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Advanced Collapsible Tank for Liquid Containment

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ABSTRACT

Title: Advanced Collapsible Tank For Liquid Containment

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Tanks for bulk liquid containment will be required to support advanced planetary exploration programs. Potential applications include storage of potable, process, and waste water, fuels, and process chemicals. The launch mass and volume penalties inherent in rigid tanks suggest that collapsible tanks may be more efficient. Collapsible tanks are made of lightweight flexible material and can be folded compactly for storage and transport. Although collapsible tanks for terrestrial use are widely available, a new design has been developed that has significantly less mass and bulk than existing models. Modelled after the shape of a sessile drop, this design features a dual membrane with a nearly uniform stress distribution and a low surface-to-volume ratio. It can be adapted to store a variety of liquids in nearly any environment with a constant acceleration field.

Three models of 10 L, 50 L, and 378 L capacity have been constructed and tested. The 378 L (100 gallon) model weighed less than 10% of a commercially available collapsible tank of equivalent capacity, and required less than 20% of the storage space when folded for transport.

ADVANCED COLLAPSIBLE TANK FOR LIQUID CONTAINMENT

INTRODUCTION

Tanks for the storage of liquids in bulk quantities will be needed to support advanced planetary exploration programs such as lunar base and Mars outpost. Tanks will be used for potable, process, or waste water storage, storage of hypergolics or other fuels, and perhaps storage of liquids which will themselves store thermal energy from the sun or from some other source.

The traditional solution to the problem of storing liquids in space has been the rigid tank. Rigid tanks, usually made of metal, have worked well to date. However, because of their mass and storage volume (bulk), rigid tanks present logistical problems proportional to their capacity. In the design of advanced planetary bases, the launch mass and volume penalties of tanks used for bulk liquid storage will be a significant consideration.

Collapsible tanks present certain advantages over rigid tanks. Such tanks are usually made of lighter weight nonmetallic materials, and may be folded into a compact space for transport. Although more easily transported than rigid tanks, currently available collapsible tanks are still needlessly heavy and bulky.

Clearly, collapsible tanks of reduced mass and bulk would be useful in the design of advanced planetary bases.

OBJECTIVE

The objective of this study is to improve the design of the collapsible tank by reducing its mass and storage volume (bulk). A secondary objective is to produce a proof-of-concept model of the new design which will hold 378 liters of potable water in a terrestrial (laboratory) environment.

PROPOSED CONCEPTS

Two factors contribute to the mass and bulk of currently available collapsible tanks. First, these tanks are usually fabricated from a single layer of a heavy, stiff polymer-coated fabric. Second, most flexible tanks are rectangular in shape and resemble pillows when full. This tank geometry exhibits an inherently high surface-to-volume ratio; that is, the amount of tank material per unit of tank capacity is quite high. Also, the tank geometry causes a nonuniform stress distribution on the tank membrane. A uniformly thick membrane that is not loaded uniformly implies that some areas of the membrane are overly strong, and thus contribute needlessly to both bulk and mass.

Thus the volume and weight of a collapsible tank may be minimized by selecting a more appropriate shape, and by redesigning the tank membrane materials.

Geometry Optimization

For maximum efficiency, the tank shape must provide for a minimum surface-to-volume ratio and an homogeneous or uniform membrane stress distribution. These criteria can be fulfilled by modelling the tank after a **sessile drop**. A sessile drop is the equilibrium shape of an axisymmetric fluid-liquid interface in which the gravitational force acts to press the fluid towards the substrate to which it is attached. A drop of water resting on a horizontal, flat, nonwetable surface is an example of a sessile drop. The surface tension of a sessile drop, which is equivalent to the operational membrane stress in a tank modelled after a sessile drop, is everywhere constant, thus providing an homogeneous membrane stress distribution. The surface tension of a sessile drop is also greater than zero, therefore the drop also exhibits the lowest possible surface-to-volume ratio given its physical environment. A tank modelled after a sessile drop would therefore also exhibit a minimum surface-to-volume ratio.

Because of these factors, the sessile drop would provide an excellent model for a flexible tank.

Membrane Material Redesign

A second, independent consideration is the material from which a tank is constructed. To minimize the weight per unit area of the membrane of a collapsible tank a dual membrane is proposed. The outer membrane can be of a porous fabric material which would confer the mechanical strength, and the inner membrane can be a thin polymer which would provide the impermeability. The inner membrane can be volumetrically larger than the outer membrane and would conform to it, but would not be bonded to it. Since neither material would need to fulfill the requirement for both strength and impermeability, the pool of candidate materials for each membrane would be significantly larger. Although the use of single membrane, dual property materials is certainly not rejected, the dual membrane approach is expected to allow the selection of lighter and thinner materials which will reduce mass and storage volume.

APPROACH

Geometry Optimization

Background Study

The shape of a sessile drop varies with respect to a number of parameters. Given a constant volume, these include the densities of the contained and surrounding fluids, the interfacial surface tension, and the strength of the acceleration field. Sessile drops are reviewed by Hartland and Hartley in "Axisymmetric Fluid-Liquid Interfaces" (1).

Notation for the sessile drop is shown in Figure 1. Significant variables include:

b: the radius of curvature at the apex. Note that $b=r_1=r_2$ at the apex

r_1: the radius of curvature in the meridional plane of the surface at any point

r_2: the radius of curvature orthogonal to r_1. The origin of r_2 is always on the axis of symmetry. Over any incremental area dA on the surface, the arc struck by r_2 is perpendicular to the arc struck by r_1

z: the vertical distance along the axis from the apex. Note $z = 0$ at the apex

x: the radius of the drop in the plane perpendicular to the axis of symmetry at any point z on the axis of symmetry

s: the distance on the surface of the drop from the apex to the plane of the circle defined by the radius x

θ: angle of the line tangent to the surface at position s with respect to a plane tangent to the apex

a: the area of the surface of the drop from the apex to the plane of the circle defined by the radius x

v: the volume of the drop from the apex to the plane of the circle defined by the radius x

The parameter b is the radius of curvature at the apex of a sessile drop. It implicitly defines the overall shape of the drop. Figure 2 shows the profiles of several sessile drops with respect to the log of the dimensionless form of this radius of curvature, log(B). It is convenient to refer to log(B) as the "shape factor".

The profile of a particular sessile drop is determined by numerically solving a second-order ordinary differential equation which relates z and x. Hartland and Hartley utilized a fourth-order Runge-Kutta method coded in Fortran IV for this purpose. Data tables for selected values of log(B) from -2 to +3 are provided. Table I gives the data for the sessile drop with shape factor log(B) = 0.65 by way of example.

An important feature of Hartland and Hartley's work is that the data in each table is provided in dimensionless form by using a factor c, where c is the product of the density difference between the contained liquid and the surrounding fluid and the local acceleration field, divided by the surface tension

$$c = \frac{\Delta\rho g}{\sigma} \qquad [m^{-2}]$$

To recover actual data, each linear value X_i provided in the tables must be divided by $c^{1/2}$ to obtain the actual value x_i:

$$x_i = \frac{X_i}{c^{1/2}}$$

Correspondingly, area values must be divided by c, and volumes by $c^{3/2}$.

Shape Selection

The sessile drop shape best suited to flexible tank design must be determined by performing a trade study. Parameters of interest include:

Pressure: Some minimum pressure is required to fully fill a flexible tank. The lower this pressure is the easier it will be to fill the tank. The maximum pressure, as measured at the base of the tank, is

$$p = \Delta\rho g\left(\frac{2}{bc}+z\right)$$

where z in this case is the maximum height of the tank. Using dimensionless parameters this equation becomes

$$p = \frac{\Delta\rho g}{c^{1/2}}\left(\frac{2}{B}+Z\right)$$

Membrane Stress: To reduce the mass and storage volume of a collapsible tank, membrane stress, which may be equated to the surface tension of a sessile drop, must be minimized. This allows lighter, less bulky materials to be selected for the membrane. Membrane stress is readily calculated. Since

$$v = \frac{V}{C^{3/2}}$$

where v is the selected capacity of the tank in m^3, and V is the dimensionless volume at θ=180 associated with the selected drop shape. Then

$$C = \frac{V^{2/3}}{v^{2/3}}$$

and, since

$$C = \frac{\Delta\rho g}{\sigma}$$

then

$$\sigma = \frac{\Delta\rho g}{V^{\frac{2}{3}}} v^{\frac{2}{3}}$$

Surface-to-Volume Ratio: Minimizing the surface-to-volume ratio of a collapsible tank reduces mass and bulk. Hartland and Hartley provide dimensionless values in their data tables for both the surface area and volume of a sessile drop. As noted above, the actual volume v is related to the dimensionless V. Similarly, the actual surface area is related to the dimensionless surface area by

$$s = \frac{S}{C}$$

Thus the actual surface-to-volume area may be found by

$$\frac{s}{v} = \frac{S}{V} C^{1/2}$$

Note that Hartland and Hartley's treatment of the surface area considers only the area of the curved surface and does not include the area in contact with the substrate (footprint area). This footprint area needs to be included if the sessile drop is to be used as a model for a collapsible tank. The surface area thus becomes

$$s = \frac{S}{C} + \pi \left(\frac{X_{\theta=180}}{C^{\frac{1}{2}}} \right)^2$$

As previously noted, the volume would remain

$$v = \frac{V}{C^{3/2}}$$

and the surface-to-volume ratio can be readily calculated.

Dimensions: The height of the tank, its maximum diameter, and its footprint diameter must be considered in designing a sessile drop tank for a particular application. These linear parameters are obtained in dimensionless form from the data tables provided by Hartland and Hartley as previously discussed.

Modelling Method

Gore Design

The smoothly curved surface of a sessile drop cannot be exactly duplicated by connecting flat pieces of fabric. Dividing the surface into a finite number of identical gores (as in a parachute) is an obvious approach. The shape of these gores may be determined as follows:

Referring to Figure 3, for the selected number of gores n, the central angle in the plane of the circle defined by the radii x which intersect the gore borders is

$$\measuredangle = \frac{2\pi}{n}$$

The secant line sl can be drawn and is found by

$$sl = 2x\sin\frac{\pi}{n}$$

Then, the value for r_2 is calculated from x and θ associated with the point s

$$r_2 = \frac{x}{\sin\theta}$$

And, using r_2 and the secant line sl, the angle α in the plane of r_2 and sl is determined by

$$\frac{sl}{2r_2} = \sin(\frac{\alpha}{2})$$

or

$$\alpha = 2\arcsin(\frac{sl}{2r_2})$$

Substituting in the values previously obtained for r_2 and sl

$$\alpha = 2\arcsin(\frac{2x\sin\frac{\pi}{n}}{\frac{2x}{\sin\theta}})$$

and simplifying

$$\alpha = 2\arcsin(\sin\frac{\pi}{n}\sin\theta)$$

Now, if r_2 is assumed to be the radius of a circle over an incremental $d\alpha$ in the plane defined by itself and the secant line, the gore width w on the surface is related to the circumference of that circle by

$$\frac{w}{2\pi r_2} = \frac{\alpha}{2\pi}$$

where α is in radians. This simplifies to

$$w = \alpha r_2$$

Substituting the values previously obtained for α and r_2 gives

$$w = \frac{2x\arcsin(\sin\frac{\pi}{n}\sin\theta)}{\sin\theta}$$

To define the boundary of a gore, this value, divided in half, is used as the radius of an arc drawn at each point s along the axis of gore symmetry. Once the arcs are in place, they may be joined by line segments tangent to each arc to define the gore edges.

As noted, this method only approximates the actual curved surface. However, in the limit as the number of gores approaches infinity, the shape does become the ideal surface.

Other methods of approximating a similar curved surface are presented in reference 2.

Correction For Stress

A collapsible tank modeled after a sessile drop will have a specific optimum shape. The outer membrane of the tank may experience stress and exhibit strain. Failure to correct for membrane stress can result in deformation of the tank from optimum shape and induce a nonuniform stress distribution.

The construction dimensions for the component gores of the outer membrane of a tank may therefore need to be corrected for the predicted level of membrane stress. This may be done by determining the tensile modulus of the material and applying to each linear dimension of the gore a correction coefficient based on that tensile modulus.

Tensile Modulus Testing

The tensile modulus relates stress to strain

$$Y = \frac{stress}{strain}$$

or

$$\frac{\Delta L}{L} = \frac{1}{Y}\frac{F}{A}$$

where Y is Young's Modulus with units in N/m^2, $\Delta L/L$ is the strain, or change in length per unit original length, and F/A is the stress applied in N/m^2. Although this equation applies to fabric without change, it is convenient to modify the equation to reflect the symmetry of the tested items. Where the material is of a constant thickness the equation for tensile modulus can be approximated by

$$\frac{\Delta L}{L} = \frac{1}{Y_m}\frac{F}{w}$$

where Y_m is the modulus in N/m and w is the width of the strip under test in meters. This equation may be solved for Y_m

$$Y_m = \frac{F}{w}\frac{L}{\Delta L}$$

which will allow determination of this value from experimental results.

Stress Correction Coefficient

Given the experimentally determined value of Y_m, a stress correction coefficient can be developed for the linear construction dimensions.

As noted, the equation for the tensile modulus of the membrane material can be written

$$\frac{\Delta L}{L} = \frac{1}{Y_m}\frac{F}{w}$$

The left hand side of this equation is the ratio of the stress induced change in length ΔL to the initial unstressed length L. The right hand side contains a term for stress in force per unit width. This stress F/w is the uniform envelope membrane stress which is equivalent to the surface tension of a sessile drop, σ, or

$$\frac{F}{w} = \sigma$$

so the equation for tensile modulus becomes

$$\frac{\Delta L}{L} = \frac{1}{Y_m}\sigma$$

Adding unity to both sides yields

$$\frac{L}{L} + \frac{\Delta L}{L} = \frac{1}{Y_m}\sigma + \frac{Y_m}{Y_m}$$

Now let L_s be the desired final, stressed, dimension. It is the combination of the initial unstressed length L and the change in length due to stress ΔL,

$$L_s = L + \Delta L$$

Therefore

$$\frac{L_s}{L} = \frac{\sigma + Y_m}{Y_m}$$

or

$$L = L_s \frac{Y_m}{\sigma + Y_m}$$

This equation states that a **corrected** unstressed dimension L is equal to the product of the desired, final, stressed length L_s and the correction factor F_c, where

$$F_c = \frac{Y_m}{\sigma + Y_m}$$

As the membrane stress σ increases the stress correction coefficient decreases, which in turn shortens the linear dimensions to which it is applied.

<u>Correction For Sewing Take-Up</u>

The fabric joints which form the outer membrane from component pieces may be made by sewing. Generally, sewing a seam can shorten its linear dimension by up to ten percent, although this will vary with fabric type, stitch selected, number of stitches per inch, thread tension, operator technique and other factors (3). The extent of this take-up must be determined, and a correction factor developed.

Sewing Take-up Testing

Fabrication take-up may be determined experimentally by sewing a seam of the proposed type along a doubled piece of membrane fabric. Take-up may be calculated by

$$T_f = \frac{L_f}{L_o}$$

where 100% x T_f would be the percent of the original length remaining, L_o the original length of the coupon, and L_f the final length of the coupon after sewing.

Sewing Take-up Correction Coefficient

Based on the data determined above, one method of compensating for sewing take-up can be to apply a correction factor $1/T_f$ to the linear gore construction dimensions.

Computer Design Program

The dimensionless data for the selected sessile drop shape from reference 1, plus factors for material elasticity and sewing take-up, and any other corrections to the modelling method can be readily incorporated into a computer program. From input of the desired capacity of the tank in liters, the theoretical parameters of the fully stressed tank and the corrected data required to manufacture a gore pattern can be produced.

Membrane Material Redesign

Adopting the dual membrane envelope design using almost any appropriate materials is expected to reduce tank storage volume (bulk) and mass. However, further reductions in mass and bulk could be obtained by selecting the best material for each of the two membranes. This selection would be based on a trade study of available materials and take into account the intended use and environment of the tank.

Outer Membrane Material

Parameters for any trade study of materials for the outer membrane of a tank will include, at a minimum, mechanical strength, tensile modulus, dimensional stability, weight, workability, and cost. Additional parameters relevant to the specific application of the tank such as vacuum tolerance, abrasion, radiation, and puncture resistance, also need to be considered. No single material will be suitable for all applications.

An extensive selection of candidate materials suitable for terrestrial applications exists. These materials include nylon, dacron, kevlar, nomex, and spectra, as well as hybrid materials woven from a combination of these materials.

Inner Membrane Material

Selection of the inner membrane must be made primarily on the basis of the chemical characteristics of the contained fluid and the physical characteristics of the environment the tank is in. The inner membrane must not chemically react with the contained fluid. Also, the inner membrane material should not affect the tank contents (e.g., the leaching of organic materials from a polymer membrane into potable water.) The inner membrane must also be unaffected by the external physical environment of the tank (temperature, humidity, etc) to the extent that it is not protected from these effects by the outer membrane.

Candidate materials for the inner membranes of flexible tanks intended to hold potable water are numerous, and include polytetrafluoroethylene, polyethylene, and possibly polypropylene.

Model Testing

Profile Testing

To evaluate a model collapsible tank for proper shape, its profile while full can be compared to its theoretical profile using a simple photogrammetric technique. First, a silhouette of the theoretical shape can be photographed by a camera equipped with slide film and a telephoto lens. The long focal length lens would provide a relatively flat field, and the camera-to-subject distance could be adjusted so the image filled the frame. Then, without moving the camera, the silhouette could be replaced by the filled tank, which would also be photographed. The two slides could then be projected, and comparative measurements taken.

Membrane Stress Testing

Detailed measurements of strain over the surface of the tank can be made using attached strain gauges. A simpler but less accurate estimate of stress levels can be made by visually examining the surface of the tank for strained seams, warping, or any other evidence of a nonuniform membrane stress distribution.

Capacity Testing

Capacities of a model can obtained by filling it, then measuring the amount of water it contains by weighing or by measuring the fluid as it is decanted. Maximum capacity is defined as the amount of liquid contained by the tank when the tank pressure is equal to the calculated theoretical pressure.

Mass and Storage Volume (Bulk) Testing

The mass of a model tank can be readily obtained using a laboratory scale. Storage volume, or bulk, of any flexible device is more difficult to measure accurately, but estimates can be obtained by measuring the linear dimensions of the folded tank or by some similar method.

To evaluate any reduction in mass and bulk, a commercially available flexible tank of the same capacity as a model of the new design could be obtained for use as a control.

MATERIALS & METHODS

Three model collapsible tanks of 10 L, 50 L, and 378 L capacity were constructed and tested in the course of this study. These models were designed to hold potable water in a terrestrial gravity field. A description of the materials and methods used may be found in Appendix A.

RESULTS AND DISCUSSION

Geometry Optimization

Sessile drops occur in an infinite variety of shapes. Given a constant volume, the shape of a sessile drop will vary with respect to three parameters. These are
1) the densities of the contained and surrounding fluids,
2) the strength of the local gravitational field, and
3) the interfacial surface tension. (Note that in a collapsible tank modelled after a sessile drop, surface tension is replaced by the operational membrane stress.)

In this study, models were constructed to hold potable water in a terrestrial gravity field, thus items 1 & 2 above were known.

The first model tank was intended to hold ten liters. The theoretical effects of varying the shape of the tank on various parameters were evaluated. Figure 4 shows membrane stress, the surface-to-volume ratio, and maximum tank pressure with respect to the shape factor log(B). The more spherical, or prolate, drop shapes, which have lower values for log(B), are to the left on the graph, the flatter or more oblate drops, which have higher values for log(B), are to the right.

Membrane Stress: The curve showing the levels of membrane stress with respect to shape factor in the ten liter tank is also shown. Again, it may be helpful to consider this parameter as the amount of surface tension water would have to have for a ten liter drop of water to assume the associated shape. The more spherical shapes require a higher level of membrane stress (or surface tension), while the flatter shapes require much lower levels. At log(B) = 0.65 the value is 55.3 N/m (.316 lb_f/in).

Surface-to-Volume Ratio: The behavior of the surface-to-volume ratio with respect to sessile drop shape is in almost exact opposition to the membrane stress curve. The more spherical shapes have the lower surface-to-volume ratios. This ratio increases rapidly as the shape of the drop flattens.

Pressure: The minimum pressure required to fully fill a tank modelled on a sessile drop is the highest for the most spherical shapes. This minimum pressure decreases markedly as the shape of the sessile tank becomes flatter, that is, as log(B) increases. For the shape where log(B) = 0.65 this pressure is 1737 Pa (.252 lb_f/in^2), or about seven inches of water pressure.

Note: All three of the above curves behave monotonically. There are no local minima or points of inflection which invite further investigation.

Dimensions: There appear to be no theoretical constraints to model tank dimensions. In this study, however, to minimize costs and utilize laboratory space more effectively, models with very large capacities were not considered.

Based on the above, the sessile drop with shape factor log(B)=0.65 was arbitrarily selected as a model for the tanks constructed in this study. This sessile drop shape was chosen mostly to limit membrane stress and thus minimize the chance of catastrophic failure of a model tank in the laboratory.

Materials Selection

The materials used in the three models constructed in the course of this study are described in Appendix A (Materials and Methods.)

Materials Testing

Tensile Modulus Testing

The material used for the outer membrane of the two smaller models was tested over a stress level range of approximately 350 to 1400 N/m (2.0 to 8.0 lb_f/in). The tensile modulus ranged from about 23,900 to 35,000 N/m (137 to 200 lb_f/in). The results of this testing are shown in Figure 5. The quality of the data is poor. This is believed due to the crude nature of the available test equipment and environment. Tensile modulus testing of fabric is difficult to perform under the best conditions. Clamp alignment problems, undetected slippage of the fabric, and even environmental conditions can affect the results.

The data nevertheless provided some indication of the response of the fabric to stress. The computer-generated algorithm relating stress to strain was therefore incorporated into the collapsible tank computer design program.

The dacron polyester used for the outer membrane of the 378 L model was tested only at the predicted stress level of 623 N/m (3.6 lb_f/in). The tensile modulus at this level was 95,888 N/m (548.0 lb_f/in).

Sewing Take-Up Testing

The sewing take-up test performed with the outer membrane material used for the 10 L and 50 L models showed that a seam retained 99.8% of its original length after sewing. For the dacron polyester used for the outer membrane of the 378 L model, the test results were the same. Accordingly, a sewing take-up correction coefficient of $1/T_f = 1.002$ was incorporated into the computer design program.

Model Testing

Profile Testing

The results of the photogrammetric profile testing are given in Figure 6. The data are reported as ratios of the dimensions as measured from the projected slides of the models to the corresponding dimensions measured on the projected slides of the corresponding silhouettes. In the dimensions that were readily measured with accuracy such as total height (A) and maximum diameter (E) good agreement was obtained. The footprint diameter (D) was easy to obtain from the silhouettes because they contained vertical marks denoting this dimension, but was more difficult to obtain on the model because the surface of the membrane contacted the test fixture platform at a less readily determined point of tangency. The most significant departure from the theoretical shape is seen in the vertical height of the mark on the gores of the model at θ=90 (point of maximum diameter.) Although the total height of the model was in reasonably good agreement with the silhouette, the mark at θ=90 was much higher on the model than on the silhouette. This is reflected by dimensions C, which were greater than 1.0, and B, which were generally less than 1.0. The reason for this is probably related to the necessity of approximating a 3-dimensional curved surface using flat panels of material. In support of this, note that the deviation in dimension C (View #2) decreases as the number of gores used to construct the models increases from 8 (10 L model), to 12 (50 L model), to 16 (378 L model.)

Membrane Stress Evaluation

The 50 L model exhibited a small amount of wrinkling on some gores near the apex. Wrinkles occurred perpendicularly to the axis of a gore. The seams joining the gores are quite close to each other in this area, which could have allowed dimensional or sewing tolerance errors to become evident. A similar situation at or near the maximum circumference of the tank might not be so obvious since seams at that point are more distant from each other.

The 378 L model showed an unusual concavity in each gore (scalloping) at the point of maximum diameter. This phenomenon may indicate a nonuniform stress distribution. This was not seen on either of the two smaller models, and may be a function of the higher tensile modulus of the material, which was about three times that of the tensile modulus of the material used in the smaller models.

Capacity Testing

The capacity of the 10 L and 50 L model tanks was measured, and the results are given in Table II. Results agree with theoretical predictions within plus or minus six percent worst case (the smallest tank.)

Mass and Storage Volume (Bulk) Testing

Weights and estimates of the storage volume (bulk) for the three model tanks and one control tank are shown in Table

II. The 378 L tank modelled after a sessile drop had 8.4% of the mass and required only 18% of the storage volume of the commercially available collapsible tank.

It should be noted, however, that the commercially available tank was fabricated to meet or exceed the military specifications MIL-T-53029B (4). This specification calls for the ability to resist punctures, limited overpressure, exposure to weather, and contains other design constraints (imposed at least in part because of the inherent inefficiency of the overall design.) The 378 L model developed in this study was not tested to determine if the provisions of this military specification were met.

CONCLUSIONS

It has been demonstrated that dual membrane collapsible tanks for liquid containment can be designed and constructed using as a model a sessile drop. Three models (of 10 L, 50 L, and 378 L capacities) to hold potable water in the terrestrial gravitational field have been built and successfully tested. The 378 L test model weighed only 8.4% of the weight of a commercially available model of the same capacity, and required only 18% of the space needed to store the commercially available model (empty.)

RECOMMENDATIONS

Further development of the concepts demonstrated in this investigation is possible. The collapsible tank is the interface between the contained liquid and surrounding fluid. Thus, in all cases, consideration must be given to:

1) external environmental characteristics (e.g., temperature, pressure, gravitational field, environmental hazards such as radiation, chemical reactivity, or abrasion)

2) contained liquid characteristics (e.g., volume required, density, chemical reactivity, minimum fill pressure)

This collapsible tank design presented here was developed to support the liquid containment needs inherent to advanced planetary exploration programs. Terrestrial applications of this technology exist, however. Examples could include:

1) temporary storage of oil for oil spill rapid response teams. Although the design presented here is intended to rest on land, it may be readily adapted to float on water, or any fluid whose density is greater than the density of the contained fluid.

2) temporary storage of hazardous materials for industrial

"hazmat" teams.

3) storage of gasoline, aviation fuel, lubricant, or potable water containment for the military. The reduced weight and bulk of this design would simplify logistics (transport, air-drop, etc.)

4) temporary storage of potable water following contamination of municipal water supplies or damage to distribution systems following a natural disaster.

5) storage of industrial chemicals or biological mixtures under anaerobic conditions (zero headspace.)

Collapsible tanks are manufactured by approximately twenty companies in the United States at this time. Tanks of this new design could be utilized in any application currently supported by the tanks produced by these companies.

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Table I. Dimensionless parameters for the sessile drop having shape factor log(B)=0.65, from reference 1.

LOG10B= .65 B=4.46684E+00

ANGLE θ	ARC LENGTH S	X	Z	AREA	VOLUME
5	3.82755E-01	3.82276E-01	1.65391E-02	4.59961E-01	3.81047E-03
10	7.29949E-01	7.26436E-01	6.15056E-02	1.67000E+00	5.16704E-02
15	1.02786E+00	1.01727E+00	1.25613E-01	3.30282E+00	2.09714E-01
20	1.27973E+00	1.25750E+00	2.01036E-01	5.10364E+00	5.20674E-01
25	1.49398E+00	1.45547E+00	2.82778E-01	6.93053E+00	9.96879E-01
30	1.67867E+00	1.61933E+00	3.67863E-01	8.71532E+00	1.63167E+00
35	1.84018E+00	1.75558E+00	4.54488E-01	1.04284E+01	2.40902E+00
40	1.98331E+00	1.86917E+00	5.41498E-01	1.20588E+01	3.30889E+00
45	2.11166E+00	1.96383E+00	6.28109E-01	1.36048E+01	4.30993E+00
50	2.22793E+00	2.04242E+00	7.13751E-01	1.50687E+01	5.39088E+00
55	2.33419E+00	2.10714E+00	7.97989E-01	1.64544E+01	6.53125E+00
60	2.43206E+00	2.15975E+00	8.80473E-01	1.77666E+01	7.71171E+00
65	2.52280E+00	2.20168E+00	9.60911E-01	1.90102E+01	8.91430E+00
70	2.60742E+00	2.23409E+00	1.03905E+00	2.01898E+01	1.01226E+01
75	2.68674E+00	2.25797E+00	1.11467E+00	2.13095E+01	1.13216E+01
80	2.76144E+00	2.27417E+00	1.18757E+00	2.23734E+01	1.24983E+01
85	2.83208E+00	2.28341E+00	1.25758E+00	2.33850E+01	1.36409E+01
90	2.89912E+00	2.28636E+00	1.32453E+00	2.43476E+01	1.47394E+01
95	2.96295E+00	2.28360E+00	1.38828E+00	2.52642E+01	1.57855E+01
100	3.02391E+00	2.27566E+00	1.44870E+00	2.61375E+01	1.67723E+01
105	3.08228E+00	2.26305E+00	1.50567E+00	2.69699E+01	1.76945E+01
110	3.13831E+00	2.24622E+00	1.55910E+00	2.77638E+01	1.85480E+01
115	3.19222E+00	2.22561E+00	1.60889E+00	2.85213E+01	1.93304E+01
120	3.24418E+00	2.20164E+00	1.65498E+00	2.92442E+01	2.00401E+01
125	3.29437E+00	2.17469E+00	1.69730E+00	2.99343E+01	2.06770E+01
130	3.34293E+00	2.14515E+00	1.73581E+00	3.05933E+01	2.12417E+01
135	3.38997E+00	2.11338E+00	1.77050E+00	3.12228E+01	2.17359E+01
140	3.43562E+00	2.07975E+00	1.80133E+00	3.18241E+01	2.21619E+01
145	3.47997E+00	2.04458E+00	1.82833E+00	3.23988E+01	2.25228E+01
150	3.52311E+00	2.00821E+00	1.85151E+00	3.29481E+01	2.28220E+01
155	3.56512E+00	1.97096E+00	1.87091E+00	3.34734E+01	2.30634E+01
160	3.60607E+00	1.93314E+00	1.88658E+00	3.39757E+01	2.32512E+01
165	3.64604E+00	1.89504E+00	1.89860E+00	3.44564E+01	2.33897E+01
170	3.68508E+00	1.85694E+00	1.90706E+00	3.49165E+01	2.34833E+01
175	3.72324E+00	1.81911E+00	1.91204E+00	3.53573E+01	2.35364E+01
180	3.76059E+00	1.78181E+00	1.91368E+00	3.57798E+01	2.35531E+01

Table II. Mass, storage volume, and capacities of the three model tanks and the control tank (ATL) used in this study.

Tank	Mass (kg)	Storage Volume (Bulk) (L)	Capacity (L)
10 L	0.034	0.3	10.6
50 L	0.096	0.6	49.3
378 L	0.960	5.0	ND
378 L (ATL)	11.4	28.0	ND

ND - Not determined

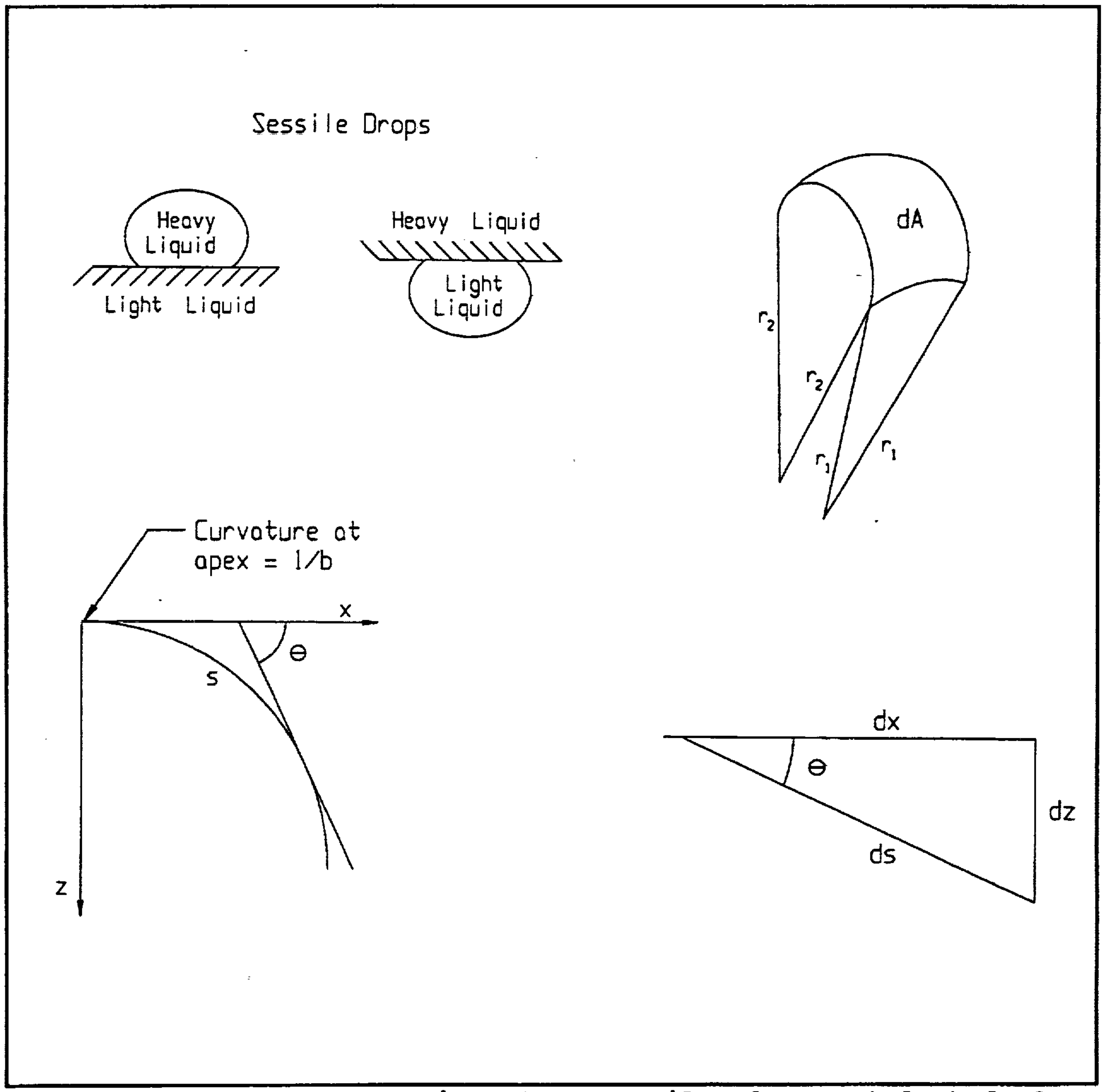


Figure 1. General notation for sessile drops (adapted from reference 1)

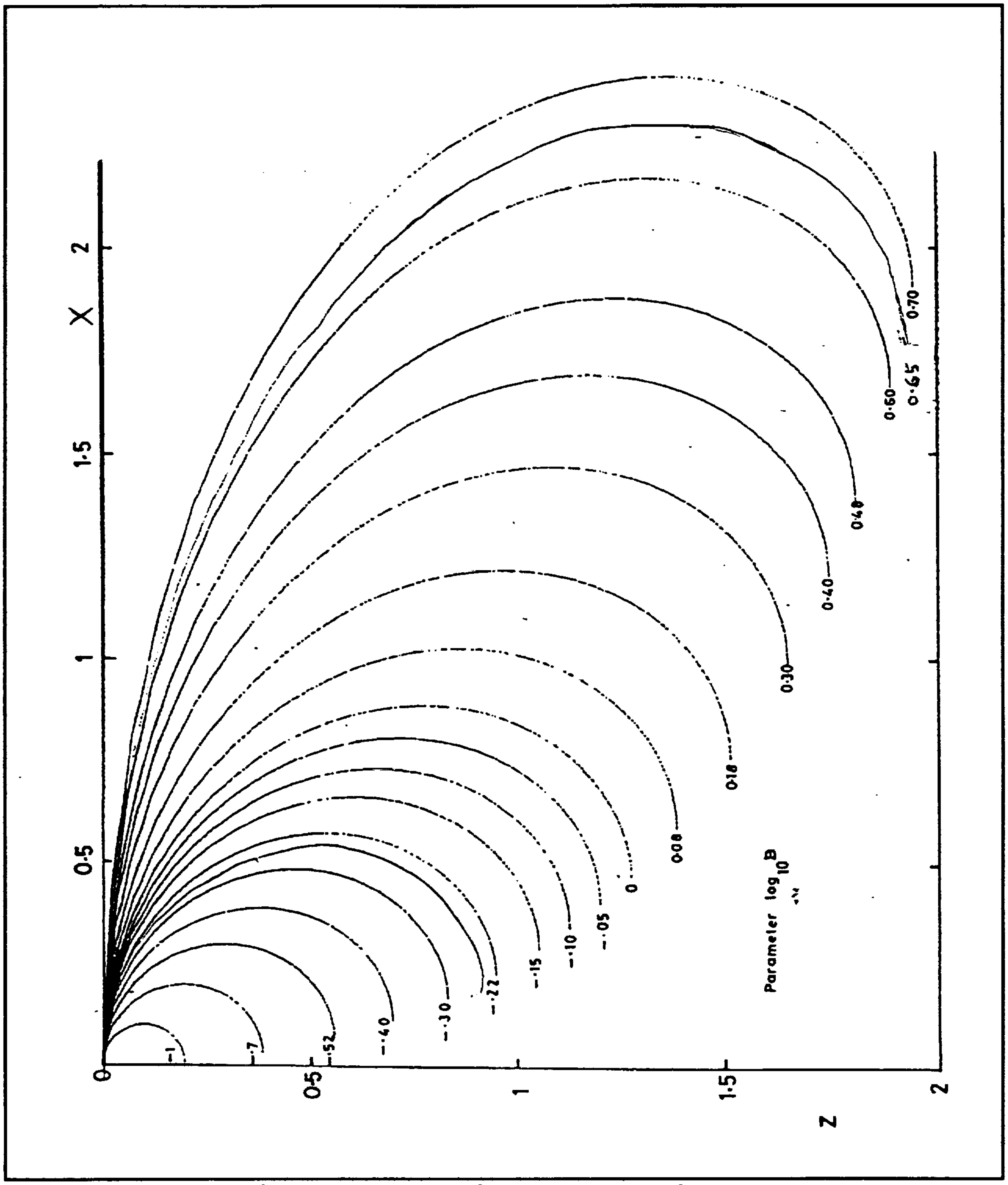


Figure 2. Profiles of sessile drops with respect to the dimensionless radius of curvature at the apex (log(B)) from reference 1.

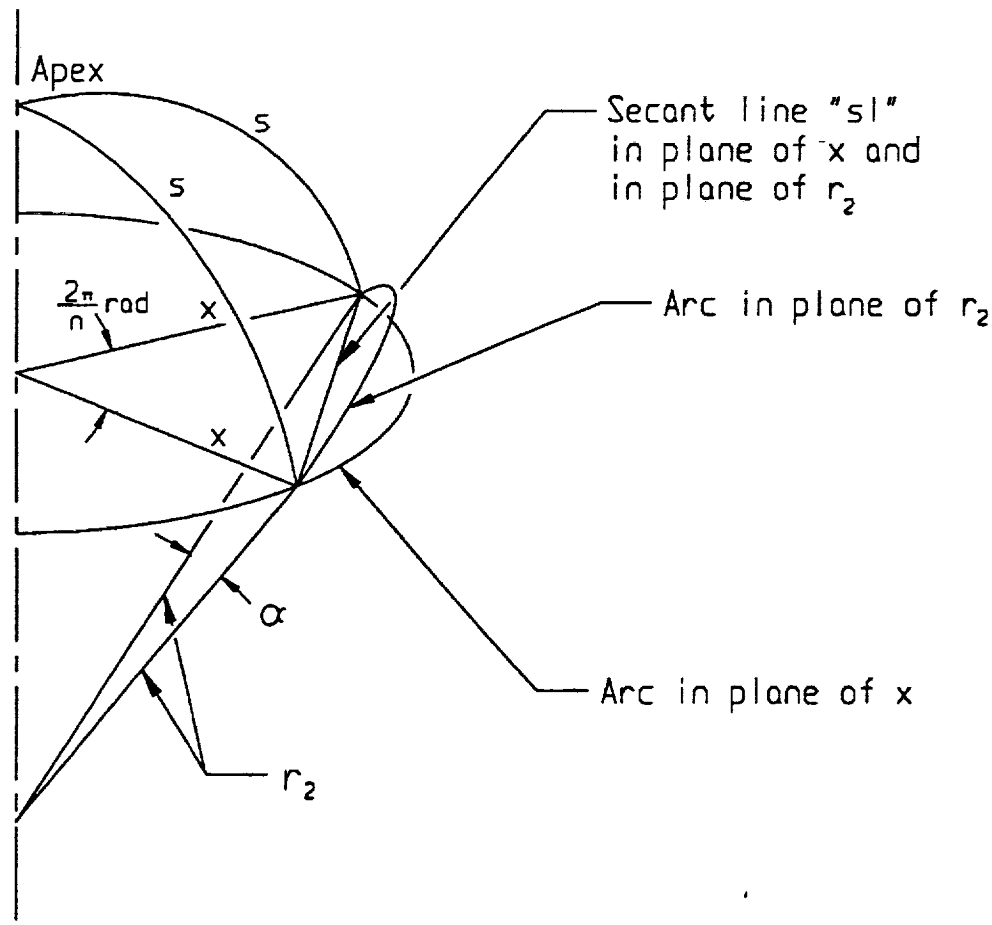


Figure 3. Parameters for developing the gore pattern. The plane created by r_2 through $d\alpha$ is orthogonal to the surface of the drop. The plane created by x through any angle $2\pi/n$ is orthogonal to the axis of symmetry.

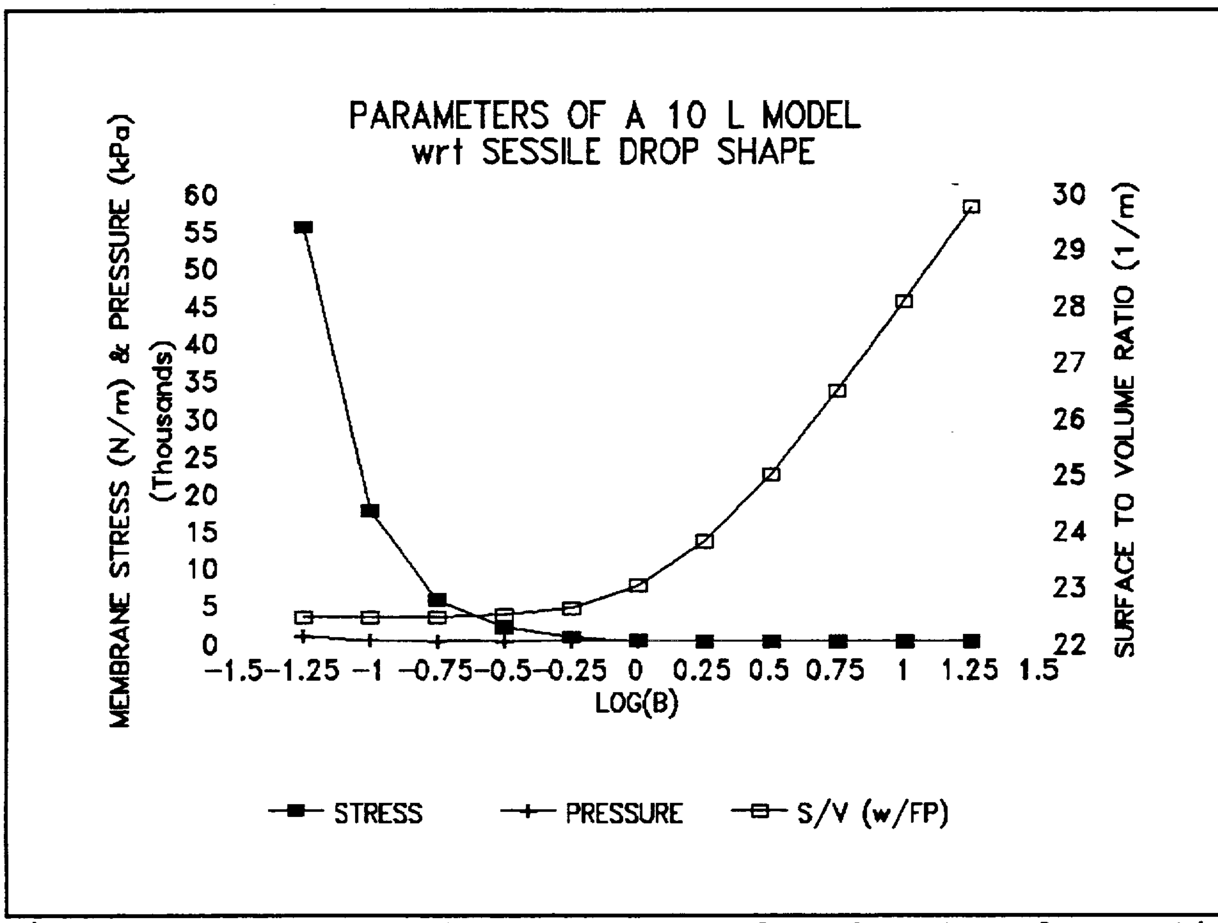


Figure 4. Pressure, membrane stress, and surface-to-volume ratio of a 10 L collapsible tank with respect to tank shape.

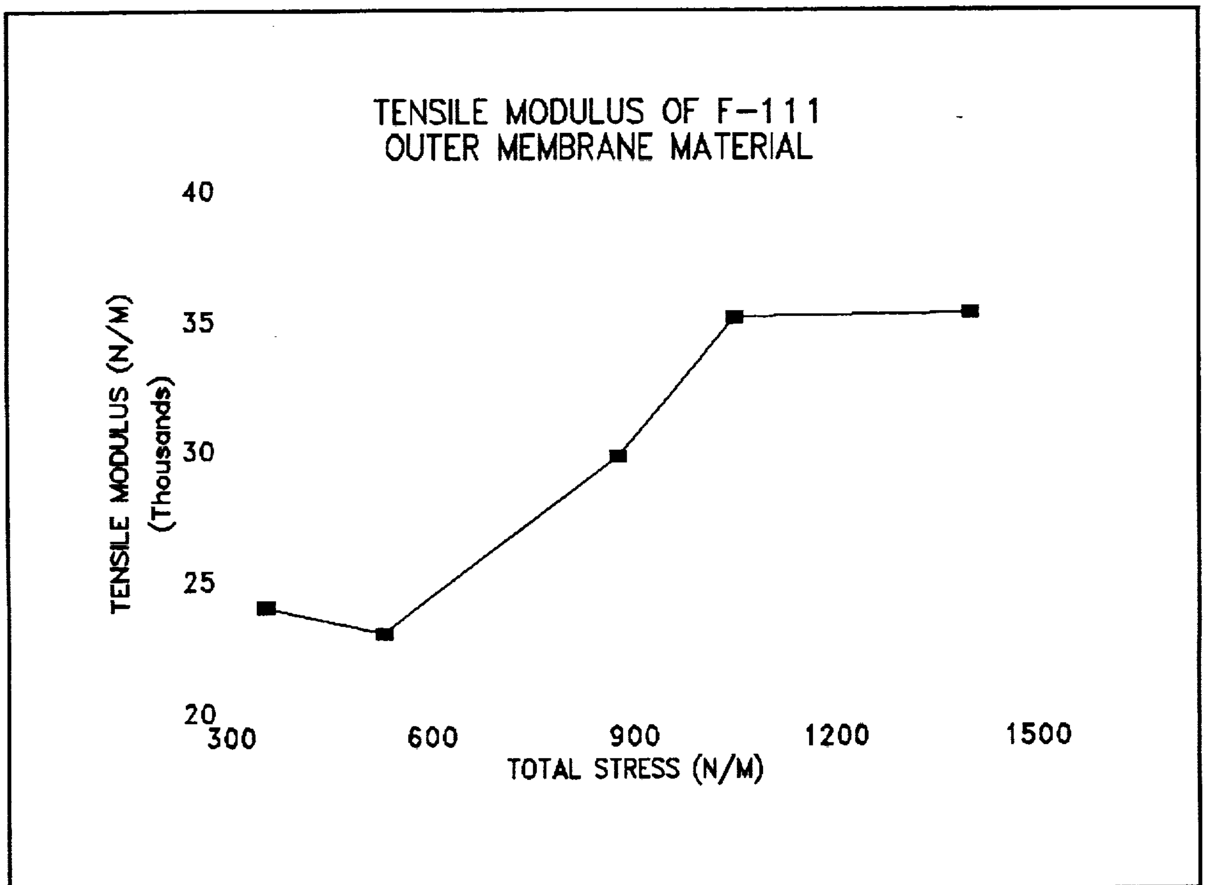
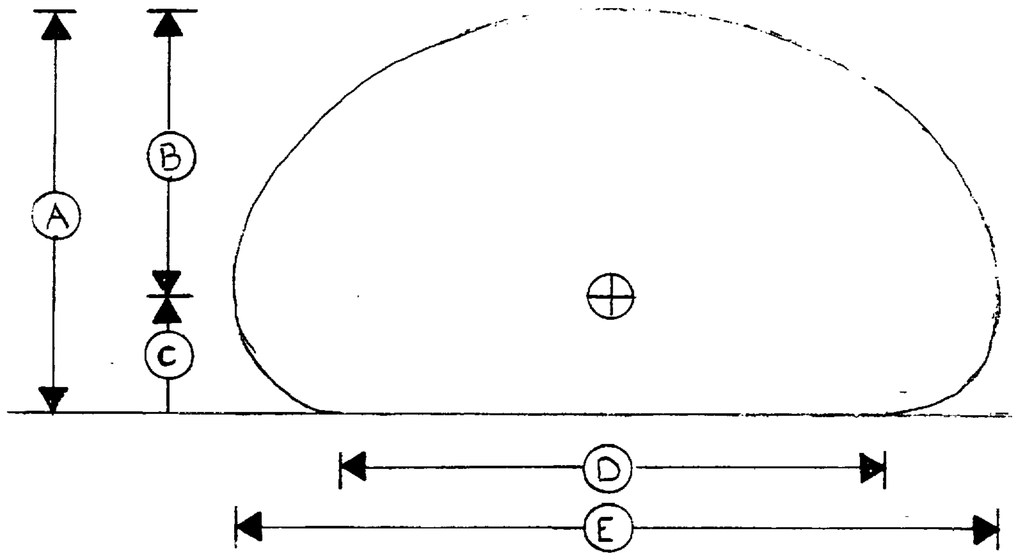


Figure 5. Tensile modulus of F-111 nylon material with respect to stress.



Dimension	10 L Model		50 L Model		378 L Model
	View #1	View #2	View #1	View #2	View #2
A	1.01	1.02	1.04	1.04	.98
B	.94	.97	.93	1.03	.94
C	1.22	1.14	1.29	1.11	1.05
D	1.06	1.12	1.06	1.06	1.02
E	.99	1.01	1.01	1.01	1.04

Figure 6. Results of the photogrammetric evaluation of the three models constructed in this study. Values given are the ratios of the measured to the theoretical dimensions shown on the diagram. View #1 indicates the model was oriented with a gore centerline facing the camera. View #2 indicates that a gore seam was facing the camera. The 378 L model was too large to be rotated when full, thus only View #2 was obtained.

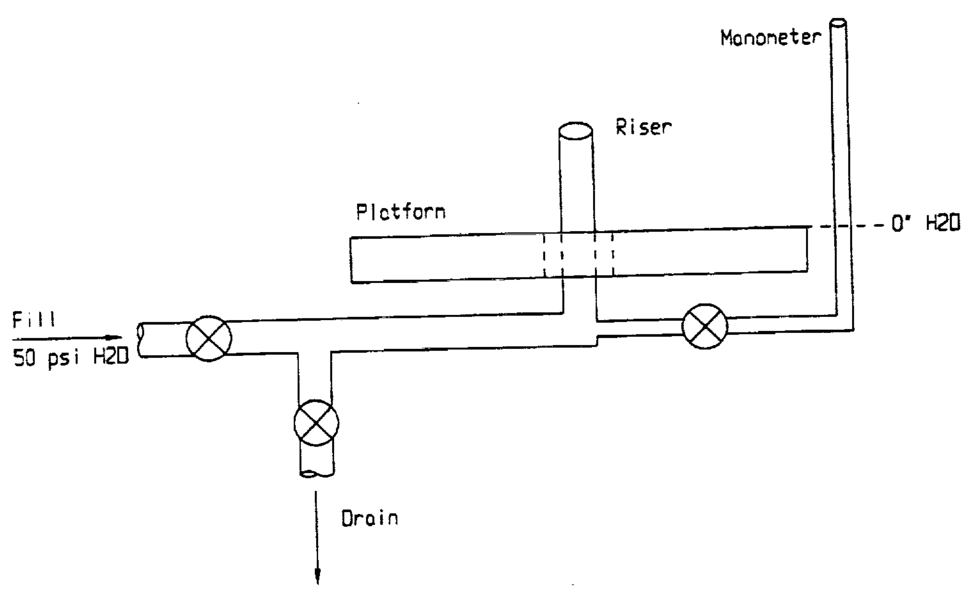


Figure 7. Simplified sketch of the two test fixtures used in this study.

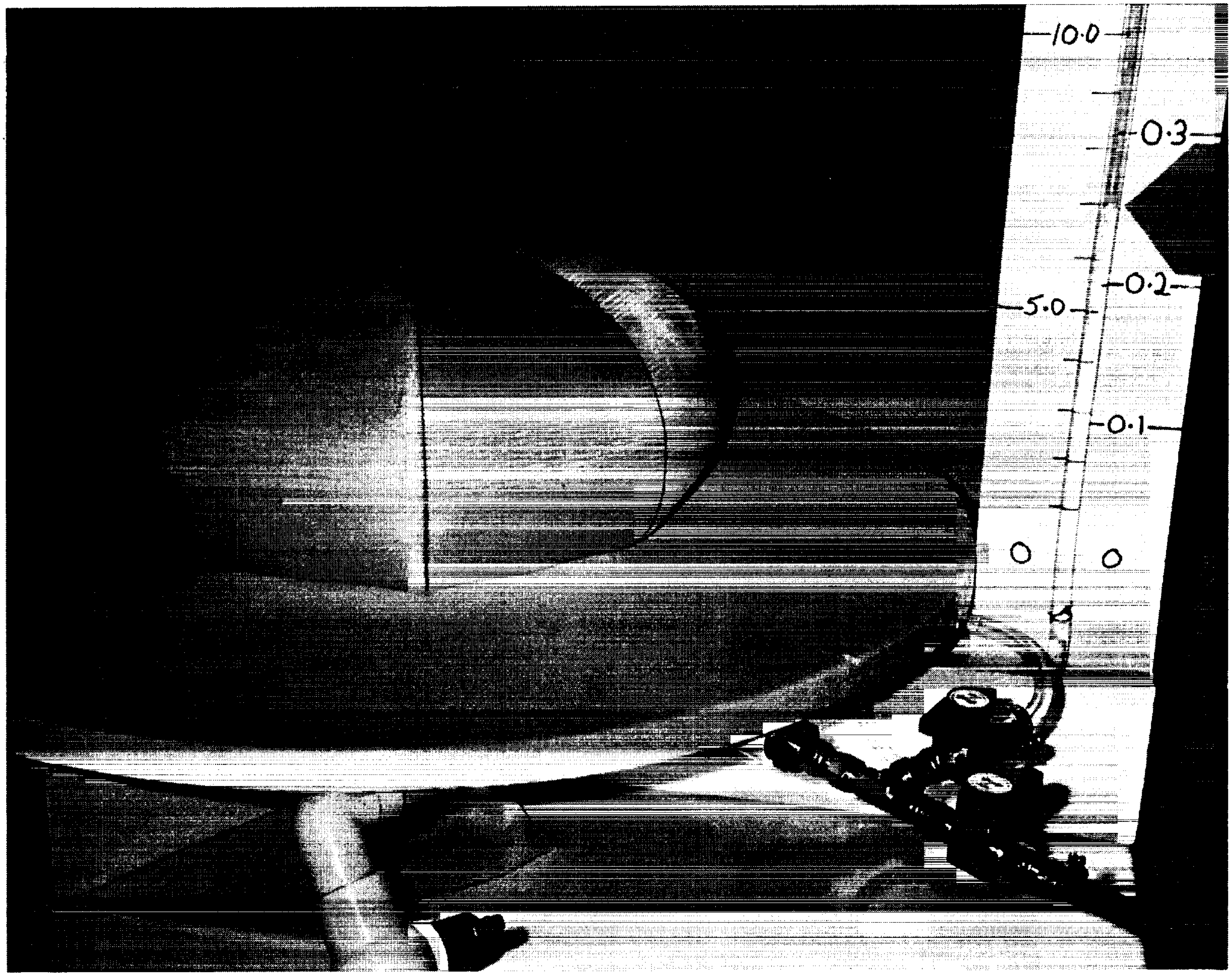


Figure 8. The 10 L collapsible tank model is shown installed on the smaller test fixture. The associated plumbing, including the open tube manometer used for measuring pressure, is clearly visible.

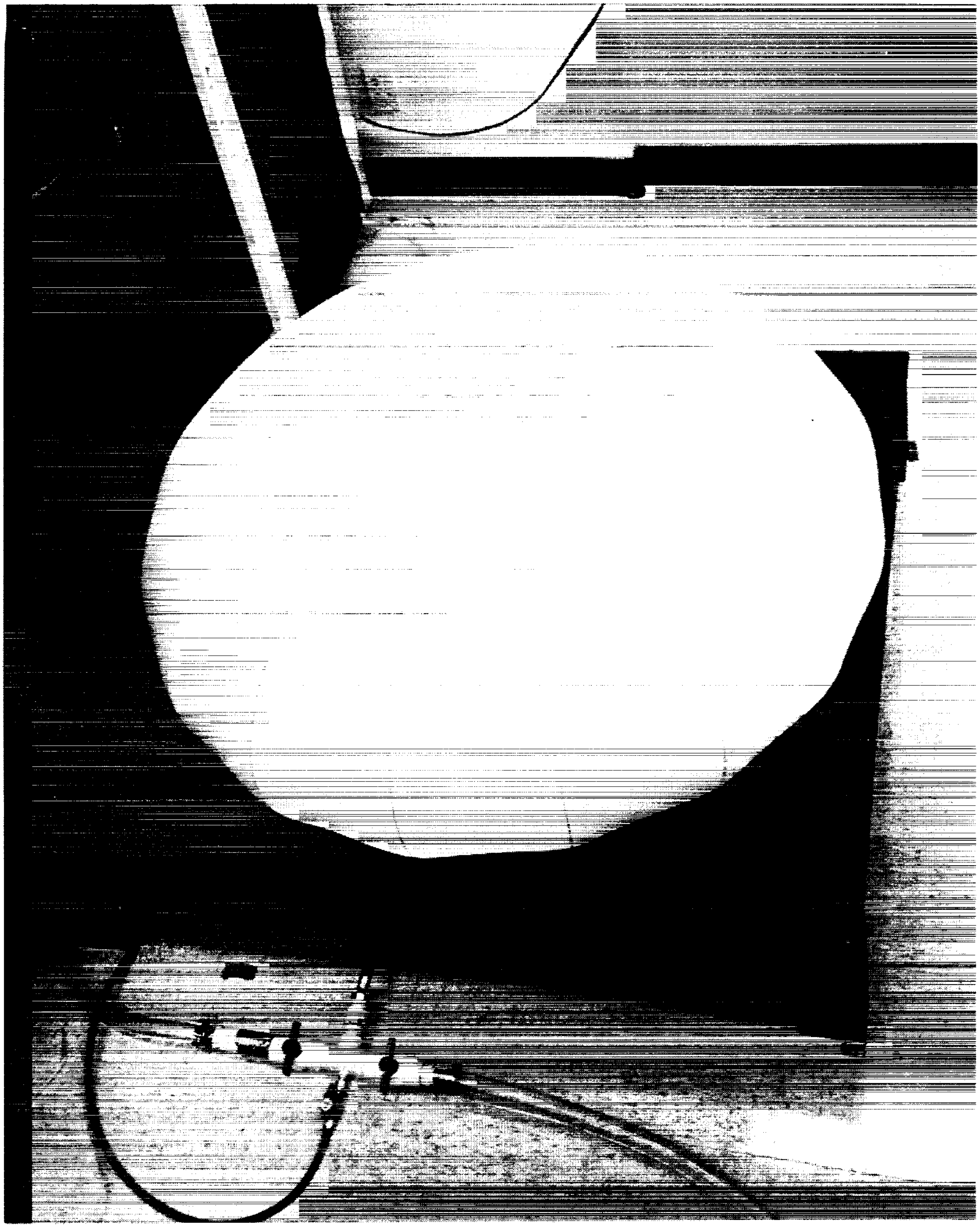


Figure 9. The largest collapsible tank model built in this study, designed to hold 378 L (100 gal), is shown here installed on the larger test fixture. This tank, when empty, weighed less than 10% of a commercially available model of the same capacity, and could be stored in less than 20% of the space.

REFERENCES

1. Hartland, S., and Hartley, R. W., Axisymmetric Fluid-Liquid Interfaces, Elsevier Scientific Publishing Company, New York, NY, 1976.

2. Flanagan, D. T., and Hopkins, R. C., Advanced Underwater Lift Device, NASA-CR-185709, March 1993. Available from the National Technical Information Service, Springfield, VA.

3. Poynter, D., The Parachute Manual, Volume II, Parapublishing Company, Santa Barbara, CA, 1991.

4. MIL-T-53029B, Tanks, Fabric, Collapsible, 10,000; 20,000; and 50,000 Gallon, Drinking Water., 21 April 1989. Available from the Superintendent of Documents, U. S. Government Printing Office, Washington, D.C.

APPENDIX A

MATERIALS & METHODS

Material Selection

The models constructed in this study were designed to contain potable water in a 1-g gravitational field (laboratory conditions.) A wide variety of materials would be suitable for this application. Thus the materials used in this study were selected primarily on the basis of the investigator's knowledge. Considerations included weight, thickness, strength, expense, and availability.

<u>Outer Membrane</u>

For the two smaller laboratory models used in this study, a common low modulus parachute canopy nylon weighing 37 gms/m^2 (1.1 oz/yd^2) was selected. This material is lightweight, strong, and dimensionally stable. For the largest model, a higher modulus white dacron polyester weighing 127 gms/m^2 (3.7 oz/yd^2) was chosen. Sources and part numbers for these materials are given in the section below describing model construction.

<u>Inner Membrane</u>

For the two smaller models, the inner membranes consisted of white, off-the-shelf polyethylene trash bags. Bags were selected to be volumetrically larger than the outer membrane so that the material of the bag would not experience tensile stress and subsequently affect the shape of the tank. The inner membrane of the largest model was fabricated from clear polyethylene sheet about three mils thick. The exact pedigree of this material is not known. The inner membrane was formed by heatsealing together the circumferences of two disks of material about 1.4 m (4.5 ft) in diameter.

Material Testing

<u>Tensile Modulus Testing</u>

The tensile moduli of the materials used for the outer membranes of the model tanks were needed to correct for membrane stress. The two materials were tested as follows.

The material used for the 10 L and 50 L models was tested over a stress level range of approximately 350 to 1400 N/m (2.0 to 8.0 lb_f/in). A strip of fabric about 5 cm wide was cut to a length of about 80 cm (31.5 in). Each end was mounted firmly in clamps with rubber-lined jaws 2.54 cm (1.0 in) wide. The fabric was aligned with warp yarns parallel to the direction of pull. One clamp was mounted on an overhead beam and the other attached to an empty weight container that was allowed to hang freely. Two marks 58 cm (22.8 in) apart were made on the fabric. Weights were sequentially added to the weight container in increments of 1.0 or 2.0 lb_f (4.45 or 8.91 N). The distance between the marks was recorded one minute after each weight was added. The delay permitted equilibrium to be established. The weight provided the stress distributed across the width of the fabric in N/m, and gave the resulting elongation in meters. The maximum stress induced on the fabric was 1749 N/m (10 lb_f/in).

The resulting data were plotted using Cricket software on a Macintosh SE personal computer. This software was also used to generate the exponential relationship incorporated into the collapsible tank computer design program.

The dacron polyester used for the outer membrane of the largest model (378 liters) was tested similarly, except that it was not tested over a range of stress levels. This fabric was tested only at the predicted level of membrane stress for that tank, which was 623 N/m (3.56 lb_f/in).

<u>Sewing Take-up Testing</u>

The fabric pieces of the outer membrane of all model tanks were joined using a simple 301 machine lockstitch (3). The sewing take-up of this stitch was documented using several long coupons of fabric. First, a doubled piece of fabric was placed under 3.10 N (0.68 lb_f) of tension. Two marks 50 cm apart were made on the fabric, and a seam of the selected type was sewn along the two layers between the two marks. After sewing, the fabric was again placed under the same level of tension, and the distance between the marks measured again. The inverse of the ratio of the final to the original dimension provided the factor $1/T_f$ needed for the sewing take-up correction coefficient.

Computer Programs

Most programming was done in generic BASIC on a 386-based personal computer. An interactive program was written to support the design of the tank models and produce the dimensional data, corrected for stress level and sewing take-up, required for their construction. A program listing may be found in Appendix B. Another program was written to provide the dimensional data needed for the construction of the silhouettes used for photogrammetric evaluations of the models.

Model Construction

Three models were constructed; a 10 L model, a 50 L model and a 378 L model. Most raw materials were obtained from ParaGear Equipment Company, Skokie, Illinois, 60076. Part numbers given below are from ParaGear Catalog #55 (1990-1991), except as noted below.

The outer membrane of each model tank was the single component which required fabrication. The computer design program was used to generate the construction data corrected for stress level and sewing take-up. A gore pattern was drawn on light cardboard stock. The pattern (without seam allowance) was traced onto the membrane material (P/N W9110, except for the 378 L model which was Cloth World P/N 31-4936-0605089). Gores were block cut: The gore axis was oriented parallel to the warp or fill of the fabric. Each gore was marked at the $\theta=90$ mark to provide a visual reference during photogrammetric testing. A seam allowance of roughly 3/4" was allowed in cutting out the gores. The gores were sewn together using an #18 gauge needle on a Sears Kenmore household sewing machine with a 301 lockstitch using nylon "E" thread (P/N T-1009) at a machine setting of six stitches per inch indicated (spi). On the 10 L and 50 L models, an apex cap of radius $r = 2.5$ cm (1.0 in) was installed using adhesive backed fabric (P/N W901) to provide dimensional stability in that area. On the 378 L model, an apex cap of $r = 6.0$ cm (2.4 in) made of the same material as the outer membrane was installed by sewing. The opening in the base of the 10 L and 50 L models (needed for insertion of the inner membrane and installation onto the test fixture) was given dimensional stability by taping it to an appropriately sized ring of photographic mat board. The opening of the 378 L model was merely hemmed.

The inner membranes of the 10 L and 50 L models consisted simply of white, commercially available generic brand 0.8 mil polyethylene trash bags. The inner membrane of the 378 L model was fabricated from clear polyethylene about 3 mil thick. The exact origin of this material, made available to this study by another laboratory, is not known. Two circular sections of this material about 1.5 m (5 ft) in diameter were heatsealed together around their circumferences, and the inlet fitting was then installed in the center of one of the circular sections.

A cardboard silhouette depicting the ideal theoretical profile of each model was also made. These were drawn in black on white photographic matte board. Several features were included on the silhouettes to allow identification of the vertical axis and the point of maximum circumference, and to allow accurate measurement of the base diameter.

Model Testing

Test Fixtures

Smooth, level non-deformable surfaces were needed to support the models during testing. Methods to allow measurement of the tank pressure and to permit filling and emptying the models at will were also required. Two test fixtures were fabricated to meet these needs.

The test fixture used for the 10 L and 50 L models consisted of a smooth, circular 1/2" (1.25 cm) plywood platform about 0.6 m (2 ft) in diameter supported by three legs about 15 cm (6.0 in) high. Attached to one of the legs was a simple open-tube manometer made from clear polyethylene tubing. Plumbing was 1/2" Schedule 40 PVC except for the supply water line and the line leading to the manometer, which were 1/4" flexible tubing. Valves were provided in the drain line, the inlet line, and in the line leading to the manometer.

Because the 378 L model was much larger and heavier when full than the 50 L model, a larger test fixture was required. A platform 1.2 m (4.0 ft) square was fabricated from 1/2" (1.25 cm) exterior grade plywood covered by smooth 1/4" composition board and supported by a framework of 1" x 6" (2.54 x 15.24 cm) yellow pine beams. Provisions were made for levelling the platform and for routing the associated plumbing which was 3/4" PVC, except for the line leading to the attached open tube manometer, which was 1/4" rubber tubing.

Except for size, the test platforms were essentially similar. A simplified sketch is provided in Figure 7.

To install a tank model, an inner membrane was first connected (usually taped) to the inlet/outlet riser extending from the center of the platform. A small amount of water was then introduced into the membrane. The outlet valve was opened, and the inner membrane manipulated to force out any trapped air. The outlet valve was then closed, and the outer membrane installed over the inner membrane. The supply water line valve was then opened, and the tank filled. During most of the filling process the manometer remained valved off. As the tank took shape, the inlet valve was occasionally closed and the pressure checked by opening the valve to the manometer. Filling was complete when the pressure as read on the manometer equalled the theoretical value calculated from the data in Reference 1.

Figure 8 shows the 10 L model installed on the smaller test fixture. Figure 9 shows the 378 L model installed on the larger test fixture.

Profile Testing

A photogrammetric technique was used to compare the profile of each model with a representation of its ideal theoretical shape. A silhouette representing the theoretical profile of the model to be tested was placed on the platform and supported by the inlet/outlet riser. A tripod mounted Minolta X-700 was loaded with Kodachrome 64 film and equipped with a 210 mm telephoto lens. Subject-to-camera distance was adjusted to allow the image of the profile to fill the frame. This distance was approximately 4 m (12 ft) in the case of the 10 L model, 6.5 m (20.5 ft) in the case of the 50 L model, and 33 ft (10 m) in the case of the 378 L model. Camera height was adjusted so that the lens was at the same level as the $\theta=90$ mark on the silhouette.

After obtaining several exposures of the silhouette, it was removed and the model tank installed in its place as described above. The camera was not disturbed during this process. With the tank filled to the proper pressure as indicated on the manometer, several more exposures were taken. The 10 L and 50 L tank models were photographed in two orientations. In one, termed View #1 in Figure 6, the center of a gore was facing the camera ("gore centerline" configuration). In the other, termed View #2 in Figure 6, a seam joining two gores was facing the camera ("gore seam" configuration). Rotating the model was accomplished without disturbing the position of the test fixture. Because of its greater size, the 378 L model could not be rotated, and photogrammetry was thus limited to View #2 ("gore seam" configuration.)

After developing, the slides were projected onto the screen of a slide viewer (Osram "Diastar 200" M/N 46226). Selected linear dimensions in centimeters were taken of each silhouette, then of each model. Results were expressed as a ratio of the measurement as taken from the slide of the model tank to the measurement taken from the slide of the silhouette.

Membrane Stress Evaluation

While each tank was full, it's outer membrane was evaluated for stress distribution. Resources to quantitatively assess membrane stress via strain gauges were not available. However, while filled to capacity the membrane of each model was examined for evidence of nonhomogeneous stress distributions (e.g., pulled seams, wrinkling, strained stitching).

Capacity Testing

The 10 L and 50 L tanks were drained by opening the outlet valve. A 2.0 L graduated cylinder was used as required to capture and quantify the amount of water. The capacity of the 378 L model was not determined.

Mass and Storage Volume (Bulk) Testing

Model Tanks

Mass of the models, including inner and outer membranes but not including plumbing fittings, was obtained by weighing on a 0-4 kg electronic balance (Mettler Model No. PM 4600). Storage volume or bulk was estimated for each tank by carefully folding it into an appropriately-sized graduated laboratory beaker, and noting the approximate volume.

Control Tank

It was not possible to obtain a commercially available flexible tank because of the cost. Most manufacturers priced a 100 potable water tank at nearly $1,000.00. However, Aero-Tech Laboratories, Inc., of Ramsey, New Jersey provided samples of their membrane material and extensive information regarding their product line. A 100 gallon potable water tank (Aero-Tech P/N 120714) was selected as a "control" tank for mass and storage volume (bulk) comparisons. The "dry weight" of the tank of 18 lb_m (8.2 kg) was provided directly by the manufacturer. The storage volume was estimated as 1 ft^3 (28 L). This is one-third of the "shipping volume" of the container, 3 ft^3 (85 L), which was also provided by the manufacturer.

APPENDIX B

```
1000  REM SESSILE DROP TANK DESIGN PROGRAM
1010  REM BY DAVE FLANAGAN - AUGUST 1992
1020  REM LOG(B)=0.65
1030  REM THIS DATA FROM HARTLAND AND HARTLEY PLUS CONSTANTS ETC
1040  V=23.5531:A=35.7798:X90=2.28636:XB=1.78181:ARCMAX=3.76059
1050  Z=1.91368:PI=3.141592654#:G=9.800101:FTUH=1!:DRHO=998.71
1060  RAD=PI/180:DEG=1/RAD:LOGB=.65:VH=1:T6=0
1070  CLS:PRINT:PRINT:PRINT
1080  PRINT "  SESSILE DROP FLEXIBLE TANK - INTERACTIVE DESIGN PROGRAM"
1090  PRINT "                         SDT65L.BAS"
1100  PRINT "                 SESSILE DROP SHAPE LOG(B)=0.65"
1110  PRINT
1120  PRINT "                  (FRESH WATER IN 1-G FIELD)"
1130  PRINT:PRINT
1140  INPUT "INPUT DESIRED CAPACITY IN LITERS: ",L
1150  PRINT
1160  INPUT "INPUT NUMBER OF GORES: ",N
1170  IF N < 6 THEN 1150
1180  PRINT
1190  PRINT "INPUT SEWING TAKE-UP COEFFICIENT. DEFAULT VALUE IS ";FTUH
1200  INPUT "SELECTION?? ",FTU
1210  IF FTU=0 THEN FTU=FTUH
1220  IF FTU=<1.1 AND FTU>=1 THEN 1240
1230  GOTO 1180
1240  PRINT
1250  PRINT "STRESS CORRECTION COEFFICIENT OPTIONS"
1260  PRINT "       F-111.......................1"
1270  PRINT "       NO CORRECTION...............2"
1280  PRINT "       USER SUPPLIED CORRECTION.....3"
1290  INPUT "SELECTION: ",T6
1300  IF (T6<>3) AND (T6<>2) AND (T6<>1) THEN 1240
1310  PRINT
1320  IF T6<>3 GOTO 1350
1330  INPUT "INPUT USER SUPPLIED CORRECTION COEFFICIENT: ",FCHOLD
1340  PRINT
1350  PRINT "INPUT THE VOLUME CORRECTION COEFFICIENT. DEFAULT VALUE IS ";VH
1360  INPUT "SELECTION?? ",VCH
1370  IF VCH=0 THEN VCH=VH
1380  IF VCH>.8 AND VCH<1.3 THEN 1400
1390  GOTO 1340
1400  REM COVERTS LITERS TO CUBIC METERS AND INCORPORATES VOL CORR COEFF
1410  VA=(L*VCH)/1000
1420  CLS
1430  REM COMPUTES C AND SQR(C) PARAMETERS
1440  LET C = (V/VA)^(2/3)
1450  LET SC = SQR(C)
1460  REM FINDS SURFACE AREA
1470  LET BSP=PI*(XB/SC)^2
1480  LET SURF = (A/C)
1490  LET FSURF = SURF +BSP
1500  REM FINDS SURF TO VOL RATIO
1510  LET SVR = SURF/(L/1000)
1520  LET FVR = FSURF/(L/1000)
1530  REM COMPUTES NONDIMENSIONAL B
1540  B=10^LOGB
1550  REM COMPUTES SIGMA (MEMBRANE STRESS) FROM C BASED ON WATER
1560  REM FILLED TANK IN 1-G FIELD
```

```
1570  LET SIG = (DRHO*G)/C
1580  LET ESIG = SIG/174.95
1590  REM COMPUTES PRESSURE AT APEX
1600  LET PA=(2*DRHO*G)/(B*SC)
1610  LET EPA=PA/6895
1620  REM COMPUTES PRESSURE AT BASE
1630  LET PB=PA+(DRHO*G*(Z/SC))
1640  LET EPB=PB/6895
1650  REM COMPUTES DIMENSIONAL DATA
1660  LET DMAX=200*X90/SC:REM IS CM
1670  LET H=100*Z/SC:REM IS CM
1680  LET DFP=200*XB/SC:REM IS CM
1690  LET FPAREA=PI*(XB/SC)^2:REM IS METERS SQUARED
1700  LET CIRCMAX=DMAX*PI
1710  LET GW=CIRCMAX/N
1720  LET GL=100*ARCMAX/SC
1730  LET OGL=GL+100*XB/SC
1740  PRINT "  SESSILE DROP FLEXIBLE TANK - THEORETICAL CHARACTERISTICS"
1750  PRINT "              SESSILE DROP SHAPE LOG(B)=0.65"
1760  PRINT "               (FRESH WATER IN 1-G FIELD)"
1770  PRINT
1780  PRINT "VOLUME OF TANK AS INPUT (L)................. ";L
1790  PRINT "NUMBER OF GORES............................. ";N
1800  PRINT "C PARAMETER (1/m^2)......................... ";C
1810  PRINT "SQUARE ROOT OF C (1/m)...................... ";SC
1820  PRINT "MEMBRANE STRESS (N/m)....................... ";SIG
1830  PRINT "MEMBRANE STRESS (lbf/in).................... ";ESIG
1840  PRINT "PRESSURE AT APEX (N/m^2).................... ";PA
1850  PRINT "PRESSURE AT APEX (psi)...................... ";EPA
1860  PRINT "PRESSURE AT BASE (N/m^2).................... ";PB
1870  PRINT "PRESSURE AT BASE (psi)...................... ";EPB
1880  PRINT "HEIGHT (cm)................................. ";H
1890  PRINT "MAX DIAMETER (cm)........................... ";DMAX
1900  PRINT "FOOTPRINT DIAMETER (cm).................... ";DFP
1910  PRINT "FOOTPRINT AREA (m^2)........................ ";FPAREA
1920  PRINT "MAXIMUM GORE WIDTH (cm).................... ";GW
1930  PRINT "GORE LENGTH TO EQUATOR (cm)................ ";GL
1940  PRINT "MAXIMUM GORE LENGTH (cm).................... ";OGL
1950  PRINT
1960  INPUT "REDESIGN (1=Y)?? ",T1
1970  IF T1=1 THEN 1000
1980  PRINT
1990  INPUT "DO YOU WANT A HARDCOPY (1=Y)?? ",T2
2000  IF T2<>1 THEN CLS:END
2010  CLS:PRINT "WORKING......................."
2020  IF T6<>1 THEN GOTO 2060
2030  YMOD=19682*10^(1.9788E-04*SIG)
2040  FC=YMOD/(YMOD+SIG)
2050  GOTO 2080
2060  IF T6 = 2 THEN FC = 1
2070  IF T6 = 3 THEN FC = FCHOLD
2080  LPRINT
2090  LPRINT "SESSILE DROP TANK DESIGN PROGRAM"
2100  LPRINT "LOG(B)=0.65             SDT65L.BAS"
2110  LPRINT
2120  LPRINT "**************************************"
2130  LPRINT
2140  LPRINT "THEORETICAL TANK CHARACTERISTICS AT FULL CAPACITY"
```

```
2150 LPRINT
2160 LPRINT "VOLUME OF TANK AS INPUT (L)................. ";L
2170 LPRINT "NUMBER OF GORES AS INPUT.................... ";N
2180 LPRINT "VOLUME CORRECTION COEFFICIENT............... ";VCH
2190 LPRINT "CORRECTED VOLUME USED IN CALCULATIONS (m^3). ";VA
2200 LPRINT "C PARAMETER................................. ";C
2210 LPRINT "SQUARE ROOT OF C............................ ";SC
2220 LPRINT "RADIUS OF CURVATURE AT THE APEX (cm)........ ";B*100/SC
2230 LPRINT "SURFACE AREA (CURVED SURFACE) (m^2)......... ";SURF
2240 LPRINT "TOTAL SURFACE AREA (w/FOOTPRINT) (m^2)...... ";FSURF
2250 LPRINT "SURFACE-TO-VOLUME RATIO (1/m)............... ";SVR
2260 LPRINT "SURFACE-TO-VOLUME RATIO (w/FOOTPRINT) (1/m). ";FVR
2270 LPRINT "MEMBRANE STRESS (N/m)....................... ";SIG
2280 LPRINT "MEMBRANE STRESS (lbf/in).................... ";ESIG
2290 LPRINT "PRESSURE AT APEX (N/m^2).................... ";PA
2300 LPRINT "PRESSURE AT APEX (psi)...................... ";EPA
2310 LPRINT "PRESSURE AT BASE (N/m^2).................... ";PB
2320 LPRINT "PRESSURE AT BASE (psi)...................... ";EPB
2330 LPRINT "MAXIMUM DIAMETER (cm)....................... ";DMAX
2340 LPRINT "HEIGHT (cm)................................. ";H
2350 LPRINT "FOOTPRINT DIAMETER (cm)..................... ";DFP
2360 LPRINT "FOOTPRINT AREA (m^2)........................ ";FPAREA
2370 LPRINT "MAXIMUM GORE WIDTH (cm)..................... ";GW
2380 LPRINT "GORE LENGTH APEX TO 180 DEG (cm)............ ";GL
2390 LPRINT "OVERALL GORE LENGTH (INCL BASE) (cm)........ ";OGL
2400 LPRINT
2410 LPRINT "***************************************"
2420 LPRINT
2430 LPRINT "GORE PLANFORM CONSTRUCTION DATA":LPRINT
2440 LPRINT "MEMBRANE STRESS CORRECTION COEFFICIENT...... ";FC
2450 LPRINT "SEWING TAKE-UP CORRECTION COEFFICIENT....... ";FTU
2460 LPRINT "MAXIMUM GORE WIDTH (cm)..................... ";GW*FTU*FC
2470 LPRINT "OVERALL GORE LENGTH (INCL BASE) (cm)........ ";OGL*FTU*FC
2480 LPRINT "GORE LENGTH, APEX TO 180 DEG (cm)........... ";GL*FTU*FC
2490 LPRINT "FOOTPRINT RADIUS (cm)....................... ";(DFP*FTU*FC)/2
2500 LPRINT
2510 LPRINT "      GORE PLANFORM DIMENSIONS (cm)"
2520 LPRINT "THETA    AXIAL DISTANCE    RADIUS OF ARC"
2530 THD=5:ARC=.382755:X=.382276:Z=.0165391:GOSUB 2950
2540 THD=10:ARC=.729949:X=.726436:Z=.0615056:GOSUB 2950
2550 THD=15:ARC=1.02786:X=1.01727:Z=.125613:GOSUB 2950
2560 THD=20:ARC=1.27973:X=1.2597:Z=.201036:GOSUB 2950
2570 THD=25:ARC=1.49398:X=1.45547:Z=.282778:GOSUB 2950
2580 THD=30:ARC=1.67867:X=1.61933:Z=.367863:GOSUB 2950
2590 THD=35:ARC=1.84018:X=1.75558:Z=.454488:GOSUB 2950
2600 THD=40:ARC=1.98331:X=1.86917:Z=.541498:GOSUB 2950
2610 THD=45:ARC=2.11166:X=1.96383:Z=.628109:GOSUB 2950
2620 THD=50:ARC=2.22793:X=2.04242:Z=.713751:GOSUB 2950
2630 THD=55:ARC=2.33419:X=2.10714:Z=.797989:GOSUB 2950
2640 THD=60:ARC=2.43206:X=2.15975:Z=.880473:GOSUB 2950
2650 THD=65:ARC=2.5228:X=2.20168:Z=.960911:GOSUB 2950
2660 THD=70:ARC=2.60742:X=2.23409:Z=1.03905:GOSUB 2950
2670 THD=75:ARC=2.68674:X=2.25797:Z=1.11467:GOSUB 2950
2680 THD=80:ARC=2.76144:X=2.27417:Z=1.18757:GOSUB 2950
2690 THD=85:ARC=2.83208:X=2.28341:Z=1.25758:GOSUB 2950
2700 THD=90:ARC=2.89912:X=2.28636:Z=1.32453:GOSUB 2950
2710 THD=95:ARC=2.96295:X=2.2836:Z=1.38828:GOSUB 2950
2720 THD=100:ARC=3.02391:X=2.27566:Z=1.4487:GOSUB 2950
```

```
2730  THD=105:ARC=3.08228:X=2.26305:Z=1.50567:GOSUB 2950
2740  THD=110:ARC=3.13831:X=2.24622:Z=1.5591:GOSUB 2950
2750  THD=115:ARC=3.19222:X=2.22561:Z=1.60889:GOSUB 2950
2760  THD=120:ARC=3.24418:X=2.20164:Z=1.65498:GOSUB 2950
2770  THD=125:ARC=3.29437:X=2.17469:Z=1.6973:GOSUB 2950
2780  THD=130:ARC=3.34293:X=2.14515:Z=1.73581:GOSUB 2950
2790  THD=135:ARC=3.38997:X=2.11338:Z=1.7705:GOSUB 2950
2800  THD=140:ARC=3.43562:X=2.07975:Z=1.80133:GOSUB 2950
2810  THD=145:ARC=3.47997:X=2.04458:Z=1.82833:GOSUB 2950
2820  THD=150:ARC=3.52311:X=2.00821:Z=1.85151:GOSUB 2950
2830  THD=155:ARC=3.56512:X=1.97096:Z=1.87091:GOSUB 2950
2840  THD=160:ARC=3.60607:X=1.93314:Z=1.88658:GOSUB 2950
2850  THD=165:ARC=3.64604:X=1.89504:Z=1.8986:GOSUB 2950
2860  THD=170:ARC=3.68508:X=1.85694:Z=1.90706:GOSUB 2950
2870  THD=175:ARC=3.72324:X=1.81911:Z=1.91204:GOSUB 2950
2880  THD=180:ARC=3.76059:X=1.78181:Z=1.91368:GOSUB 2950
2890  LPRINT
2900  LPRINT "COMPLETE PER SDT65L.BAS........"
2910  LPRINT CHR$(12)
2920 CLS:PRINT:PRINT
2930 PRINT "COMPLETE PER SDT65L.BAS......."
2940  END
2950 REM CALCULATES AXIAL DISTANCE AND RADIUS OF ARC
2960 LET DS=FC*FTU*ARC*100/SC
2970 LET THR=THD*RAD
2980 LET ARG=(SIN(PI/N)*SIN(THR))
2990 LET INVSIN=ATN(ARG/SQR(-ARG*ARG+1))
3000 LET AR=100*FC*FTU*X*INVSIN/(SIN(THR)*SC)
3010 LPRINT USING "###.#      ####.###          ####.###";THD,DS,AR
3020 RETURN
```

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13. ABSTRACT *(Maximum 200 words)*

Tanks for bulk liquid containment will be required to support advanced planetary exploration programs. Potential applications include storage of potable, process, and waste water, fuels, and process chemicals. The launch mass and volume penalties inherent in rigid tanks suggest that collapsible tanks may be more efficient. Collapsible tanks are made of lightweight flexible material and can be folded compactly for storage and transport. Although collapsible tanks for terrestrial use are widely available, a new design has been developed that has significantly less mass and bulk than existing models. Modelled after the shape of a sessible drop, this design features a dual membrane with a nearly uniform stress distribution and a low surface-to-volume ratio. It can be adapted to store a variety of liquids in nearly any environment with a constant acceleration field.

Three models of 10L, 50L, and 378L capacity have been constructed and tested. The 378L (100 gallon) model weighed less than 10% of a commercially available collapsible tank of equivalent capacity, and required less than 20% of the storage space when folded for transport.

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