June 17, 1969 W. E. JOOR II 3,449,884

METHOD OF CONSTRUCTING SUSPENSION ROOFS

Filed Feb. 8, 1967 Sheet 1 of 6

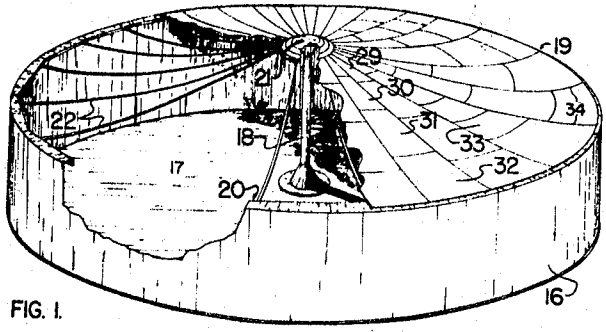


FIG. 1.

FIG. 2

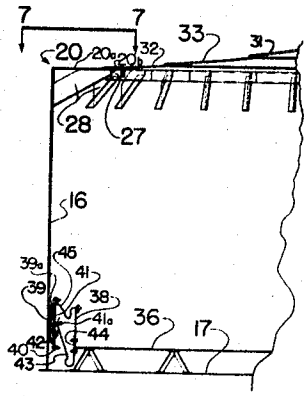
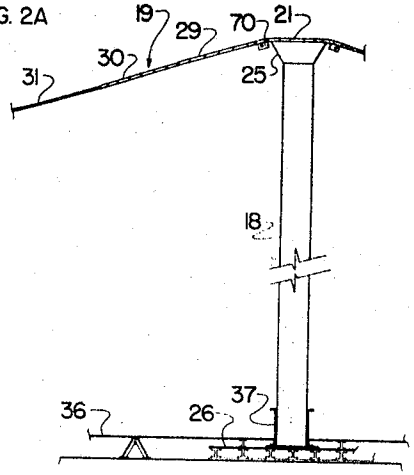


FIG. 2A



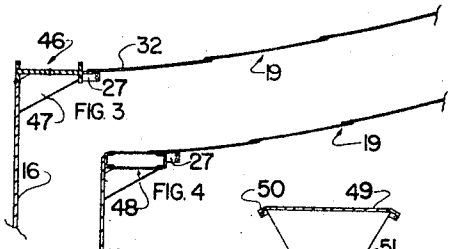


FIG. 3

FIG. 4

FIG. 5

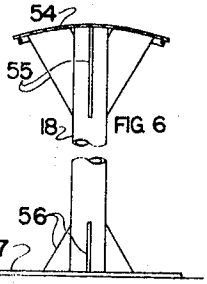


FIG. 6

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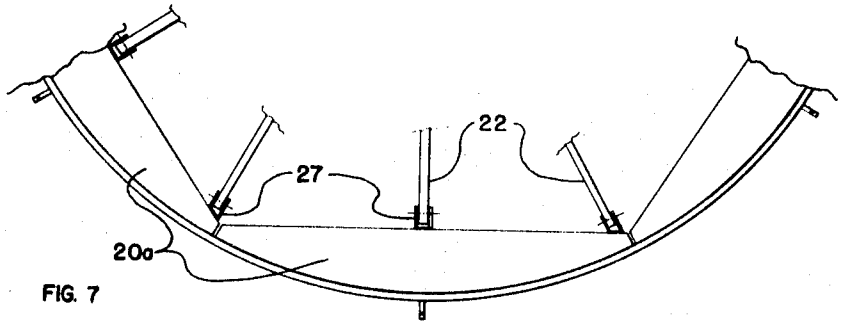


FIG. 7

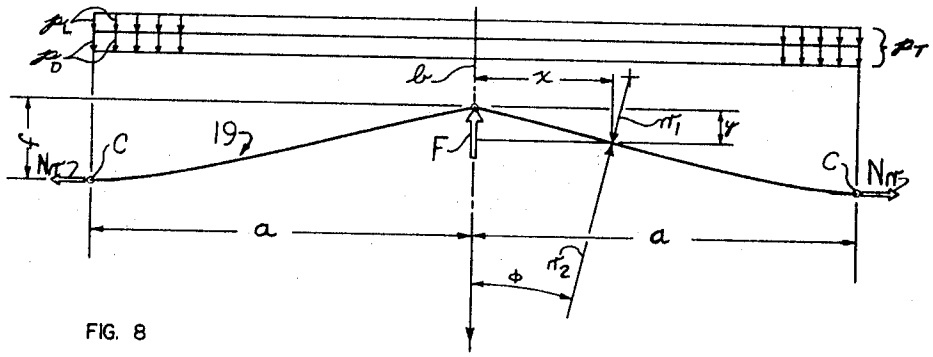


FIG. 8

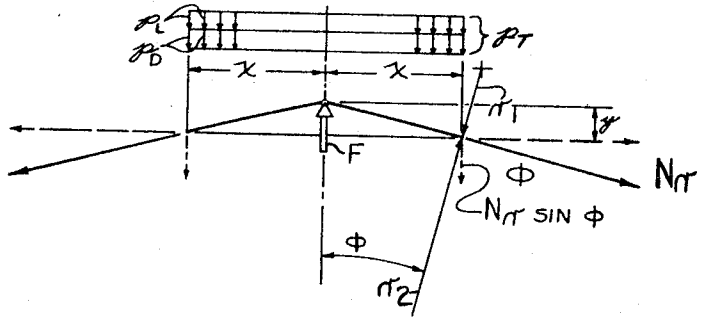


FIG. 8a

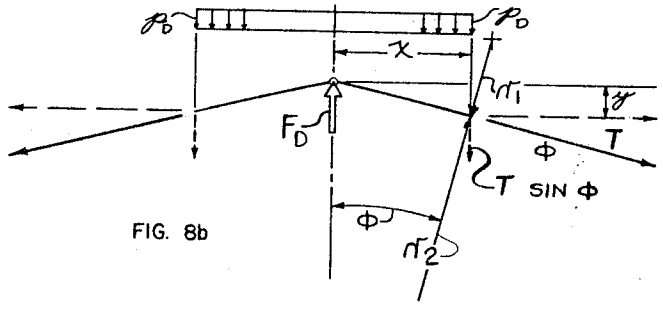


FIG. 8b

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June 17, 1969 W. E. JOOR II 3,449,884

METHOD OF CONSTRUCTING SUSPENSION ROOFS

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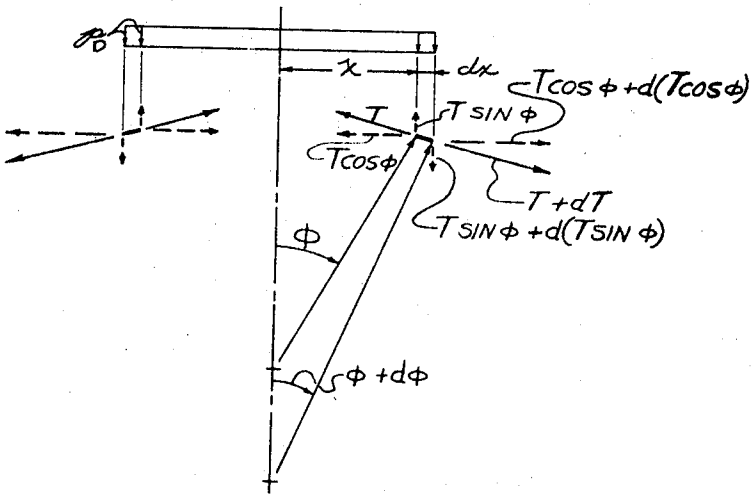


FIG. 8c

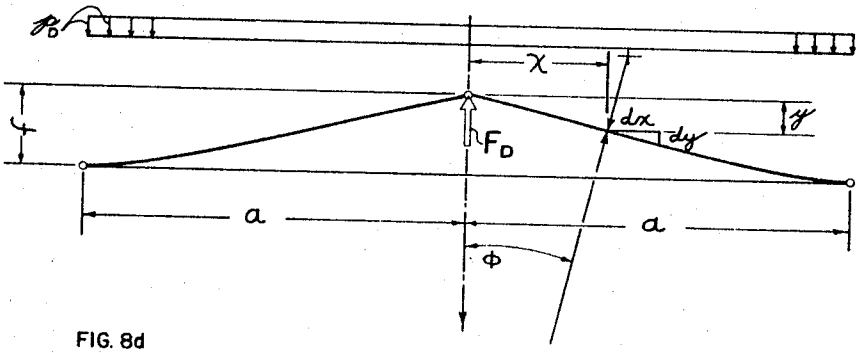


FIG. 8d

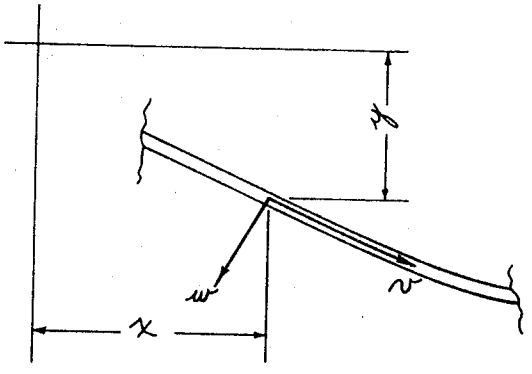


FIG. 8e

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June 17, 1969 W. E. JOOR II 3,449,884

METHOD OF CONSTRUCTING SUSPENSION ROOFS

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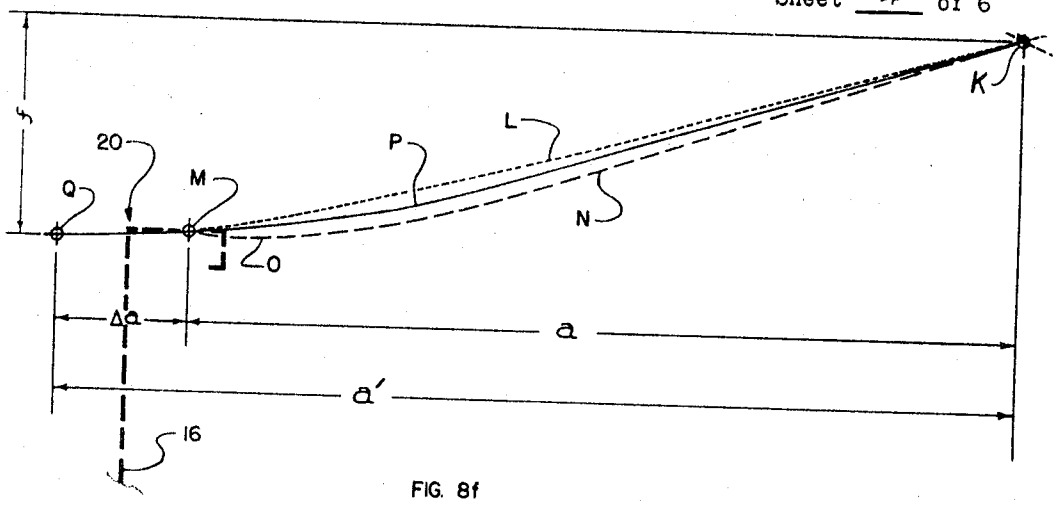


FIG. 8f

FIG. 9

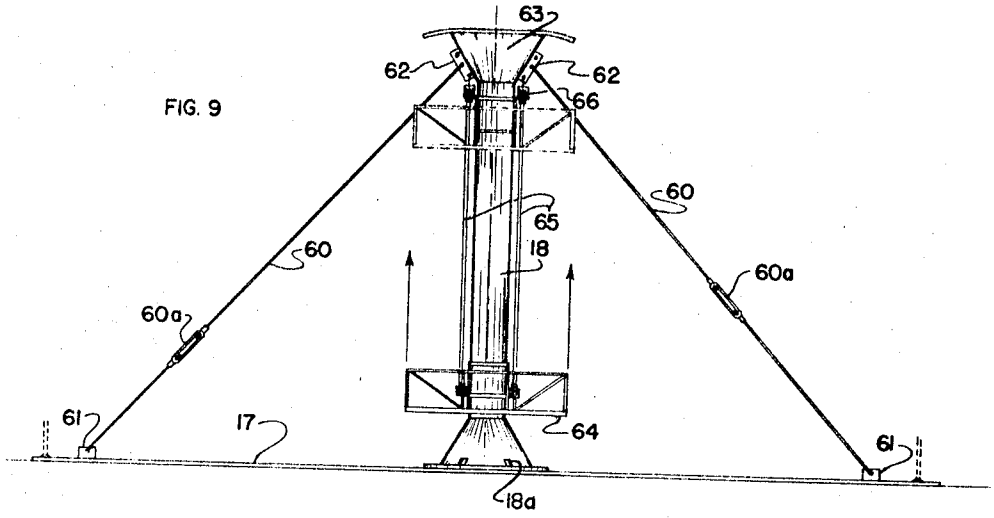
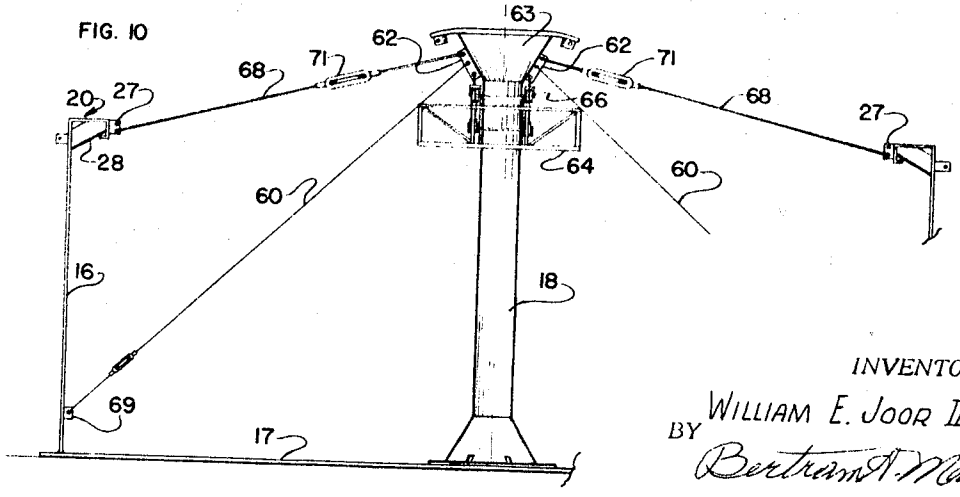


FIG. 10



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June 17, 1969 W. E. JOOR II 3,449,884

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FIG. 11

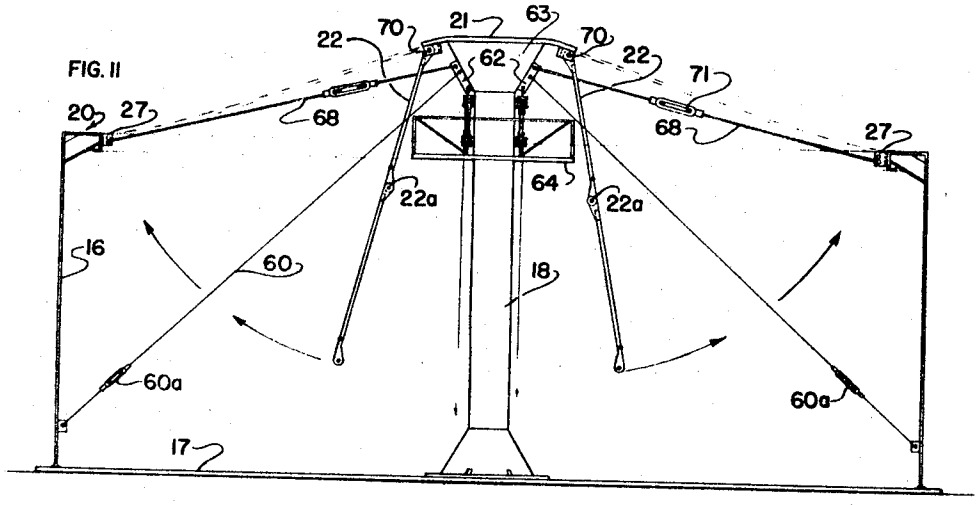
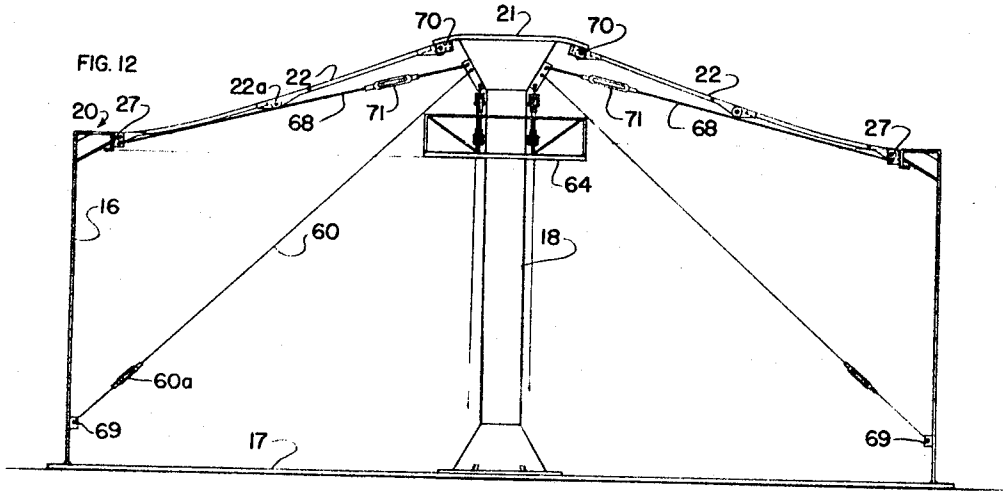


FIG. 12



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FIG. 13

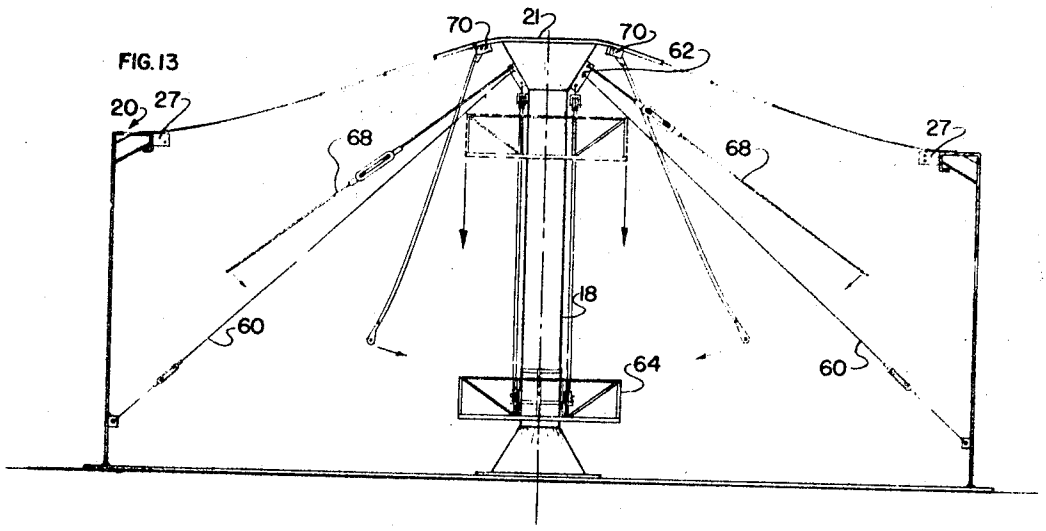
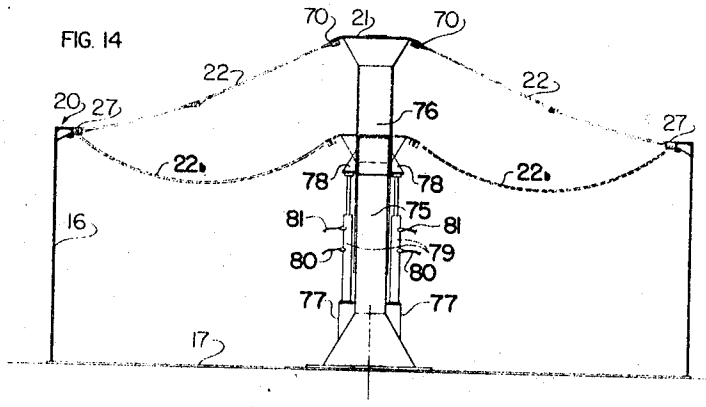


FIG. 14



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United States Patent Office 3,449,884 Patented June 17, 1969

3,449,884

METHOD OF CONSTRUCTING SUSPENSION ROOFS

William E. Joor II, Houston, Tex., assignor, by mesne assignments, to U.S. Industries, Inc., a corporation of Delaware

Filed Feb. 8, 1967, Ser. No. 614,722
Int. Cl. E04g 21/14, 11/04; E04b 7/14
U.S. Cl. 52—747 7 Claims

ABSTRACT OF THE DISCLOSURE

A roof for large, cylindrical tanks is assembled on sagging tension bars which are initially suspended between a collapsed, telescoping center column and a compression girder at the top of the tank shell. The center column is expanded to tensionally stress the bars and enforce accurate circular curvature of the compression girder. Thereafter, roof sheeting is laid on top of the bars to provide a roof which slopes continuously downwardly and outwardly from center to periphery, and the tension bars are then removed.

BACKGROUND OF THE INVENTION

Field of the invention

This invention relates to storage tanks and, particularly, fixed roof constructions therefor and methods of erecting the same.

Prior art

Since such tanks usually are cylindrical and may be 100 to 200 feet or more in diameter, the design and construction of fixed roofs therefor, particularly with minimum obstruction of the tank interior, involves substantial difficulties. Heretofore, in some instances, such roofs have been supported upon additional interior columns and/or massive girder or trusswork constructions, which, of course, limit the tank capacity and hinder or prevent the provision of an interior floating roof. In other instances, suspension roofs have been provided with intermediate gutters therein which complicate the roof and have the effect of undesirably increasing the axial and radial loading of the peripheral compression ring and tank wall. Of course, the slope of the roof sheets is not critical in such gutter arrangements.

SUMMARY OF THE INVENTION

Consequently, an object of the present invention is to provide a novel fixed roof construction for large fluid tanks, particularly cylindrical tanks, which requires for support only a single center column in addition to the ring girder at the upper edge of the outer shell.

Another object is to provide a fixed roof construction for large, cylindrical liquid tanks, particularly of a suspension type, in which water and other fluent materials cannot be trapped on the roof even when deflected by large live loads.

Another object is to provide a suspension roof for large cylindrical tanks in which the transmission of vertical forces to the compression ring girder and tank wall is minimized.

Still another object is to provide a novel method of constructing a fixed suspension membrane type roof for large liquid storage tanks.

In accordance with the present invention, the novel suspension roof is erected by suspending flexible tension bars between a center column and the accurately trued compression ring girder at the upper edge of the tank shell. Roof sheets or plates are laid on the tension bars

and properly secured together and to the ring girder. The curve of the roof is calculated, with due regard for the weights and strengths of the roof sheeting and anticipated loading, so that the roof will slope at all times and at all points downwardly and outwardly toward its outer periphery and fluent materials will be readily and quickly shed from the roof. The critical design and disposition of the curve-determining tension bars is achieved with the aid of computer techniques, and novel method steps are disclosed for insuring the uniformly accurate disposition of the roof.

BRIEF DESCRIPTION OF THE DRAWINGS

In the accompanying drawings which illustrate the invention:

FIG. 1 is a perspective view of a liquid tank during construction of the new roof, portions being broken away to illustrate the tension rods used in erecting the roof;

FIG. 2 is an enlarged partial radial section illustrating the outer parts of the completed roof structure of FIG. 1;

FIG. 2A is a similar view showing the inner parts of the roof construction;

FIGS. 3 and 4 are detail radial sections illustrating different forms of compression ring girders for use with the novel roof construction;

FIGS. 5 and 6 are elevations illustrating different forms of vertical center columns and crown plates for the novel roof;

FIG. 7 is an enlarged detail plan viewed from the line 7—7 of FIG. 2 and showing the shape of the compression ring structure, the overlying roof being removed;

FIGS. 8, 8*a*, 8*b*, 8*c*, 8*d*, 8*e*, and 8*f* are diagrams illustrating the geometry of the new roof and its mathematical development as utilized in designing the same to bear the dead and live loads expected;

FIG. 9 is an elevation of the center column and supporting guys and illustrating a first step in an exemplary method of erecting the roof;

FIGS. 10, 11, 12, and 13 are views similar to FIG. 9 and illustrating further steps in the erection of the roof; and

FIG. 14 is an elevation of the center column, tank shell, tank bottom, and erection cables illustrating a modified, preferred method of erecting the roof.

DESCRIPTION OF THE PREFFERED EMBODIMENTS

FIG. 1 illustrates a large tank of the type used in storing petroleum or other volatile liquids and having a cylindrical side wall or shell **16**, a flat floor **17**, a center column **18**, and a suspension-type roof, generally designated **19**. Extending around the upper edge of shell **16** is a compression ring girder **20**, and a roof crown plate **21** is mounted on top of center column **18**. Roof **19**, made up of a series of plates forming a sheet or membrane, as will be described, bridges the space between crown plate **21** and ring girder **20**. Flexible tension rods, bars, or cables **22** extend radially between plate **21** and the ring girder for use in erecting the roof.

FIG. 2A shows the inner portion the completed roof with erection rods **22** removed. Crown plate **21** is shown as connected to center column **18** by means of an inverted, load-dispersing cone **25** and the center column rests upon floor reinforcement platform **26**. Compression girder **20**, as best shown in FIGS. 2 and 7, is formed of segmental plates **20***a* preferably welded to the upper edges of tank shell **16** and provided with inner flanges **20***b* from which project inwardly extending attachment clevices **27**, for a purpose to be described. Plates **20***a* are braced by gussets **28**. The roof sheeting or membrane itself (FIG. 1) is made up of frusto-conical or gore-shaped plate sections, as at **29**, **30**, **31**, **32** and **33**, of staggered heights and

placements and assembled radially, as represented by the radial lines **34** in FIG. 1. Since the radial stresses in the roof membrane are greatest adjacent the center post and decrease outwardly, the roof plates may be reduced in thickness outwardly, as suggested in FIG. 2A, wherein crown plate **21** is thicker than gore plates **29**, which are thicker than plates **30**, and so on. All plates may be welded together at their abutting edges. Plates **21**, **29**, **30**, and **31** are shown as butt-welded to their adjacent plates, while the outer tiers of plates **32** and **33** slightly overlap their adjacent plates and are lap welded thereto. The outermost roof plates are lap welded to the upper surface of compression girder plates **20***a*.

A floating roof **36** of the pan type is received within the tank (FIGS. 2 and 2A) and is provided with a central sleeve **37** (FIG. 2A) which slidably receives and seals about center column **18**. At the outer edge of the floating roof **36** (FIG. 2) there is provided a vertical flange **38** which mounts wall seal structure. This structure consists of a shoe-forming pad **39**, preferably of foam rubber or foam synthetic plastic material such as polyurethane encased in a scuff band and cover **39***a*, for instance, of nylon cloth reinforced polyurethane. The seal pad or pads extend entirely around and sealingly engage the inner surface of tank shell **16**. A back-up sheet **41** is secured to the face of the pad and is connected, as by studs **41***a*, to generally U-shaped spring straps each having legs as **43** and **44**, the latter being bolted to peripheral roof flange **38** previously mentioned. Seal fabric **45** is secured to the upper edges of pad **39** or backing sheet **41** and peripheral flange **38** and traverses the space therebetween. As is customary with this type of floating roof, the deck **36** floats on the surface of the liquid in the tank and is carried vertically with pad **39** sealingly rubbing against the inner face of the tank shell as the quantity of liquid stored in the tank is varied. The purpose of the floating roof or deck plate is to prevent or reduce the vaporization of liquids within the tank while protecting the stored liquids from contamination. Where the floating desk is provided beneath a fixed roof, as in this instance, it may be built for supporting reduced live and dead loads and, accordingly, such less expensively.

FIG. 3 shows a modified form of compression ring **46** formed substantially of a built-up I-beam welded as indicated and provided with reinforcing gussets as at **47**. FIG. 4 shows still another form of compression ring in the form of a built-up box girder **48**.

FIGS. 5 and 6 show slightly modified center column details. In FIG. 5, the crown plate **49** is flat for a greater extent than is plate **21** is FIG. 2A and has a relatively small, inclined flange **50** for welding to the abutting roof sheet plates. A relatively large, inverted cone **51** transmits vertical forces from the crown plate to center column **18**. The center column and bottom plate **52** are reinforced at the bottom by a frusto cone **53**. In FIG. 6, crown plate **54** is of generally curved cross section and is supported from center column **18** by means of corner braces **55**. At the bottom, vertical forces are transmitted from column **18** to the tank floor **17** by means of guessets **56** and base plate **57**.

FIG. 8 is a geometrical and force diagram of the suspension roof, in which the roof membrane structure **19** is depicted as having assumed the sagging shape of erection rods **22** (FIG. 1). Due to the shape of the roof, the horizontal component of the tension in the roof membrane varies at different radial distances from the center column and, therefore, the cross-sectional curve of the roof membrane is not a true catenary.

Since the essence of this invention is a roof design for a vertical cylindrical storage tank (1) which will drain all rain water over the eaves as it falls on the roof, (2) which will be of a membrane-type construction, (3) which will permit elimination of the vast tonnage of structural steel in the form of rafters, beams, girders, and columns (except one center column) required in previous

fixed roof constructions, and (4) which will be economical and easy to build, the invention may be better understood from an analysis of the engineering, mathematical, and construction techniques involved.

Within my experience this is the first design of a vertical cylindrical storage tank structure which requires the use of the sophisticated disciplines of mechanical engineering using the "Theory of Elasticity" and the "Membrane Theory," mathematical dexterity using differential equations to establish the curvature, i.e., the shape, of the vertical cross section of the membrane steel roof plates, numerical integration or approximate integration employing the trapezoidal rule or the Simpson rule or other approximations to determine the deflection of the membrane steel roof plates, the logic required to convert the engineering and mathematical problems into an electronic computer program acceptable by a powerful computer, and the engineering knowledge of an experienced tank builder.

In order that those skilled in the art may better understand the invention, the design principles are here mathematically developed. FIG. 8 diagrams a vertical cross section of the roof which is a surface of revolution about its vertical axis b, with anticipated live loads and dead loads represented as uniform loads symbolized by the arrows, p_L and p_D, respectively, over the entire plan area of the roof and p_T, the total load. Then

$$p_T = p_D + p_L$$

It is assumed, with good engineering judgment, that the height of the roof f is so shallow that the dead weight of the roof may be taken as uniformly distributed on the horizontal projection. Then considering any point (x, y) on the roof curve, let

ϕ=the angle formed between the normal (r_2) to the roof tangent, through the point under consideration and the vertical axis b

r_1=the radius of the roof curvature

n=the number of erection cables or rods used in the construction of the roof

H=the horizontal component in pounds of the stress in one erection cable under the dead load only of the membrane roof plates

N_r=the radial membrane force at point (x, y)

N_θ=the circumferential membrane force at point (x, y)

σ_r=radial membrane stress at point (x, y)

σ_θ=circumferential membrane stress at point (x, y)

h=assumed uniform thickness of roof membrane

a=radius of the roof membrane

Then by the nature of the erection method of the roof and its basic geometry, the differential equation of the roof cross section becomes

$$\frac{dy}{dx} = \frac{\pi p_D}{nH}(a^2 - x^2) \tag{1}$$

The solution of this equation gives the cross section of the roof as follows:

$$y = \frac{3}{2} f \left[\frac{x}{a} - \frac{1}{3} \left(\frac{x}{a} \right)^3 \right] \tag{2}$$

The membrane solution for the roof stresses yields the following equations:

$$\tan \phi = \frac{3}{2} \frac{f}{a} \left[1 - \left(\frac{x}{a} \right)^2 \right] \tag{3}$$

$$\sigma_r = \frac{Nr}{h} = \frac{p_T (a^2 - x^2)}{2xh \sin \phi} \tag{4}$$

$$\sigma_\theta = \frac{N_\theta}{h} = 0 \tag{5}$$

To find σ_r first find ϕ from Equation 3, then find σ_r from Equation 4. It is noted that for this particular roof configuration, σ_θ has a value of zero everywhere in the membrane.

The compression ring girder, which restrains the horizontal force in the membrane roof plates around its perimeter, must be designed to resist circumferential compressive force P in the girder. which may be calculated as follows:

$$P=\frac{p_T a^3}{3f} \tag{6}$$

In order for the compression ring girder to resist buckling in its own plane, the cross section of the girder must have a moment of inertia I about its vertical neutral axis equal to or greater than $I_{(min)}$. It is customary, in good engineering practice in the design of such a structure, to use a safety factor of 2 or more. Therefore, the design value of $I_{(min)}$ may be determined as:

$$I_{(min.)}=\frac{2p_T a^5}{9Ef} \tag{7}$$

where:

E=the modulus of elasticity of the material of the compression ring

The central column which supports the entire live and dead load of the roof may be designed using the conventional engineering formulas for column design for an axial compressive load, symbolized by the arrow F, where:

$$F=\pi p_T a^2 \tag{8}$$

Now consider FIG. 8*a* showing a free-body diagram of a portion of the roof:

Again, let F=the load (dead load plus live load) on the center column supporting the roof
If N_r=the radial force in the roof membrane at any point (x, y) under construction
Then $N_r \sin \phi$=the vertical component of the force N_r
And $N_r \cos \phi$=the horizontal component of the force N_r

Now for static equilibrium of the vertical forces in FIG. 8*a*:

$$F=p_T \pi x^2+N_r \sin \phi \cdot 2\pi x$$

For equilibrium of the vertical forces in the entire roof:

$$F=p_T \pi a^2$$

Therefore,

$$N_r \sin \phi \cdot 2\pi x=p_T \pi (a^2-x^2)$$

or

$$N_r=\frac{p_T(a^2-x^2)}{2x \sin \phi} \tag{9}$$

To proceed further, we now need to know the geometry of the roof membrane, i.e., the relationship between x and ϕ.

To determine this geometry, refer to FIG. 8*b*. When erected, the only load considered is the dead load. Now:

Let n=the number of erection cables
And T=the tensile force exerted in each cable at radius x

For equilibrium of the vertical forces in FIG. 8*b*:

Let F_D=the vertical loading of center column under dead loading
Then $F_D=p_D \pi x^2+n\ T \sin \phi$

For equilibrium of the vertical forces in the entire roof:

$$F_D=p_D \pi a^2$$

Therefore,

$$n\ T \sin \phi=p_D \pi (a^2-x^2)$$

or

$$T=\frac{p_D \pi (a^2-x^2)}{n \sin \phi} \tag{10}$$

Now consider the elemental sections of the membrane shown in FIG. 8*c*.

For static equilibrium of the horizontal forces acting on the element:

$$n \cdot T \cos \phi=n \cdot T \cos \phi+n \cdot d(T \cos \phi)$$

Therefore,

$$d(T \cos \phi)=0$$

And

$$T \cos \phi=\text{constant}=H \tag{11}$$

For static equilibrium of the vertical forces:

$$n \cdot T \sin \phi=p_D \pi (x+dx)^2-p_D \pi x^2 +n \cdot T \sin \phi+n \cdot d(T \sin \phi)$$

canceling, transposing, and simplifying the above equations may be written

$$-p_D \pi (x^2+2x dx+dx^2-x^2)=n \cdot d(T \sin \phi)$$

or

$$\frac{d(T \sin \phi)}{dx}=-\frac{2\pi p_D x}{n}$$

solving

$$T \sin \phi=-\frac{\pi p_D x^2}{n}+C \text{ (a constant)}$$

and

$$n \cdot T \sin \phi=-\pi p_D x^2+C$$

at

$$x=0,\ n \cdot T \sin \phi=F_D=p_D \pi a^2$$

therefore

$$p_D \pi a^2=K \text{ (a constant)}$$

and

$$n \cdot T \sin \phi=-p_D \pi x^2+p_D \pi a^2$$

or

$$n \cdot T \sin \phi=\pi p_D (a^2-x^2)$$

or

$$T \sin \phi=\frac{\pi p_D (a^2-x^2)}{n} \tag{12}$$

Now consider FIG. 8*d*:

$$\frac{dy}{dx}=\tan \phi=\frac{T \sin \phi}{T \cos \phi}=\frac{\pi p_D (a^2-x^2)}{n \cdot H}$$

solving

$$y=\frac{\pi p_D}{n \cdot H}\left(a^2 x-\frac{x^3}{3}\right)$$

at

$$x=a,\ y=f$$

and

$$f=\frac{\pi p_D}{n \cdot H}\left(a^3-\frac{a^3}{3}\right)=\frac{2\pi p_D a^3}{3n \cdot H}$$

or

$$H=\frac{2\pi p_D a^3}{3nf} \tag{13}$$

the value of the horizontal component in each erection cable.

Therefore,

$$y=\frac{\pi p_D\left(a^2 x-\frac{x^3}{3}\right)3nf}{n2\pi p_D a^3}$$

$$y=f\left[\frac{3}{2}\left(\frac{x}{a}\right)-\frac{1}{2}\left(\frac{x}{a}\right)^3\right]$$

or

$$\frac{y}{f}=\frac{3}{2}\left(\frac{x}{a}\right)-\frac{1}{2}\left(\frac{x}{a}\right)^3$$

or

$$y=\frac{3}{2}f\left[\frac{x}{a}-\frac{1}{3}\left(\frac{x}{a}\right)^3\right] \tag{14}$$

which is the equation of the curve taken by the erection cables and the roof membrane upon erection and is the same as Equation 2.

Now to relate x and ϕ:

$$\tan\phi=\frac{\pi p_D(a^2-x^2)}{n\cdot H}=\frac{\pi p_D(a^2-x^2)3nf}{n\cdot 2\pi p_D a^3}$$

Therefore,

$$\tan\phi=\frac{3f}{2a}\left[1-\left(\frac{x}{a}\right)^2\right] \quad (15)$$

Now to find N_r for fixed values of f and a, and a particular value of x,

(1) Find tan ϕ from Equation 15
(2) Find the value of ϕ and sin ϕ from tan ϕ
(3) And for a given p_T find N_r from Equation 9

To find T for a fixed value of f and a, and a particular value of x,
(1) Find tan ϕ from Equation 15
(2) Find H from Equation 13
(3) Find the value of ϕ and cos ϕ from tan ϕ
(4) Find T from Equation 11

Thus the geometry and shape of the roof membrane may be established for any given set of parameters.

Having thus established the basic geometry of the roof membrane, it now becomes necessary to determine whether or not rain water will drain off of the roof under all anticipated loadings or will collect in a trough inwardly of the compression ring girder. If it is determined that a rain-collecting trough may develop, it then is necessary to slightly modify the geometry of the roof membrane to assure that no such trough or gutter can form. This modification, if necessary, requires an analysis of the displacement v [tangent to the curve of the membrane at any point (x, y)] and w, the displacement [normal to the tangent] at the same point under consideration. Refer to FIG. 8*e*.

From basic relationships it can be shown that

$$w=\mu r_2\cdot\frac{N_r}{Eh}+v\frac{\cos\phi}{\sin\phi} \quad (16)$$

and

$$v=\sin\phi\left[\int\frac{f_{(s)}dx}{\sin\phi\cos\phi}+C\right] \quad (17)$$

where

$$f_{(s)}=\frac{N_r}{Eh}\left[1+\mu\frac{r_2}{r_1}\right] \quad (18)$$

$$r_1=\frac{1}{\cos^3\phi}\cdot\frac{1}{\frac{d^2y}{dx^2}},\quad r^2=\frac{x}{\sin\phi} \quad (19)$$

and

$$\frac{d^2y}{dx^2}=-\frac{3fx}{a^3} \quad (20)$$

where:
μ=Poisson's ratio and C=a constant of integration.

Equation 17 can be solved by a numerical integration procedure for any particular problem for a number of points on the roof, following which Equation 16 can be solved for these same points. From these numerical values of v and w, the horizontal and vertical components of displacement of the chosen points can be calculated and the vertical components summed and added to the value of y for the corresponding points to determine if these summed values for any point in the membrane are greater than f. If any of these summed values is greater than f, then the membrane may develop a trough inwardly of the compression ring and the geometry or strength of parts must be modified until the summed values are less than f. The herein-described exemplary roof construction will drain continuously even though it is under full anticipated live load.

In the procedure of modifying the geometry it becomes desirable to incrementally increase the value of a, e.g.,

the radius of the roof periphery, so a becomes a' and $a'=a+\Delta a_1+\Delta a_2+$ . . . etc., until the requirement,

$$u_v+w_v+y\leq f$$

is met. In increasing the value of a incrementally, the imaginary point Q is established radially outwardly and downwardly of the point of attachment of the membrane to the compression ring and having the radial value a', as explained. This imaginary point Q may be beyond the tank shell radius. However, the geometric curve of the membrane must pass through the point M of attachment to the compression ring. This is shown in FIG. 8*f*.

In FIG. 8*f*, the dotted line L shows the shape of the membrane as determined by Equation 2 with dead load only. The dashed line N shows the shape and membrane may take when loaded with live plus dead load. Note that the point O may be below the point of attachment to the compression ring M, resulting in a liquid-trapping trough.

Now by increasing the value of a to $a+\Delta a$ and computing the geometry of the roof membrane under total loading conditions, we can develop a geometric shape such as is indicated by solid line P which passes through the point of attachment M to the compression ring and in which no point on the curve is below the point M even with maximum total loading. In other words, all points of the roof membrane will at all times slope downwardly and outwardly, as desired.

The manual solution for the values v and w, using numerical integration or integration by approximation as by use of the trapezoidal rule or Simpson's rule, becomes a very laborious operation and will consume many hours. When it is considered that this must be done for each trial solution and if the solution is not satisfactory, additional trial calculations must be undertaken, increasing the value of a by differential values Δa until a solution is obtained in which the membrane under total load does not sag below the level of its periphery M, and it is realized that the proper solution of the problem by manual means becomes impractical.

However, the above-developed equations mathematically defining the novel roof construction are such as to be solvable by modern computer techniques for various sets of parameters. This possibility makes the novel roof practical, from engineering as well as economic considerations, particularly in the cases of the very large tanks frequently used for storing volatile liquids, such as petroleum and its products.

In the erection of a roof of this type it is necessary that the cables, bars, or rods **22** be fabricated so that they are alike and of the proper lengths to shape as desired the roof sheet or membrane formed by the gore plates which are laid thereon and welded together. The lengths of the erection rods **22** are also calculated on an electronic computer to assure the desired ultimate shaping of the roof.

FIGS. 9–13 illustrate the sequential operations in a novel method of erecting the roof. In FIG. 9, the center column **18** is centrally mounted on floor plate **17** and guyed in the upright position by means of cables **60** with turnbuckle tighteners **60***a* and extendng between lugs **61** projecting from the floor plates and the central holes in lugs **62** on force-dispersing inverted cone **63**. A workman's cage **64** is then supported adjacent or about column **18** upon cables **65** carried by pulley blocks **66** suspended from the bottom holes of lugs **62**. A drain port is symbolized at **18***a*. Then, as shown in FIG. 10, carriage **64** is elevated by means of tackle **65**, **66** to permit workmen to attach ring girder truing rods **68** which are equally spaced about column **18** to the upper holes of lugs **62** and then attach the other ends of these rods to the bottom holes of apertured clevis lugs **27** on compression girder **20**. Turn buckles **71** provide for adjusting the lengths of rods **68**. When this is accomplished and the compression girder **20** is surveyed and found to be round, the joints between the adjacent sections of the compression girder

must be welded. The roundness of the girder should again be surveyed and corrected if necessary. FIG. 10 also shows tank shell **16** erected and guys **60** moved to lugs **69** near the base of wall **16**.

Next, as shown in FIGS. 11 and 12, the roof erection rods **22**, formed of two or more parts hinged as at **22***a*, are pivotally attached to lugs **70** at the periphery of roof crown plate **21** and then elevated toward lugs **27** of the now accurately circular compression ring. All of erection rods **22** are constructed of sufficient length to bridge the pairs of lugs **70** and **27** so as to parallel the surface of revolution ultimately to be assumed by the superposed roof plates. After erection rods **22** are pinned to the upper holes in compression ring lugs **27**, as explained, roof sheet plates **29**, **30**, **31**, **32**, and **33** are applied upon the rods and securely welded to each other and to crown plate **21** and the compression girder. Ring truing rods **68** are then disconnected first from lugs **27**, then dropped, as shown in FIG. 13, and disconnected from crown plate lugs **70**.

After the completion of the roof in this manner, erection rods **68** may be disconnected first from lugs **27**, then lowered, and disconnected from upper end lugs **70**. Finally, guying cables **60** may be released and carriage **64** lowered and removed. The roof structure is now complete, as shown in FIGS. 2 and 2A, with all roof loads carried by the roof membrane between the center column and ring girder.

Although we have described one novel erection method, the preferred novel erection method will now be described and is illustrated in FIG. 14. In this figure it will be noted that the center column is fabricated in two parts **75** and **76** so that the lower part will telescope within the upper part. The column parts are provided with lugs **77** and **78** designed to mount hydraulic jacks **79** between the lugs so that after the two telescoped parts are erected in the center of the tank, the jacks may be inserted between the lugs. Hydraulic connections **80** and **81** provide for actuating the hydraulic jacks so that the upper column part may be jacked upward to a position a few inches above its normal designed height.

While column part **76** is in its convenient, lower, dot-dash line position of FIG. 14, the erection cables or bars (having been fabricated to their exact required lengths) are bolted to the lugs **70** on the underside of the flange of the crown plate and to clevices **27** on the compression ring. This operation is performed prior to welding the radial joints in the compression ring but after the compression ring has been welded to the upper edge of the tank shell. At this stage, the erection cables or bars will sag in a loose curve as is shown at **22***b* in FIG. 14, since the crown plate is about the same elevation as the compression ring.

The upper section **76** of the center column, then, is jacked upward to an elevation of a few inches above its final erected position (FIG. 14, solid lines). Now, since the erection bars are of accurately calculated lengths, these bars will be pulled taut, coincidentally rounding up the compression ring and applying the same tensile force to all erection bars so that they will all have only slight but uniform sag.

Next, the roundness of the compression ring should be checked and then the radial joints at the adjacent ends of the segmental sections of the compression ring girder are welded. When this is done, the compression ring will remain circular as the upper section of the center column is lowered a few inches to its designed height and the erection cables or rods **22** will all have the same sag required to give the membrane roof plates their required geometrical shape.

The center frusto conical plates **29** are first applied in position on the rods around the crown plate **21** and butt welded or in some cases lap welded to the crown plate and to each other. Then the remainder of the membrane plates are moved into place on the erection bars, adjusted to the proper position, and butt or lap welded together in a developed welding sequence which will minimize plate warpage due to welding. In this manner a smooth shaped roof membrane fitting the design geometry of the roof may be erected.

However, if a survey of the erected roof membrane plates indicates that a trough in the membrane may be formed inside the compression ring which will accumulate rain water, the jacks may be used to increase the height of the center column a few inches, stretching the roof membrane to eliminate the possibility of a trough forming.

At this period in the erection procedure, the upper section of the center column is welded inside and outside to the lower section, making it an integral column. Access to the inside is usually provided by a manhole in the crown plate.

Finally, the erection rods and the jacks may be removed and the fabrication work on an internal floating roof or other uncompleted work finished.

This erection procedure may be used to secure the required geometrical shape of the roof with a minimum of erection labor. The described design and methods may be used for constructing tanks having a diameter in excess of two hundred feet. The heavy, long, radial girders and numerous columns, joists, and rafters heretofore frequently utilized to support large, fixed roofs are, as stated, eliminated by the present construction. If an internal floating roof is to be installed, for instance, in a conventional cone roof tank of large size, there will usually be many columns passing through the floating roof which require vapor seals at each column. This type of tank construction is much more difficult to build than is the hereindescribed tank and considerably more expensive, the saving in cost per tank with the use of the present invention amounting to several thousand dollars, or more.

The invention may be modified in various respects, as will occur to those skilled in the art, and the exclusive use of all modifications as come within the scope of the appended claims is contemplated.

I claim:

1. The method of constructing a tank comprising the steps of erecting the tank shell and a center column therein and extending thereabove, providing a horizontal compression ring on said shell and a movable crown member on said column, accurately positioning and shaping said compression ring in a circle about said column, connecting said ring and crown member with radially-disposed, flexible tension members distributed uniformly about the tank, moving said movable crown member to tension said tension members, said crown member being so positioned above the level of said compression ring and said tension members being of such uniform lengths as to assume uniform outward and downward curvature between said crown member and said ring, mounting roof plates on said tension members,, and securing together the edges of said plates to form continuous roof sheeting in the shape of the upper surfaces of said tension members.

2. The method described in claim **1** including the step of providing adjustable radial links in addition to said tension members between said ring and said crown member for enforcing true circular configuration of said ring prior to suspension of said flexible tension members therefrom.

3. The method described in claim **1** including the further steps of removing said tension members after completion of said roof sheets and securing said roof sheets together and to said ring and crown member.

4. The method described in claim **1** in which the tank shell is cylindrical and said center column has telescoping parts and said roof structure suspending step includes the steps of suspending accurately-measured, elongated, flexible tension members between said movable crown member and the tank shell, elevating said movable crown member for truing the tank shell and establishing the

ultimate roof shape and disposition, and applying roof sheeting to said members.

5. The method described in claim 4 including the further step of removing said tension members after said roof sheeting is secured in position.

6. The method described in claim 4 including the further step of positioning the roof sheeting to incline downwardly and outwardly at all points under dead loading and maximum anticipated live loading.

7. The method of constructing a suspension roof for a tank comprising the steps of forming a cylindrical shell, erecting a telescoping center column within the shell, providing a crown member on said column and an accurately cylindrical compression ring on said shell, suspending accurately-measured, elongated, flexible tension members between said crown member in the lowered position thereof and said ring, expanding said column to elevate said crown member for truing said ring and for establishing the continuous outward and downward contour of the roof, and applying roof sheeting to said tension members.

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