

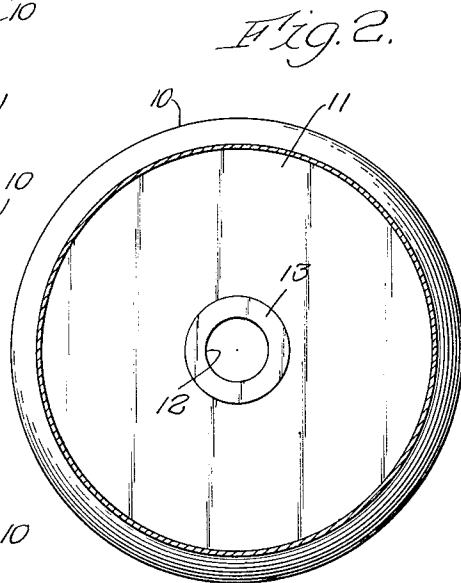
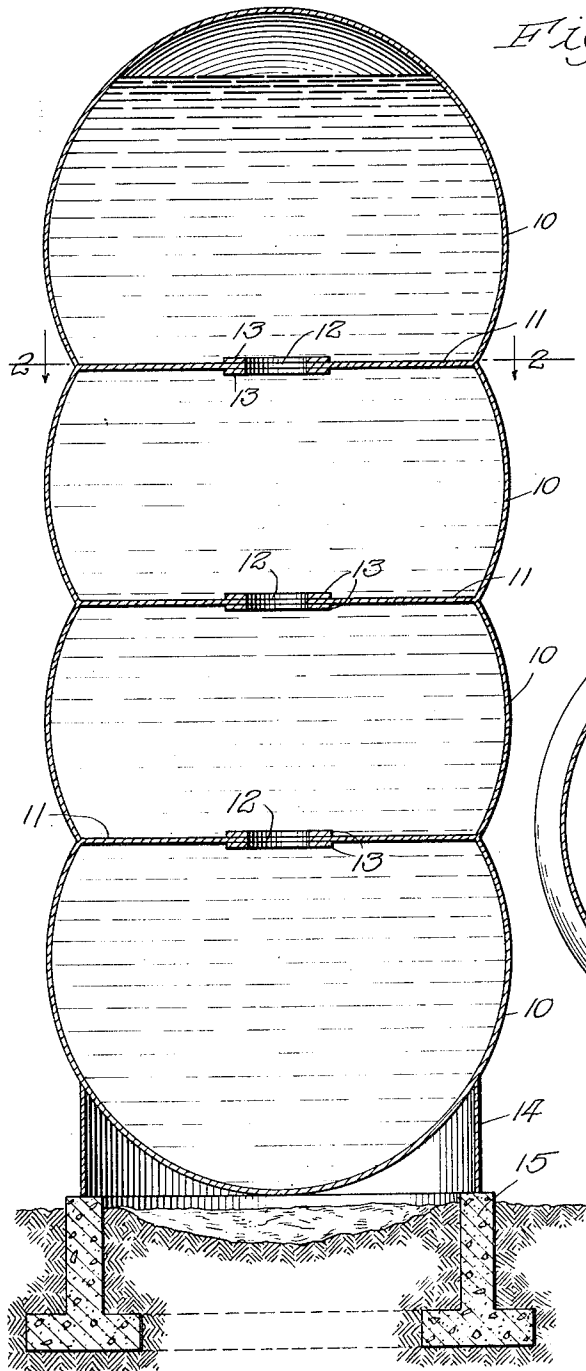
March 16, 1954

H. C. BOARDMAN
LIQUID STORAGE VESSEL

2,672,254

Filed Aug. 4, 1945

2 Sheets-Sheet 1



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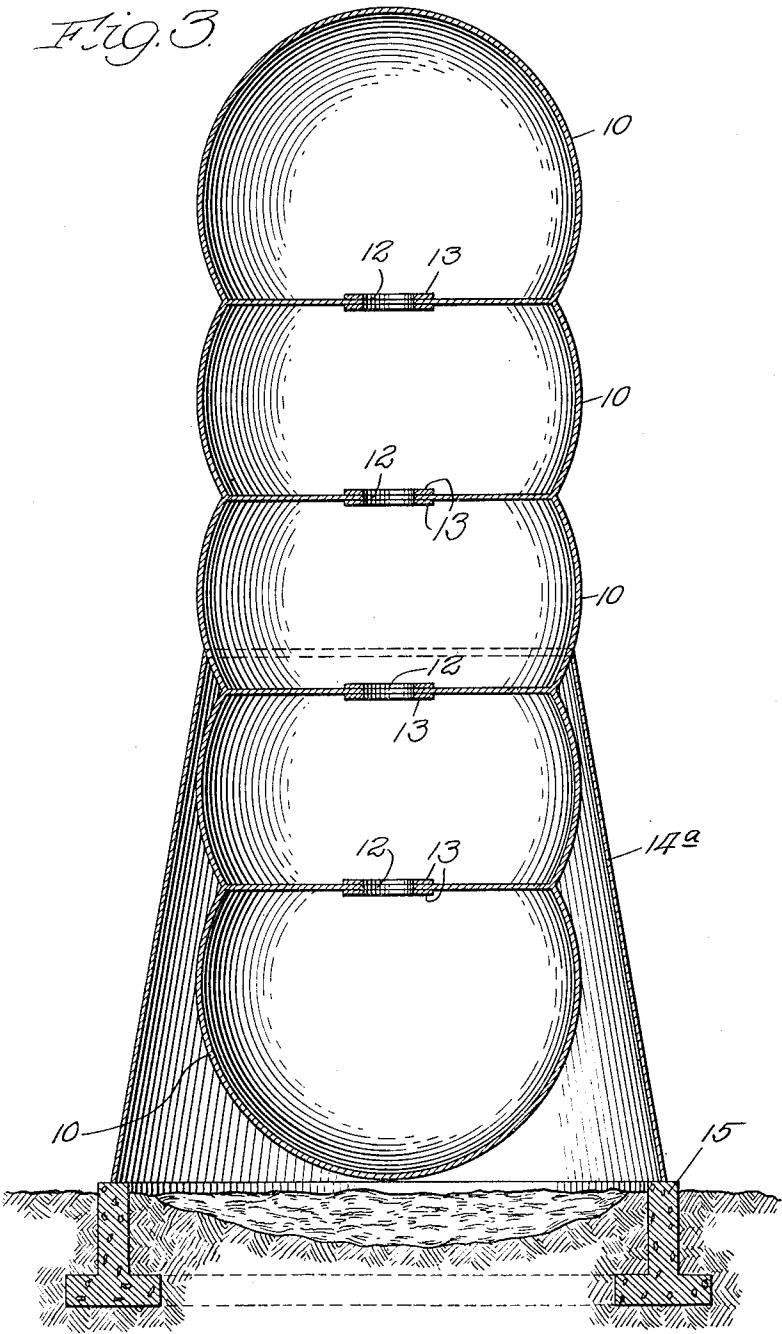
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LIQUID STORAGE VESSEL

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This invention relates to storage vessels for the storage of liquids.

Vessels of large size are widely used for the storage of various gases and liquids. When liquids are to be stored, the vessels must be strong enough to sustain the weight of the liquid as well as the vapor pressure of this liquid. As the size of the vessels increases the thickness of the steel used in their construction becomes quite large. As it is difficult to weld steel plates over certain thicknesses, such as $1\frac{1}{4}$ ", this creates many problems.

I have invented a storage tank wherein large amounts of liquid may be stored, and the thickness of the metal plates used in constructing the vessel may be kept to a minimum. In accomplishing this I construct my vessel of a series of intersecting spheres with diaphragms positioned coincident with the plane of intersection of each pair of adjacent spheres. The vessel is arranged vertically with the spheres aligned along a vertical axis of rotation. This vessel has sides that are thinner than would be the sides of a single sphere of the same capacity, and thus permits building a larger vessel for a given thickness of metal plates.

In order to make the most economical use of metal the storage vessel which is the subject of this invention is constructed according to certain mathematical formulae that I have found are applicable to this type of construction.

The invention will be described as related to the embodiment of the same set out in the accompanying drawings. Of the drawings, Fig. 1 is a vertical section taken through the center of a storage vessel constructed according to the method of this invention; Fig. 2 is a horizontal section taken along line 2—2 of Fig. 1; and Fig. 3 is a vertical section through a modified form of storage vessel.

In the embodiment shown the vessel comprises intersecting spheres 10 arranged along a vertical axis with diaphragms 11 extending along the plane of intersection. These diaphragms have circular cut-out portions 12 in the centers of the diaphragms with reinforcements around the edges of the cut-out portions. These reinforcements may consist of circular flat plates 13 arranged one on top and one on the bottom of the section of diaphragm surrounding each hole. These plates are welded or otherwise attached to the diaphragms. The entire vessel is supported by a cylindrical or conical support 14 resting on a foundation 15.

Although the vessel is shown constructed of spheres having equal radii of curvature, this is not required, as the radii may differ one from

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the other. The intersecting spheres, each of which has a constant radius of curvature, may be replaced by members having different radii of curvature in different planes.

In order to make the most economical use of construction material, I have developed mathematical formulae for the thickness of each sphere and each diaphragm; this makes possible the fabrication of a storage vessel of a given capacity with the smallest amount of construction material possible. The development of these mathematical formulae will be presented in the discussion following.

The basic equation for curved surfaces under load:

$$\frac{T_1}{R_1} + \frac{T_2}{R_2} = P \quad (1)$$

expresses equilibrium of radially inward and outward forces when T_1 equals latitude stress in pounds per inch of meridian arc, T_2 equals meridian stress in pounds per inch of latitude arc, R_1 equals radius of curvature in inches at right angles to a meridian plane, R_2 equals radius of curvature in inches in a meridian plane, and P equals combined gas and liquid pressure in pounds per square inch. If the radius of curvature of the surface is constant for each individual shell the R_1 equals R_2 equals R , and Equation 1 becomes

$$T_1 + T_2 = PR \quad (1a)$$

and

$$T_1 = PR - T_2 = R \left(P - \frac{T_2}{R} \right) \quad (2)$$

$$T_2 = PR - T_1 = R \left(P - \frac{T_1}{R} \right) \quad (3)$$

The point of greatest stress in a spherical shell above the support is just above its bottom diaphragm. The weight of liquid above the diaphragm per square inch of diaphragm equals

$$\frac{W}{\pi h^2}$$

where W equals the total weight of liquid above the diaphragm and h equals the radius of the diaphragm in inches. This unit weight of liquid is designated herein as L .

In all the equations set out herein the diaphragm area is taken as the overall area covered by the diaphragm and bounded by its circumference. No allowance is made for any cut out areas of the type shown in the drawings, as these will ordinarily be reinforced at their margins.

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If all above the diaphragm is considered a free body, the equilibrium equation of vertical forces at the diaphragm will be

$$2\pi h T_2 \left(\frac{h}{R} \right) = P\pi h^2 - W \quad (4)$$

when $P\pi h^2$ equals the total pressure at the diaphragm. Equation 4 becomes

$$T_2 = \frac{1}{2}R \left(P - \frac{W}{\pi h^2} \right) \quad (5)$$

$$T_2 = \frac{1}{2}R(P - L) \quad (6)$$

The horizontal component of T_2 is equal to T , the diaphragm stress in pounds per inch of the periphery of the diaphragm. Then

$$T = \frac{1}{2}a(P - L) + \frac{1}{2}b(P - L) = \frac{1}{2}V(P - L) \quad (7)$$

where a equals distance from the diaphragm in inches to the center of curvature of its top spherical shell, b equals distance from the diaphragm to the center of curvature of its bottom shell, and the total distance between centers of curvature ($a + b$) equals V . Substituting in Equation 2 the value of T_2 from Equation 6 there is obtained the expression

$$T_1 = R \left[P - \frac{\frac{1}{2}R(P - L)}{R} \right] \quad (8)$$

or

$$T_1 = \frac{1}{2}R(P + L) \quad (9)$$

When the spherical shells and diaphragms are below the support, then the weight of liquid below the diaphragm becomes the important factor. Here

$$L_1 = \frac{W_1}{\pi h^2}$$

where W_1 is the weight of the liquid below the diaphragm and h is the radius of the diaphragm. The equations for stresses below the support become

$$T = \frac{1}{2}V(P + L_1) \quad (10)$$

$$T_1 = \frac{1}{2}R(P - L_1) \quad (11)$$

$$T_2 = \frac{1}{2}R(P + L_1) \quad (12)$$

For all points above the shell to which the support is attached the greatest stress in the spherical shell will be just above the diaphragm located at the bottom of the shell. For all spherical shells below the shell to which support is attached the greatest stress will be just below the diaphragm located at the top of the shell.

For each shell above the shell to which the support is attached the latitude stress (T_1) is always greater than the meridian stress (T_2). For each shell below the shell to which the support is attached the meridian stress (T_2) is greater than the latitude stress (T_1). This can be seen by inspection of the Equations 6 and 9 and of Equations 11 and 12. Therefore above the shell to which the support is attached the latitude stress (T_1) governs the designs, while below the shell to which the support is attached the meridian stress (T_2) governs the design.

The analysis of stresses given herein for a vessel constructed according to my methods shows that the stresses vary over the entire vessel. As a practical matter a large storage vessel is seldom made with sides varying in thickness from one level to another on the vessel. Therefore in constructing this improved storage vessel each shell is made of uniform thickness, and each diaphragm is made of uniform thickness.

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but the shells vary in thickness one from the other, and the diaphragms vary in thickness one from the other. In designing spherical shells to be used above the shell to which the support is attached the latitude stress (T_1) at a level just above the diaphragm at the bottom of the shell is used as the design basis. For shells to be used below the shell to which the support is attached the meridian stress (T_2) at a level just below the diaphragm at the top of the shell is used as the design basis. For the diaphragms the stress (T) at the periphery of the diaphragm is used as the design basis.

The thickness of the shells and diaphragms may be found by dividing the design stress by the product of the allowable working stress and the joint efficiency. The allowable working stress is determined by the type of construction material used, as well as other factors well understood by the workman skilled in the art. The joint efficiency depends upon the type of joint used in building the vessel. This efficiency factor has been assigned to the different types of joints, such as welded joints, riveted joints, and the like. This, too, is well understood by the man skilled in the art.

From the foregoing it is evident that for shells and diaphragms above the shell to which the support is attached the thicknesses are determined by dividing Equations 9 and 7, respectively, by the product of the allowable working stress and the joint efficiency. For shells and diaphragms below the shell to which the support is attached, the thicknesses are found by dividing Equations 12 and 10 respectively by the product of allowable working stress and joint efficiency. The thickness equation for shells above the shell to which the support is attached becomes

$$A = \frac{R(P + L)}{2SE} \quad (13)$$

and for diaphragms above the shell to which the support is attached becomes

$$B = \frac{V(P - L)}{2SE} \quad (14)$$

which should be compared with

$$B = \frac{VP}{2SE} \quad (15)$$

where p is the gas pressure alone, and the larger value of B used in the design. In the ordinary normal storage vessel Equation 15 will always be greater than Equation 14. The thickness for shells below the shell to which the support is attached becomes

$$A_1 = \frac{R(P + L_1)}{2SE} \quad (16)$$

and for diaphragms below the shell to which the support is attached becomes

$$B_1 = \frac{V(P + L_1)}{2SE} \quad (17)$$

where A and A_1 equal shell thickness above and below the shell to which the support is attached, respectively, and B and B_1 equal diaphragm thickness above and below the shell to which the support is attached, respectively. S equals the allowable working stress, and E equals the joint efficiency.

When the support is on an intermediate shell, as shown in Fig. 3, Equation 9 should be applied to both the level of the upper diaphragm and the level of the support; and Equation 12 should be applied to both the level of the lower diaphragm

and the level of the support. At the level of the support W is the weight of liquid above the support, and W_1 the weight of liquid below the support, and h is the horizontal radius of the shell in the plane of the support. The greatest stress given by these four equations is the design stress for this shell.

When the support is on the bottom shell, as shown in Fig. 1, Equation 9 should be applied to both the level of the upper diaphragm and the level of the support; Equation 12 should be applied to the level of the support, and to the lowest point on the bottom where L_1 equals zero. The greatest stress given by these four equations is the design stress for this shell.

In the normal storage vessel constructed according to the method of this invention, the shells are progressively thinner the farther they are above and below the support; the diaphragms above the support are of equal thickness, and the diaphragms below the support are progressively thinner the farther they are below the support. When the storage vessel is constructed in its preferred form with the support on the lowermost shell, with the radius of each shell the same and with the distances between centers of adjacent shells the same, the diaphragms will all be the same thickness and this thickness will be determined by means of Equation 15.

Each individual shell and each diaphragm is preferably of uniform thickness. It is also preferred that each shell have a constant radius of curvature, although the radii of curvature of all the shells will not necessarily be the same. Preferably the storage vessel is constructed with the support connected to the vessel at a circle determined by a horizontal plane intersecting the vessel. In order to provide economy of material in constructing the support, it may conveniently be located at a horizontal circle on the bottom portion of the lowermost shell. This means that the support is joined to the lowermost shell at or below the equator of this shell.

Having described my invention in considerable detail as related to one embodiment, it is my intention that the invention not be limited by these details of description unless otherwise specified, but rather be construed broadly within its spirit and scope, as set out in the accompanying claims.

I claim:

1. A storage vessel for liquids having a substantially vertical axis and comprising a series of intersecting spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support therefor joined to one of the shells above the bottom shell at a circle determined by a horizontal plane intersecting said shell, said spherical shell segments being thinner than a single spherical shell of the same capacity with the thickness of succeeding spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support, the thickness of each shell segment being substantially uniform over its entire area and the thickness of each diaphragm being substantially uniform over its entire area.

2. A storage vessel for liquid having a substantially vertical axis and comprising a series of intersecting spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support therefor joined to one of the shells above the bottom shell at a circle determined by a horizontal plane intersecting said shell, said

spherical shell segments being thinner than a single spherical shell of the same capacity with the thickness of succeeding spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support and the thickness of succeeding diaphragms being constant from the top of the vessel to the support and increasing in thickness from the bottom of the vessel to the support, the thickness of each shell segment being substantially uniform over its entire area and the thickness of each diaphragm being substantially uniform over its entire area, said spherical shell segments each having a constant radius of curvature.

3. A storage vessel as set out in claim 2 wherein the stress in any shell section above the support is largest at its junction with its lower diaphragm and the thickness of the shell section in inches is the quotient of the product of the radius of curvature in inches and the sum of the combined gas and liquid pressure in pounds per square inch of lower diaphragm area and the weight in pounds of liquid above said diaphragm per square inch of diaphragm area, divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

4. A storage vessel as set out in claim 2 wherein the thickness in inches of any diaphragm is the quotient of the product of the distance in inches between the centers of curvature of the shell sections adjoining the diaphragm and the gas pressure in pounds per square inch of diaphragm area, divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

5. A storage vessel as set out in claim 2 wherein the normal shell thickness in inches below the support is the quotient of the product of the combined gas and liquid pressure in pounds per square inch at the bottom of the vessel and the radius of curvature in inches of the bottom shell divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

6. A storage vessel as set out in claim 2 wherein the thickness in inches of any shell section above the support is the quotient of the product of the radius of curvature in inches and the sum of the combined gas and liquid pressure in pounds per square inch of lower diaphragm area and the weight of liquid in pounds above said diaphragm per square inch of diaphragm area, divided by twice the product of the design stress in pounds per square inch and the joint efficiency; the thickness in inches of any diaphragm is the quotient of the product of the distance in inches between the centers of curvature of the shell sections adjoining the diaphragm and the gas pressure in pounds per square inch of diaphragm area, divided by twice the product of the design stress in pounds per square inch and the joint efficiency; and the normal shell thickness in inches below the support is the quotient of the product of the combined gas and liquid pressure in pounds per square inch at the bottom of the vessel and the radius of curvature in inches of the bottom shell divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

7. A storage vessel having a substantially vertical axis and comprising at least three spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support for supporting the

entire weight of the shell joined to a shell segment intermediate the top and bottom shell segments, said spherical shell segments being thinner than a single spherical shell of the same capacity with the thickness of succeeding spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support, the thickness of each shell segment being substantially uniform over its entire area and the thickness of each diaphragm being substantially uniform over its entire area.

8. A storage vessel as set out in claim 7, wherein the thickness in inches of any shell section above the support is the quotient of the product of the radius of curvature in inches and the sum of the combined gas and liquid pressure in pounds per square inch of lower diaphragm area and the weight of liquid in pounds above said diaphragm per square inch of diaphragm area, divided by twice the product of the design stress in pounds per square inch and the joint efficiency; and the normal shell thickness in inches below the support is the quotient of the product of the combined gas and liquid pressure in pounds per square inch at the bottom of the vessel and the radius of curvature in inches of the bottom shell divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

9. A storage vessel as set out in claim 7 wherein the thickness in inches of any diaphragm is the quotient of the product of the distance in inches between the centers of curvature of the shell sections adjoining the diaphragm and the gas pressure in pounds per square inch of diaphragm area, divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

10. A storage vessel for liquids having a substantially vertical axis and comprising a series of intersecting spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support for supporting the entire weight of the vessel attached to a shell segment below the top segment, said spherical shell segments being thinner than a single spherical shell of the same capacity and each shell segment having a uniform thickness with the thickness of succeeding spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support, and the thickness in inches of any spherical shell above the support being equal to the quotient of the product of radius of curvature in inches and sum of the combined gas and liquid pressure in pounds per square inch of diaphragm area on the diaphragm at the bottom of said shell and the weight in pounds of liquid above said diaphragm per square inch of diaphragm area divided by twice the product of the allowable working stress in pounds per square inch on said shell and the joint efficiency.

11. A storage vessel for liquids having a substantially vertical axis and comprising a series of intersecting spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support for supporting the entire weight of the vessel attached to a shell segment below the top segment, said spherical shell segments being thinner than a single spherical shell of the same capacity and each shell segment having a uniform thickness with the thickness of succeeding

spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support, and the thickness in inches of any diaphragm above the support being equal to the quotient of the product of the distance in inches between the centers of curvature of the shell sections adjoining the said diaphragm and the gas pressure in pounds per square inch of diaphragm area divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

12. A storage vessel for liquids having a substantially vertical axis and comprising a series of intersecting spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support for supporting the entire weight of the vessel attached to a shell segment above the bottom segment, said spherical shell segments being thinner than a single spherical shell of the same capacity and each shell segment having a uniform thickness with the thickness of succeeding spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support, and the thickness in inches of any spherical shell below the support being equal to the quotient of the product of the radius of curvature in inches of said shell and sum of the combined gas and liquid pressure in pounds per square inch of diaphragm area on the diaphragm at the top of said shell and the weight of liquid in pounds below said diaphragm per square inch of diaphragm area, divided by twice the product of the allowable working stress in pounds per square inch and the joint efficiency.

13. A storage vessel for liquids having a substantially vertical axis and comprising a series of intersecting spherical shell segments intersecting in substantially horizontal planes with diaphragms located at the intersections, and a support for supporting the entire weight of the vessel attached to a shell segment above the bottom segment, said spherical shell segments being thinner than a single spherical shell of the same capacity and each shell segment having a uniform thickness with the thickness of succeeding spherical shell segments increasing from the top of the vessel to the support and from the bottom of the vessel to the support, and the thickness in inches of any diaphragm below the support being equal to the quotient of the product of the distance in inches between centers of curvature of the shell sections adjoining said diaphragm and sum of combined gas and liquid pressure in pounds per square inch of diaphragm area and weight of liquid in pounds below the diaphragm per square inch of diaphragm area, divided by twice the product of the allowable working stress in pounds per square inch and joint efficiency.

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