sections **91** between the beams of the roof panels **24** and **25** the forms at the adjacent ends of the beams and concrete sections are removed with concrete then being poured along the top edge surfaces of the partitions and outer walls filling the gap between the ends of the beams and concrete sections to provide a continuous impermeable roof structure. After the roof structure is fabricated on the partitions and outer wall it is preferred that the inside of the completed storage tank be coated with a suitable material such as a coal tar epoxy to minimize leakage from the tank.

The longitudinal and lateral roof curves are defined by inverted catenaries to optimize the load distribution resulting from the buoyant upward force of the oil stored in the tank on the roof panels and the downward forces on the partitions and outer wall. By definition a catenary is a curve assumed by a uniformly loaded cord hanging freely between two points, see Applied Mechanics by Alfred T. Poorman, second edition, McGraw-Hill Book Company, Inc., 1923. The tension forces in the cord at its points of support at each end are directed along lines tangent to the cord at such support points. Obviously, the exact shape of a catenary curve is an empirical function to the extent that it varies in accordance with such factors as the span between the points of suspension and the sag in the line. Thus, for a given span in the storage tank **20** between the top edge surfaces of adjacent walls supporting a particular panel, a catenary curve may range between almost flat to very bulbous shapes, neither extreme of which is desired for the storage tank. A catenary curve is chosen for the roof structure which, preferably, under the load conditions encountered both when the tank is empty and when full provides resultant forces from the weight of the roof structure or the buoyant forces of the oil stored in the tank which extending tangent to the curve of the roof are in directions which lie within the structure of the supporting outer wall and the partition walls. For example, FIGURE 7 diagrammatically illustrates some of the forces acting on the roof panels **24** and **25** and the forces resulting from the roof panel weight and the buoyancy of the stored oil on the outer wall **22** and the partition **31**. The buoyant force of the oil stored within the tank acts upwardly along the lines **100** against the roof panel **24** with oppositely directed reaction forces to offset the buoyant force acting at opposite ends of the inverted catenary shaped roof panel along a line **101** within the outer wall **22** and a line **102** at the partition **31**. The oil stored within the tank under the adjacent roof panel **25** exerts a buoyant force along the lines **103** opposed by a resultant force **104**. The resultant of the reaction forces along the lines **102** and **104** is a resultant force along the line **105** which is applied along the partition **31** through the connecting bracket **81**, FIGURE 5. The partition **31** is sloped with respect to its vertical orientation toward the outer wall so that the reaction force **105** from the two adjacent roof panels **24** and **25** extends within the body of the partition.

FIGURE 7 also illustrates the force conditions existant when the tank is in air or is at an underwater location and filled with water such as before it has petroleum products pumped into it or at some time during operation when it is emptied with the petroleum fluids being replaced by surrounding water. Under either water filled or air filled conditions the outer wall **22** along with the partition walls are subjected to downward forces due to the weight of the panels comprising the roof structure. The vectors **120** represent the weight of the roof panel **24** while the vectors **121** and **122** represent reaction forces in the outer wall **22** and the partition wall **31**, respectively, which are equal and opposite to the resultants of the weight forces as applied to the outer wall and partition wall. Because of the catenary form of the roof panel **24** the resultant weight forces of the panel on the wall and partition are exerted along the same lines as and in opposite directions to the resultant forces due to the buoyant force of oil stored under the roof panel. The resultant of the weight force of the panel **25** on the partition **31** is opposed by a reaction force in the partition along the line **123**. The direction of the resultant reaction force of the weight forces **122** and **123** is along a line **124** which lies within the partition **31** coincident with and in a direction opposite to the reaction force **105** of the upward buoyant forces of stored oil under the roof panels on the partition. Thus, alignment and strength characteristics of the outer wall and partitions satisfactory to oppose the buoyant forces of stored fluids in the tank are equally satisfactory to sustain the weight forces of the roof structure when the tank is empty and either in the air or within a body of water and filled with water.

FIGURE 9 illustrates some of the functions represented in FIGURE 7 in terms of a conventional catenary curve in upright position along a cord **110** supported between points A and B with point A representing the connection point of the roof panel **24** with the partition **31** and the point B representing the connection point of the panel **24** with the outer wall **22**. The distance *x* represents the lateral or horizontal distance between the points of connection of the panel **24** with the outer wall **22** and partition **31** while the distance *y* represents the difference in elevation between the point of connection of the panel **24** with the partition **31** and its point of connection with the outer wall **22**. Thus, the curve of the cord **110** between the points A and B when inverted to the position of FIGURE 7 defines the curve of the roof panel **24** along a lateral plane between side wall **22** and the inner partition **31**. FIGURE 9 represents the lateral curvature of the roof panel at a given location, it being understood that all sections both lateral and longitudinal of the roof panels are in the form of inverted catenaries. Preferably, the lateral curvature of the roof panels is uniform so that each of the roof beams **80** are cast with the same longitudinal curvature though varying in length in accordance with their position longitudinally along the tank.

It will be obvious in considering the diagrammatic representation in FIGURE 9 that within practical limits the length of the cord **110** and consequently the extent to which it will sag between the points A and B may be varied and with such variations the line will hang along a curve or arc defined as a catenary. For example, increased storage capacity is obtainable in the storage tank by making each of the roof panels more bulbous or upwardly extending, which, in terms of FIGURE 9, increases the length of the cord **110** while it still conforms to a catenary curvature.

The longitudinal curvature of the roof panels, FIGURE 3, as previously indicated, is also an inverted catenary curve. The longitudinal curve of the roof panels is thus generally controlled by substantially the same factors which enter into the determination of the lateral curvature of the panels though the additional factor of water depth generally precludes the use of roof structure having as much longitudinal as lateral curvature thus resulting in the catenary curve along the length of the storage tanks being substantially flatter than the lateral curvature. The major controlling reason for the more flat longitudinal curvature is the necessity that the high point of the tank remain below the water surface sufficiently for surface craft to freely navigate over it. Since the tank often is several hundred feet in length, when it is used in relatively shallow water, the longitudinal curvature of its roof structure obviously cannot be as great as its lateral curvature and permit the high point of the roof structure of the tank to be at a safe level below the water surface. It will also be clear that the lateral and longitudinal curvatures of the roof structure of the tank are interrelated in that a more severe curvature in the lateral direction obviously increases the height of the tank and necessitates more curvature in a longitudinal direction. As the tank length increases the extent to which the longitudinal curvature is affected by the lateral curvature is reduced.

It is well known that while concrete is capable of sustaining very substantial compressive forces it is not especially adapted to function under equally substantial tension forces. The prestressing of the beams **80** and the concrete section **91**, as previously discussed, is effected by tensioning the wire or cables extending through the conduits cast into both the concrete sections and the beams. The prestressing is a function of the buoyant load applied to the roof panels by the stored fluid within the tank. The beams and concrete sections are prestressed to the extent that when the storage tank contains the maximum quantity of stored fluid which will impose maximum buoyancy on the roof it sustains the buoyant forces of the fluids while remaining in compression. In other words, the panels and sections are prestressed to such a degree that the compression effected by the prestressing is not fully counteracted by the tension forces applied to the panels by the buoyant forces of the stored product and thus a full tank of stored product at a underwater location will not exert sufficient buoyant force to completely overcome the compressed condition of the concrete. Therefore, even when subjected to the buoyant forces of a full load, the tank panels will remain slightly in compression due to the load imposed on them by the prestressing.

The storage tank is preferably constructed with sufficient mass in its wall and roof structure to fully counteract the total buoyant forces of the maximum quantity of storable fluids in the tank so that the tank rests on bottom with the pilings **61** functioning only to counteract lateral forces caused by such factors as the current of the water around the tank. The major portion of the tank mass resides in the outer and partition walls with the catenary configuration of the roof structure panels permitting a roof minimum thickness and thus minimum mass thereby simplifying problems inherent in the weight of a flat roofed concrete structure.

When a tank is completed in a dry dock the dock is flooded to a desired depth for floating the tank from the dock so that it is towed from the dock through water to the location at which it is sunk and moored. The gas flare and oil flow lines are sealed along with any other flow passage means leading into the upper portions of the tank so that air is trapped within the tank as the water level is raised in the dry dock to provide the necessary buoyancy for floating the tank while towing it to its operational location. When the water level within the dry dock is sufficiently high to float the tank the center of gravity of the tank is preferably substantially below the center of buoyancy so that the tank remains stable while being towed to location to minimize any possibility of accidental capsizing. While additional air may be injected into the tank to increase its buoyancy the draft of the tank should remain low enough to keep its center of gravity at the desired distance below the center of buoyancy.

The tank is towed by suitable means, such as one or more tugs, to the site at which it is to be used. When properly located, the trapped air within the tank is vented through the oil flow and gas flare lines allowing the tank to settle to the bottom. The tugs are used to hold the tank against drifting and stabilize it while it sinks to its operational position on the bottom. Each of the tugs thus remains connected with the tank during the sinking operation by one or more lines which are adjusted to allow the tank to sink. Whether the tank comes to rest on the bottom edge surfaces of its partitions and outer wall or sinks into the bottom to some extent depends upon the characteristic of the soil comprising the bottom.

When the tank comes to rest on the bottom M, the piling holes are drilled beneath the outer wall **22** by guiding a drill through the sleeves in the holes **60** in the wall until the holes are at the desired depth within the bottom. The desired number of pilings **61** are then inserted through the holes in the wall into the holes drilled in the bottom. The pilings may be cemented in place by utilizing suitable known procedures. The pilings are then cut off at or near where they project upwardly from the wall **22**, or, if a walkway is to be installed on the pilings for diver use, they are cut off at the desired height above the peripheral wall. The weight of the tank structure is enough to hold it on bottom even when filled with a stored material of less density than the water and then the piles function basically to prevent drift along the bottom due to currents.

If the surface of the bottom is so irregular that grouting between it and the bottom edge of the outer wall **22** is necessary, suitable cement pumping facilities on a barge positioned over the tank are connected to the riser **71** leading to the grout conduit **70** within the outer wall. The grout is pumped through the conduit **70** until the needed amount has been forced outwardly beneath and around the base of the outer wall. The piling requirements and the extent to which the outer wall is grouted to the bottom are dependent upon such factors as the current rate of the water at the tank, the slope of the bottom, and the surface characteristics of the bottom.

If the bottom is so irregular that positioning the tank directly on it is not feasible, the tank may be supported on the piles **61** spaced above the bottom by utilizing piles having suitable locking means, such as expandable slips, for securing the piles within the holes **60** against longitudinal movement of the tank relative to the piles whereby the tank is held against lateral movement and also supported within the water above the bottom.

After the tank is thus installed on the bottom the required flow conductor connections are made for flowing fluids into it for storage and for withdrawal of such fluids by tankers or barges moored to the platform **21**. Facilities may be connected with the tank for flowing the fluids to be stored into it through the flow lines **51**, or, in the alternative submerged flow lines, not shown, may be connected into the tank running either beneath the outer wall or through flow connections, not shown, in either the outer wall or through the roof structure. If the fluids to be stored comprise petroleum products including oil and gas the vapor pressure of the liquids may necessitate the maintenance of a gas cap in the upper portion of the tank with the gas being vented and burned at necessary times through the gas flare line **52**.

The fluids stored within the tank are distributed substantially uniformly through its inner and outer compartments laterally through the flow passages **43** in the longitudinal partition walls and longitudinally through the flow passages **44** in the lateral partition walls. As the fluid flows into the tank for storage an equal quantity of water is displaced from the tank into the surrounding water through the flow passages **40** in the outer wall **22**. The lower flow passages **42** in the lateral partition walls and the lower flow passages **41** in the longitudinal partition walls allow substantially free lateral and longitudinal flow of the water as it is displaced from the tank by incoming fluids. Since the fluids generally stored within the tank are lighter than the water they will first occupy the upper portions of the internal storage chambers on either side of the longitudinal partition **30** and fore and aft of the central lateral partition **32** since the highest portions of the tank, due to its domed roof configuration, are in the vicinity of the central lateral partition wall 32 along either side of the longitudinal partition wall **30**. The fluids to be stored first occupy this space expanding outwardly and downwardly as an increased quantity of fluids flows into the tank. If the fluids are introduced into the tank through the oil flow lines **51** they will be distributed into the upper portions of the tank through the manifolds **53**. If, on the other hand, the fluids are introduced into the tank at some other location, such as through submarine gathering lines connected into lower portions of the tank, the lighter-than-water will find their way upwardly through the various compartments of the tank moving laterally and longitudinally through the flow passages in the upper portions of the lateral and longitudinal partition walls reaching the highest portions of the tank available to them.

The tank may be filled with the fluids to be stored displacing all of the water present within the tank outwardly into the surrounding water. The tank is equipped with suitable detection means such as a float or a series of electrical probes to determine the water and stored fluid levels in the tank. Such probes may be of the type in which water completes a circuit and water breaks the circuit.

The stored fluid is withdrawn through the intake manifolds **53** and the oil flow lines **51** to the platform **21** for loading on ships or barges moored thereto. As the fluid is withdrawn the space occupied by it is replaced by surrounding water flowing into the tank through the outer wall lower passages **40** and distributing within the tank to its various compartments through the lower flow passages within the longitudinal and lateral partitions. If all of the fluid stored within the tank is withdrawn, it is replaced by surrounding water so that the tank remains fluid filled either with stored product, a combination of stored product and water, or, when empty, with surrounding water. At times when the tank is filled with the surrounding water, the only downward forces acting on the outer and partition walls from the roof structure are those which result from the weight of the roof structure, whereas, when the tank contains stored product lighter than the water, the stored fluids exert buoyant upward forces on the roof panels which are transmitted through the connecting structure to the outer and partition walls to the extent that they exceed the weight of the roof structure. When the tank is filled with stored fluids, the mass of the tank is sufficient to overcome the buoyancy of the stored fluids and the prestressing of the reinforced concrete roof panels holds the panels in compression.

An alternate form of storage tank **20A** is illustrated in FIGURE 8 when the tank is constructed in substantially smaller sizes, which, with presently available materials such as the above discussed prestressed concrete, permit the roof structure to be self-supporting so as not to require the internal longitudinal and lateral partition bearing walls. For example, where the tank **20** may be 160 to 180 feet wide and 400 or more meet in length and thus require internal bearing partition walls, the tank **20A** may be no larger than 40 to 50 feet wide and approximately 100 feet long whereby a roof structure totally supported by an outer peripheral wall is feasible. The storage tank **20A** comprises a roof structure **130** supported on a peripheral wall **22** formed in the shape of an ellipse substantially identical to the peripheral wall of the tank **20**. The tank is an elliptic paraboloid of the same general configuration as the tank **20** having a roof arched in both lateral and longitudinal directions in the form of the inverted catenary discussed in the detail above. The tank is constructed in the same manner as the tank **20** with the same force relationships applying as illustrated in FIGURE 7. The tank supports a loading platform **21** equipped identically as the platform **21** on the tank **20** and the tank is anchored on location against lateral movement by the piles **61** as previously discussed. The installation and operational procedures relating to the tank **20** apply in all respects to the tank **20A**.

If desired, means may be provided for minimizing or preventing mechanical mixing of stored fluids, such as the oil and the water in the tank. A suitable highly viscous fluid having a density between that of the stored fluid and the water may be ejected into the tank in sufficient quantity to form an interface between the oil and the water. Also, a flexible blanket, not shown, formed of material such as reinforced rubber or a rubberized canvas may be secured around its periphery to the inside wall surface of the outer wall **22** above the flow passages **40** and may be of sufficient size to permit the tank to be filled with the displacing water with the blanket conforming to the inside surface of the peripheral wall and proof panels. Such blankets are well known in the storage tank industry for preventing mechanical mixing of unlike fluids within a tank. The flexible blanket assumes a position at the interface between the stored fluids such as between oil and the water within the tank.

If desired, the loading platform **21** may be eliminated with its function being fulfilled by either a floating buoy, not shown, connected with the tank by flexible fluid flow hoses or sinkable flow conduits, not shown, may be secured on the tank and raised to the surface as required for unloading stored fluids from the tank. For example, flexible hoses may be connected with the tank, allowed to sink when not in use, and connected with a marker buoy by a line which may serve to lift the hose or hoses to the surface when needed. Also, semirigid or rigid conduits may be hinged by means such as fluid conducting pivotal connections and similarly connected with a marker buoy so that a barge or tanker may raise the conduits to the surface when unloading fluids from the tank.

The elliptical configuration of the tank including the curved surfaces provided along its side and end portions by the domed inverted catenary roof construction minimizes the resistance of the tank to water flow past it both during the towing operation and when it is moored in operating position at or near the bottom of a body of water. Thus, the tank is relatively easy to tow and maneuver in transporting it from its location of construction to its operating position. The effect of current on the tank both laterally and longitudinally is minimized thereby reducing mooring requirements for holding the tank against drift along the bottom.

While the tanks illustrated have been discussed in terms of oil and gas storage, it is to be understood that they are readily adapted to storage of most any pipeline transportable materials such as powdered coal, wood pulp, cottonseed oil or meal, and others.

It will now be seen that a new and improved storage apparatus has been described and illustrated.

It will further be seen that a new and improved tank for underwater storage has been described and illustrated.

It will also be seen that the tank is especially adapted to storage of fluids having a density less than water surrounding the tank.

It will additionally be seen that a fluid storage tank particularly adapted for storing fluid petroleum products at underwater locations has been described and illustrated.

It will also be understood that the tank has sufficient mass to counteract the buoyancy of a maximum quantity of fluids stored in the tank.

It will also be seen that one form of the tank comprises a dome shaped structure.

It will also be seen that the storage tank utilizes a roof structure having minimum weight and thickness.

It will further be seen that a preferred form of the storage tank is constructed of prestressed concrete having a minimum thickness dome-type roof structure.

It will be further seen that a preferred form of the storage tank is in the shape of an open bottomed elliptical paraboloid.

It will also be seen that the dome shaped roof structure of the tank when formed of prestressed concrete is prestressed to a predetermined degree at which it remains in compression when upward buoyant forces from a maximum quantity of stored fluids are imposed on the roof structure.

It will additionally be seen that in its preferred shape the dome-type roof structure is curved both laterally and longitudinally in the form of an inverted catenary.

It will be further seen that in one preferred form a prestressed concrete dome-shaped roof structure for an underwater storage tank comprises longitudinally extending side by side sections each of which is shaped both in a lateral and a longitudinal direction along a curvature defined by an inverted catenary.

It will additionally be seen that a further preferred form of the tank includes an outer elliptical wall enclosing a plurality of lateral and longitudinal inner partition walls supporting a dome-shaped roof structure comprising a plurality of longitudinal panels curved in both lateral and longitudinal directions along lines defined by inverted catenaries.

It will also be seen that the outer and partition walls have lower flow passage means for distribution of water flowing into and out of the tank and the inner partition walls have upper flow passage means to facilitate distribution of stored products within the several storage compartments of the tank.

It will be further seen that the center of gravity of the tank is sufficiently below its center of buoyancy that the tank is stable when floating in water with its open base side facing downwardly in the water and supported by air trapped within the roof structure of the tank.

It will be further seen that a major portion of the mass of the tank is within its wall structure while the total mass is sufficient to exceed the buoyant forces of a maximum quantity of stored produce in the tank.

It will be further seen that a preferred form of the tank includes a mooring platform supported on its roof structure and extending above the water surface when the tank is on location for mooring loading vessels.

It will also be seen that one form of the tank includes vertical piling for holding the tank against lateral movement in a body of water.

It will be further seen that another form of the tank is supported on a plurality of piles extending through and interlocked with the outer wall of the tank.

It is to be further seen that the tank includes domed roof structure which imposes resultant forces both from its weight and from the buoyant upward forces of fluids stored therein along lines lying within the supporting wall structure of the tank.

It will be further seen that an alternate form of the tank includes a flow line resting below the surface of the water when not in use and adapted to be raised to the water surface for loading and unloading purposes.

It will also be seen that one form of the tank includes grout distribution means in the lower portion of the outer wall of the tank for grouting between the surface of the lower edge of the outer wall and an irregular bottom surface supporting the tank from below.

It will also be seen that one form of the tank comprises a dome shaped roof supported on only an outer wall.

The foregoing description of the invention is explanatory only, and changes in the details of the construction illustration may be made by those skilled in the art, within the scope of the appended claims, without departing from the spirit of the invention.

What is claimed and desired to be secured by Letters Patent is:

1. A tank for storing materials at an underwater location comprising: a dome-shaped hollow structure having curved portions in the shape of an inverted catenary along vertical planes intersecting said portions; said curved portions of said structure being formed of concrete prestressed to a predetermined value exceeding the tension induced in said curved portions of said structure responsive to buoyant forces of a maximum quantity of material stored in said tank; flow passage means for introducing said materials into said structure and withdrawing said materials from said structure; and flow passage means for permitting water to flow into and out of said structure responsive to volume changes of said stored materials in said structure whereby said tank remains full at all times.

2. A tank as defined in claim **1** wherein the mass of said structure is sufficient to counteract upward forces imposed on said structure by a maximum quantity of buoyant material stored in said structure.

3. A tank for underwater storage of material comprising: an outer peripheral wall; a domed roof structure on said wall; said roof structure being curved both laterally and longitudinally in the shape of an inverted catenary and comprising a plurality of adjoining roof panels each curved laterally and longitudinally in the shape of an inverted catenary; lateral and longitudinal inner portion bearing walls connected within said outer wall supporting said roof panels; said roof panels comprising the prestressed laterally extending concrete beams in side-by-side relation and prestressed concrete sections poured on said beams; said outer and inner partition walls comprising a major portion of the mass of said tank; and said beams and said concrete sections on said beams being prestressed to a value exceeding the tension induced in said roof panels by the buoyancy of a maximum volume of stored material in said tank.

4. A tank as defined in claim **3** wherein said walls are sloped to upwardly align said walls whereby the resultants of forces imposed on each of said walls by the weight of said roof panels and the buoyant effect of material stored within said tank on said roof panels extend along the lines lying within said walls.

5. A tank as defined in claim **4** including lower flow passage means in said outer wall and said inner partitions for fluid surrounding said tank to flow into and out of said tank; and upper flow passage means in said partition walls for distribution of material within said tank.

6. A tank as defined in claim **5** including means for receiving a plurality of piles through said outer wall for mooring said tank at the bottom of a body of water.

7. A tank for storing material at an underwater location wherein said tank is immersed in water comprising: a substantially elliptical concrete outer wall; a plurality of longitudinal and lateral inner bearing walls connected at opposite ends to said outer wall extending generally parallel with the major and minor axes, respectively, of said outer wall dividing said tank into a plurality of compartments; a plurality of longitudinally extending prestressed concrete roof panels supported in side-by-side contiguous relationship on said outer and inner walls, each of said roof panels having curved upper and lower surface portions shaped both laterally and longitudinally along lines defined by inverted catenaries of predetermined span and sag; said outer and inner walls having flow passage means in lower portions thereof interconnecting said compartments with each other and with the space surrounding said tank to permit water surrounding said tank to flow freely into and out of said tank responsive to the flow of stored material in and out of said tank; each of said inner walls having flow passage means in the upper portions thereof communicating said compartments to permit flow of material between said compartments whereby stored material is substantially equally distributed in said compartments; and means providing flow passages into upper portions of said compartments for introducing and withdrawing stored material.

8. An underwater storage tank as defined in claim **7** wherein said outer and inner walls are each sloped vertically in predetermined directions whereby resultant forces applied to said walls by said roof panels responsive to the weight of said panels and the buoyant forces of stored material on said panels when said material is stored in said tank extend along lines falling within said walls.

9. An underwater storage tank as defined in claim **8** wherein said roof panels comprise a plurality of laterally extending side-by-side substantially parallel inverted T-shaped prestressed concrete beams and prestressed concrete sections poured on and supported by said beams, all of said beams being precast along a longitudinal curve defined by an inverted catenary of predetermined span and sag.

10. An underwater storage tank as defined in claim **7** wherein said prestressed concrete roof panels are each prestressed to a predetermined degree whereby said panels are compressed to a sufficient degree that said compression exceeds the maximum tension induced in said roof panels by maximum buoyant forces applied to said panels by a maximum volume of stored material in said tank whereby each of said panels remains in compression when said tank is filled with stored material.

11. An underwater storage tank as defined in claim **7** including a platform supported on said roof panels extending upwardly above the surface of water in which said tank is immersed.

12. An underwater storage tank as defined in claim **7** including a grout line formed in said outer wall having openings downwardly through the lower edge face of said outer wall for pumping cement grout outwardly below said outer wall; and means for connecting a cement grout supply line into said grout distribution line.

13. An underwater storage tank as defined in claim **12** including a plurality of vertical spaced jackets having openings longitudinally therethrough formed in said outer wall for receiving pilings to secure said tank on an earth formation below a body of water surrounding said tank.

14. An underwater storage tank as defined in claim **7** wherein said outer and inner walls comprise a major portion of the mass of said tank.

15. An underwater storage tank comprising: an outer wall substantially elliptical in shape; and a roof structure comprising prestressed concrete supported on said outer wall and having curved inner and outer surface portions formed both laterally and longitudinally in the shape of inverted catenaries of predetermined span and sag; said roof structure being prestressed to a predetermined degree whereby the compression under static conditions in said concrete is sufficient that when said roof structure is subjected to the buoyant force of a maximum volume of stored material in said tank said compression exceeds the tension force induced in said roof structure by said buoyant forces.

16. An underwater storage tank as defined in claim **15** wherein said outer wall is provided with a plurality of flow passages through the lower portion thereof to permit water to flow into and out of said tank corresponding inversely with the flow of stored material into and out of said tank whereby said tank remains full.

17. An underwater storage tank as defined in claim **16** including means for mooring said tank with the bottom of a body of water in which said tank is immersed.

18. An underwater storage tank as defined in claim **17** including platform means supported on said tank for mooring vessels thereto during loading of said vessels with material stored in said tank.

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