NASA Contractor Report 188247

Advanced Collapsible Tank for Liquid Containment

David T. Flanagan, B. S.
Robert C. Hopkins, PH. D.

June 1993

NASA

Advanced Collapsible Tank for Liquid Containment

David T. Flanagan, B. S.
Krug Life Sciences
Houston, Texas

Robert C. Hopkins, PH. D.
University of Houston Clear Lake
Houston, Texas

TABLE OF CONTENTS

TABLES

FIGURES

APPENDICES

ABSTRACT

Title: Advanced Collapsible Tank For Liquid Containment

Authors: David T. Flanagan, B.S.
        Robert C. Hopkins, Ph.D.

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

2

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

3

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

<u>Background Study</u>

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

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

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

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

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

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

5

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 $\theta=180$ 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

<u>Gore Design</u>

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

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

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

7

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

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

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

or

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

Substituting in the values previously obtained for r_2 and sl

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

and simplifying

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

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

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

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,

8

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

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

9

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,

$$L_s = L + \Delta L$$

10

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.

Correction For Sewing Take-Up

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

16

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 $\theta=90$ (point of maximum
diameter.) Although the total height of the model was in
reasonably good agreement with the silhouette, the mark at
$\theta=90$ 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.

ACKNOWLEDGEMENTS

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	6.15356E-02	1.67003E+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	1.84013E+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	2.01893E+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
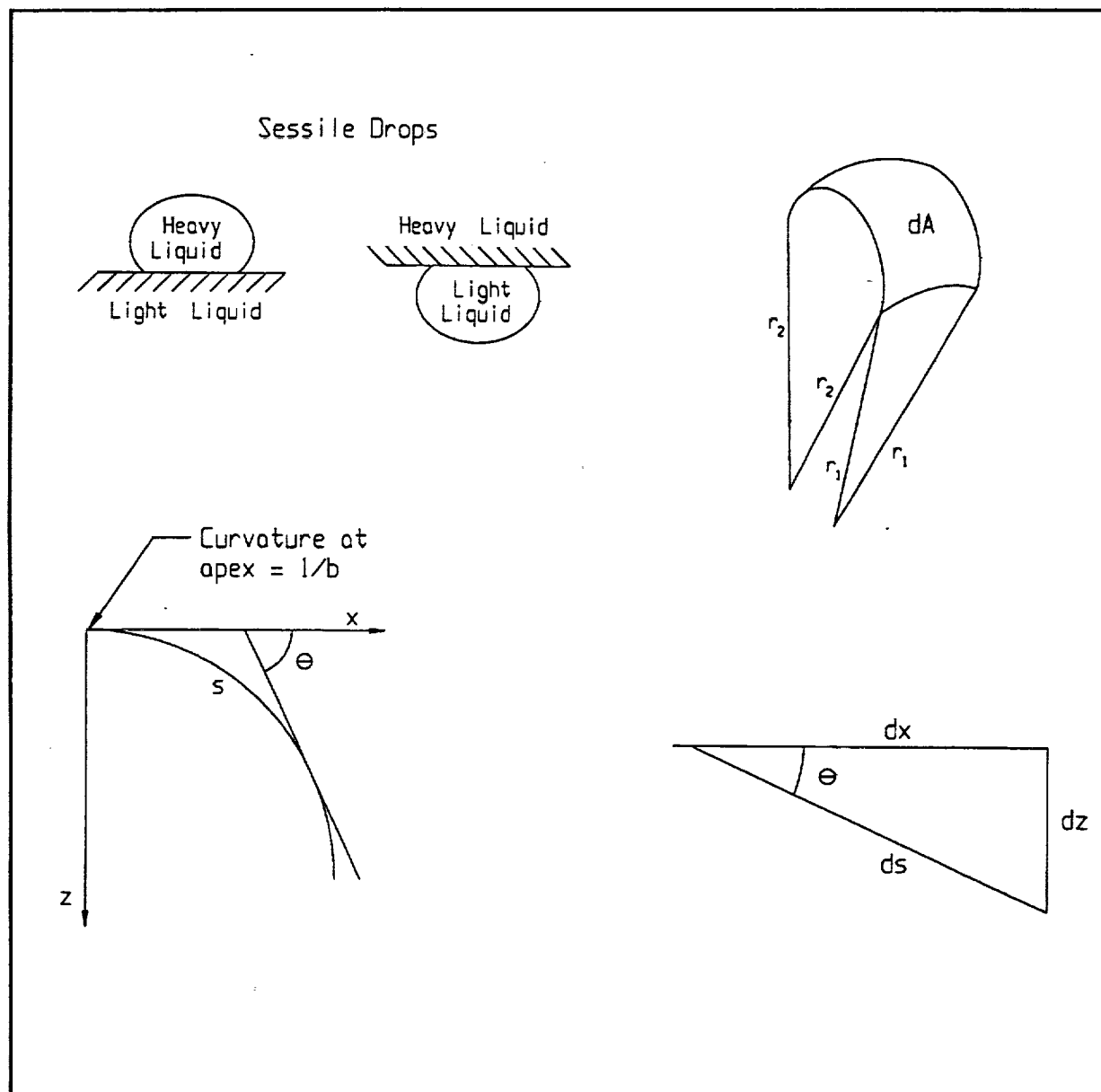
Sessile Drops

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

22
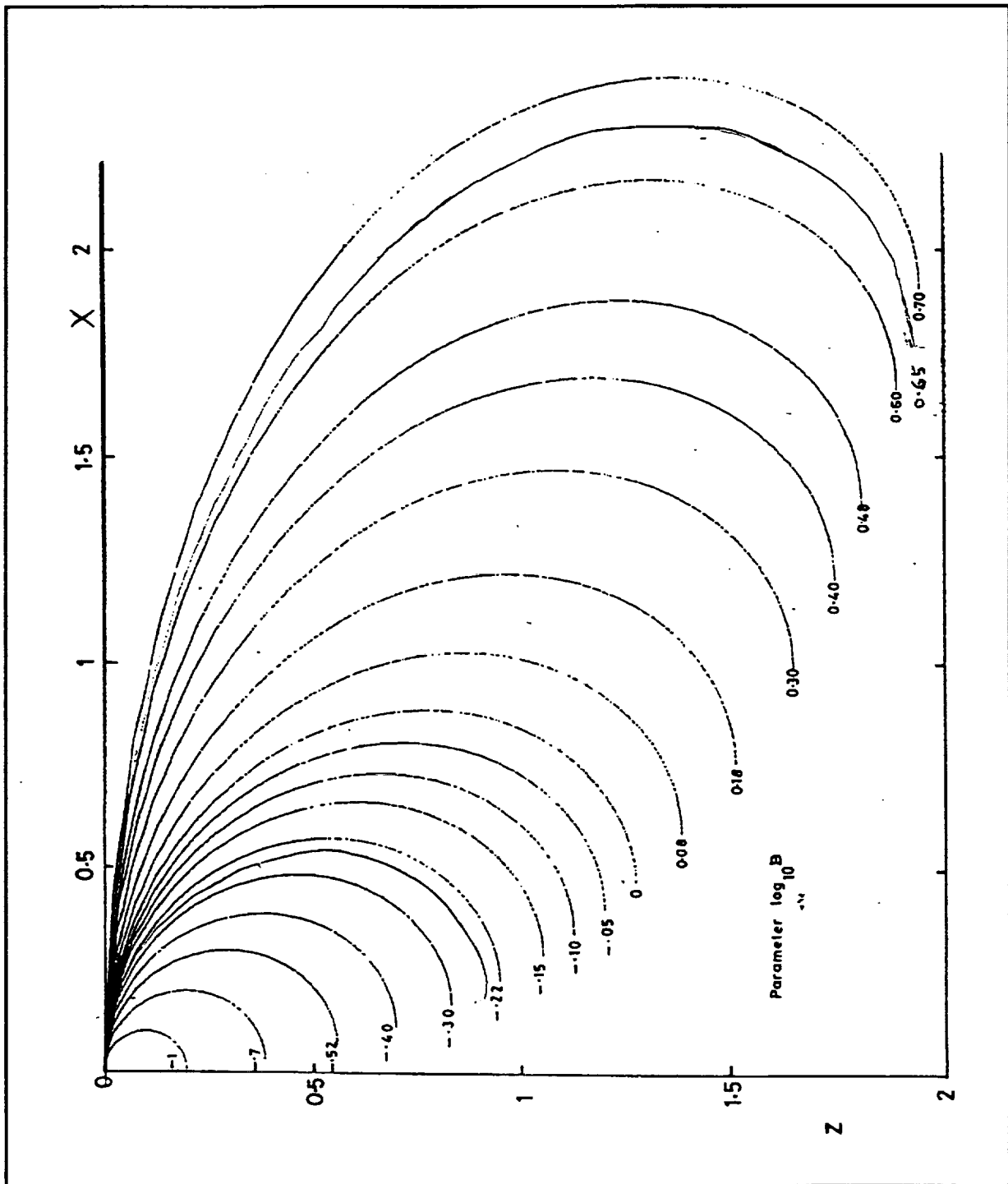
Figure 2. Profiles of sessile drops with respect to the dimensionless radius of curvature at the apex (log(B)) from reference 1.
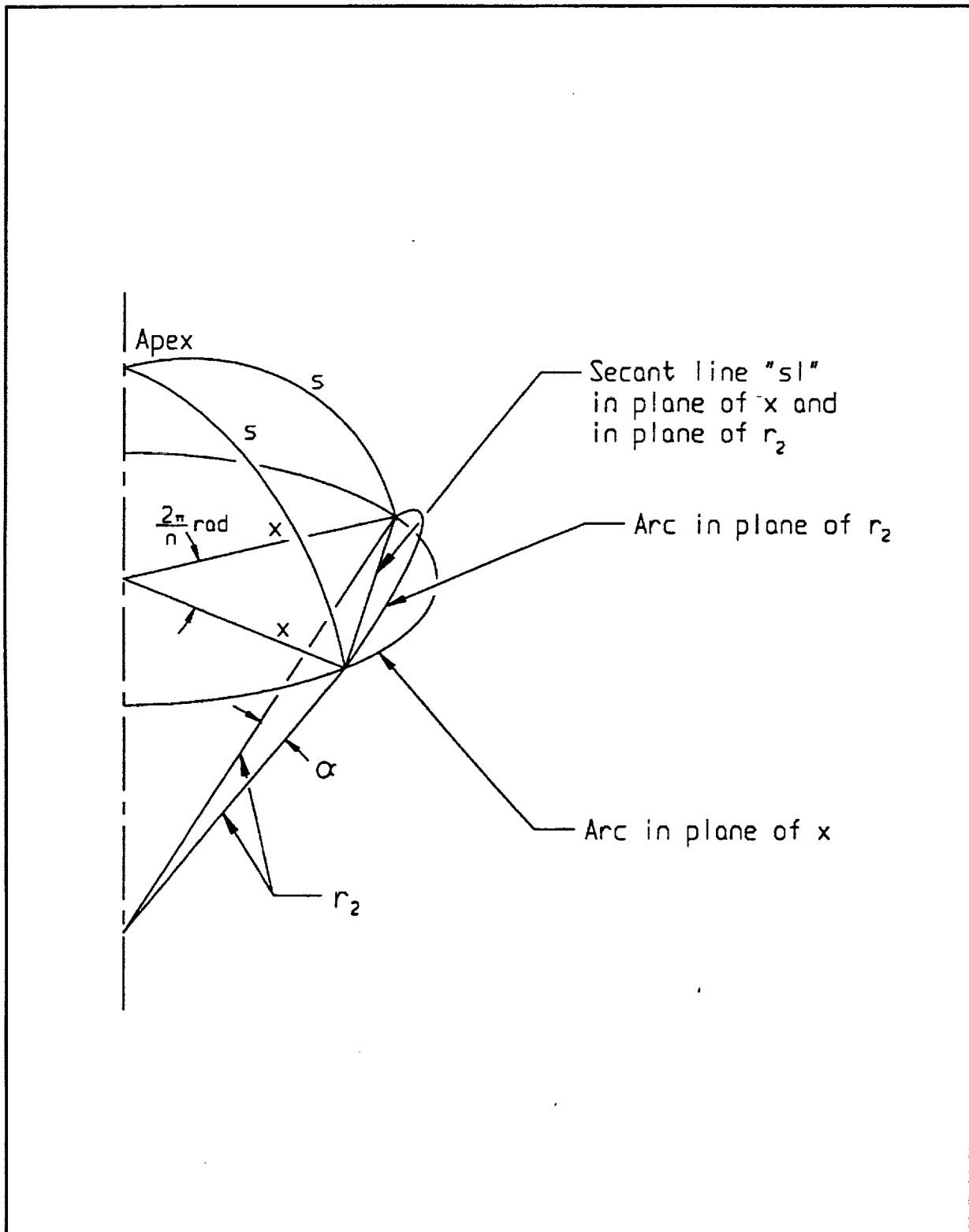
Figure 3. Parameters for developing the gore pattern. The plane created by r_2 through $d\alpha$ is orthogonal to the surface of the drop. The plane created by x through any angle $2\pi/n$ is orthogonal to the axis of symmetry.

24

PARAMETERS OF A 10 L MODEL
wrt SESSILE DROP SHAPE
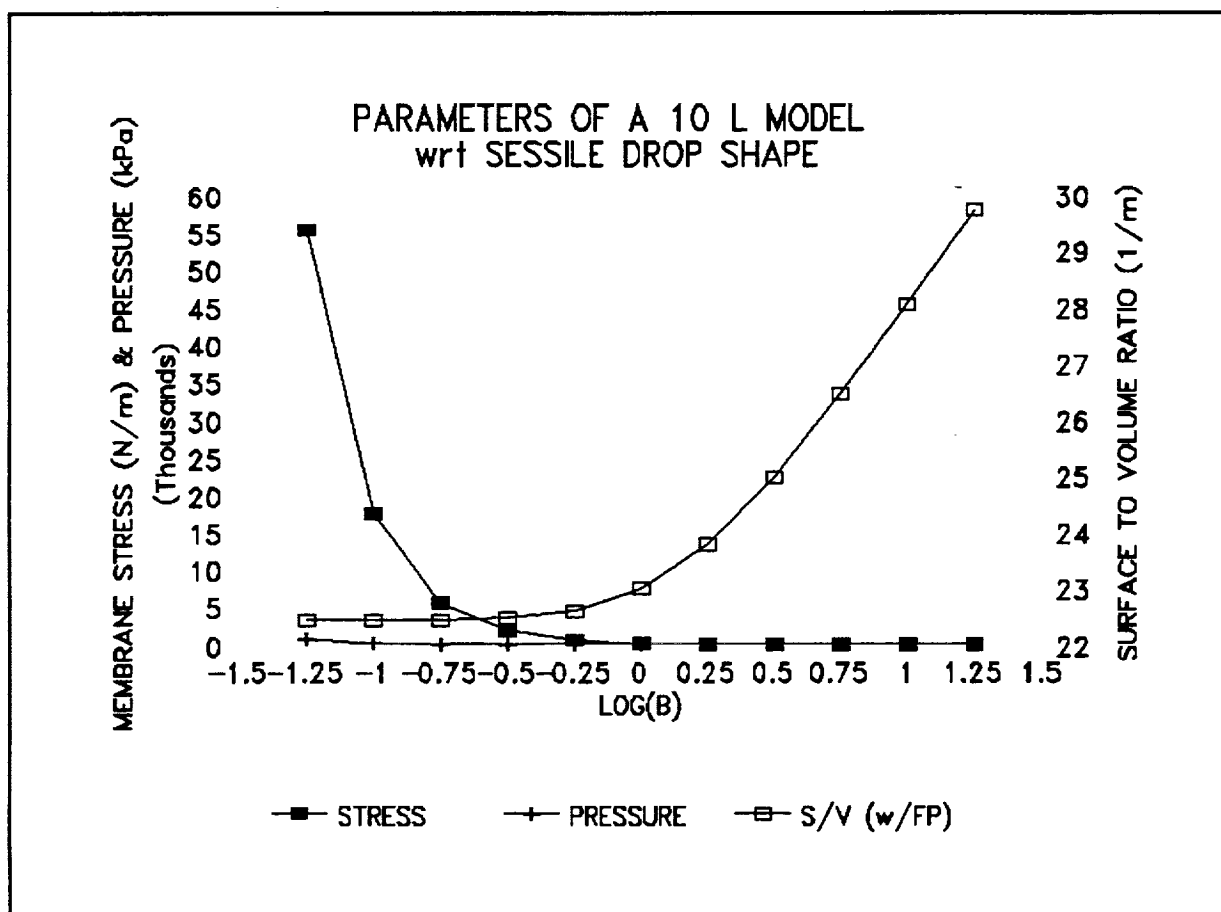
Figure 4. Pressure, membrane stress, and surface-to-volume ratio of a 10 L collapsible tank with respect to tank shape.

**TENSILE MODULUS OF F-111
OUTER MEMBRANE MATERIAL**
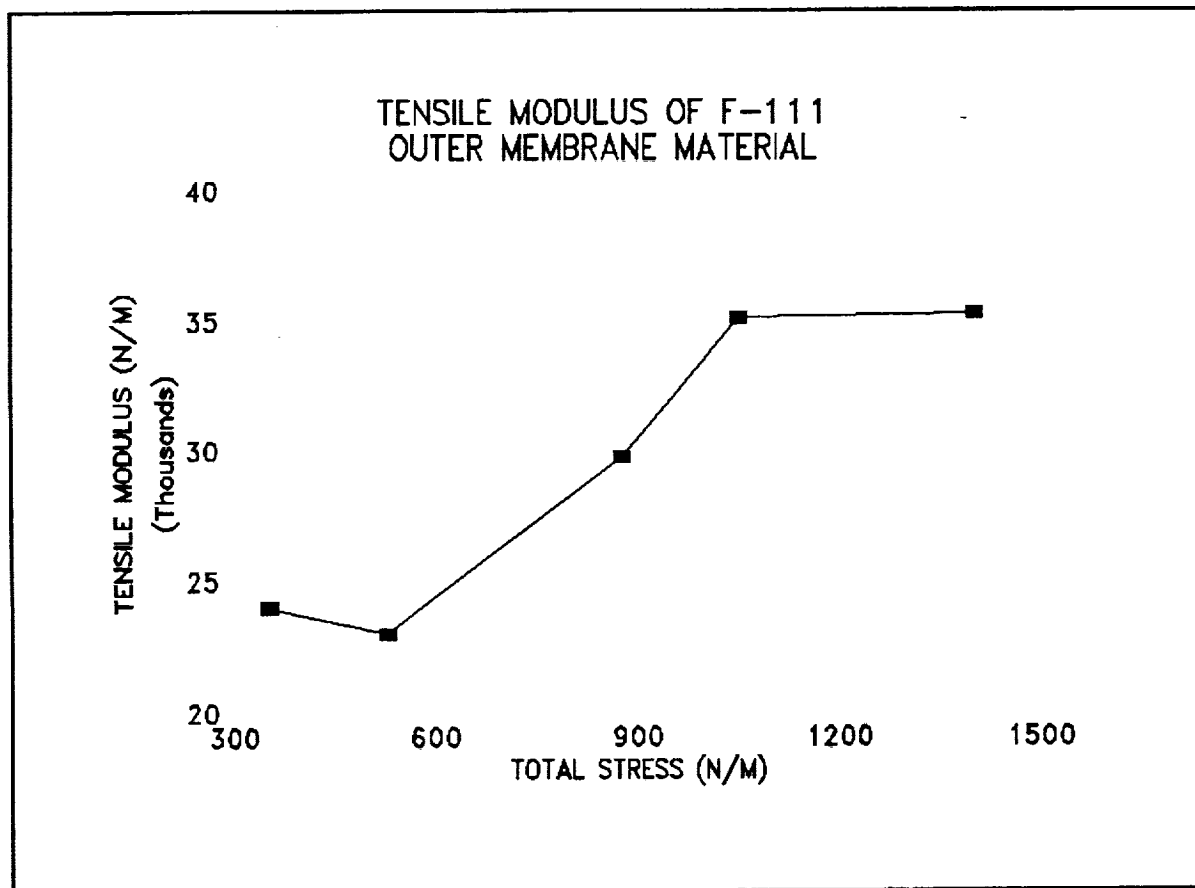
Figure 5. Tensile modulus of F-111 nylon material with respect to stress.
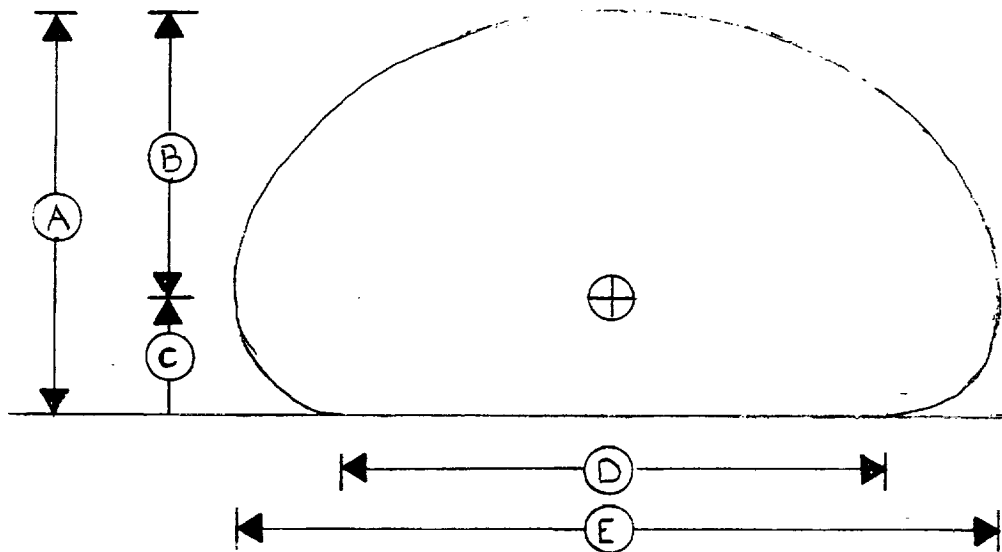
Dimension	10 L Model		50 L Model		378 L Model
	View #1	View #2	View #1	View #2	View #2
A	1.01	1.02	1.04	1.04	.98
B	.94	.97	.93	1.03	.94
C	1.22	1.14	1.29	1.11	1.05
D	1.06	1.12	1.06	1.06	1.02
E	.99	1.01	1.01	1.01	1.04

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.
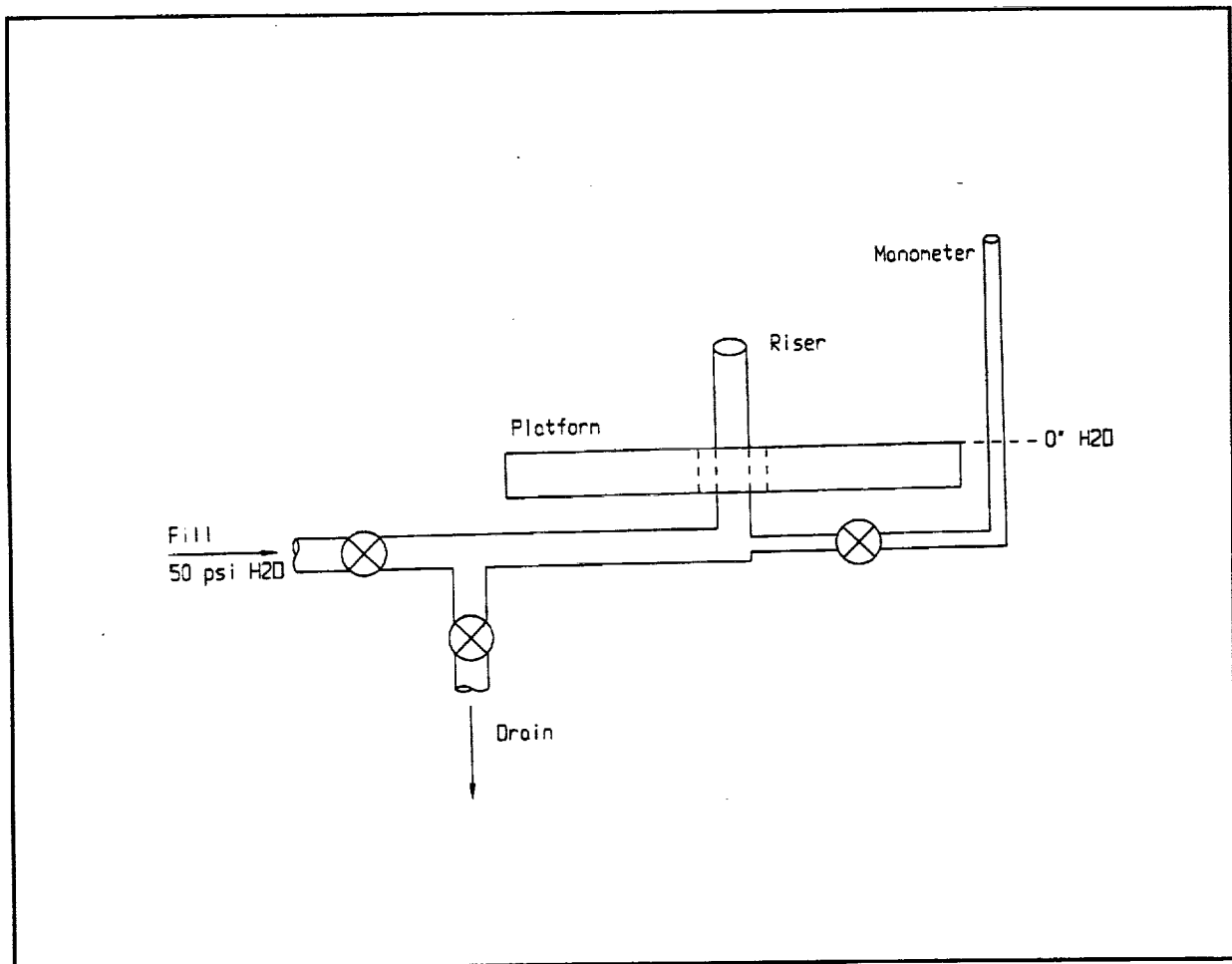
Figure 7. Simplified sketch of the two test fixtures used in this study.
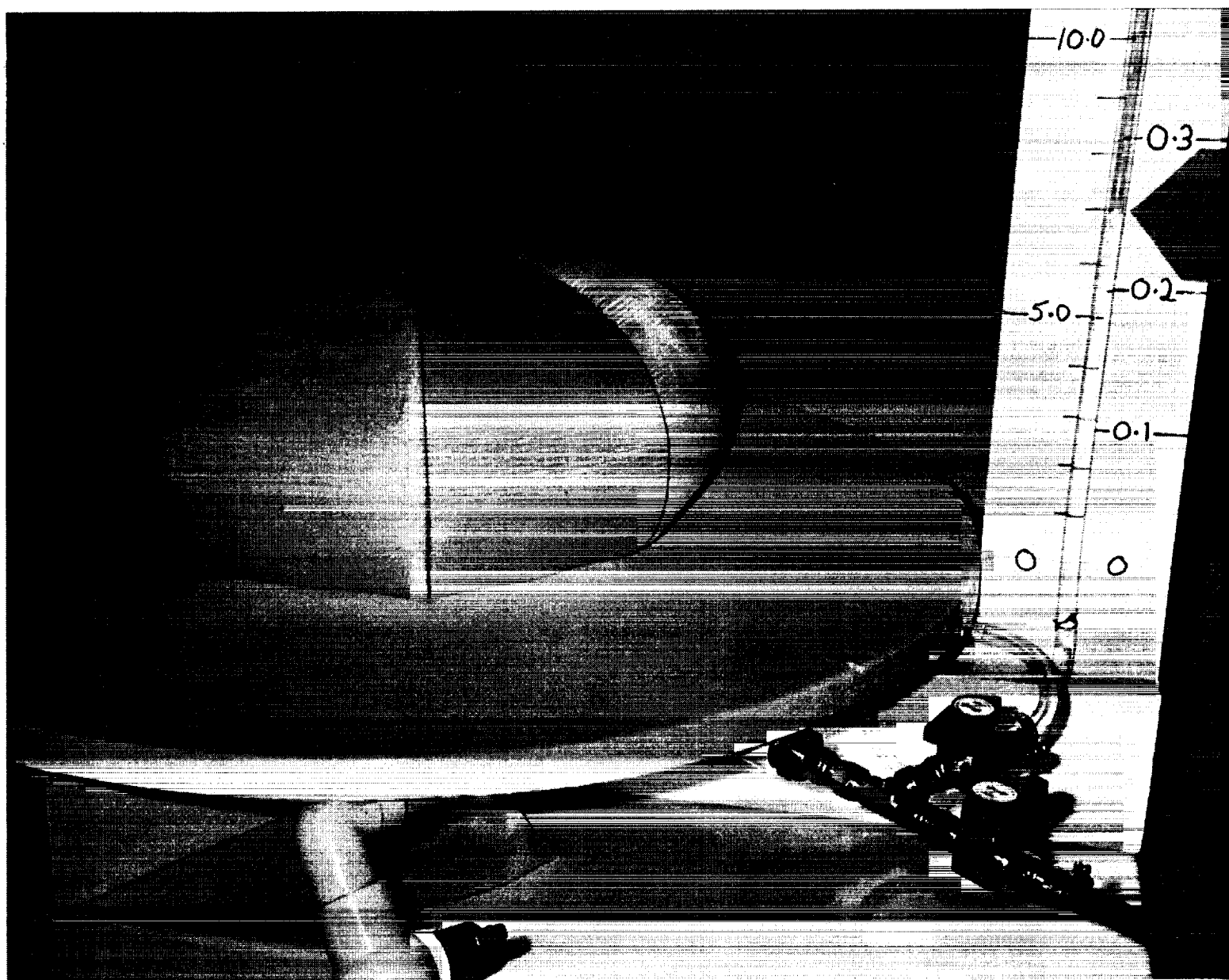
Figure 8. The 10 L collapsible tank model is shown installed on the smaller test fixture. The associated plumbing, including the open tube manometer used for measuring pressure, is clearly visible.
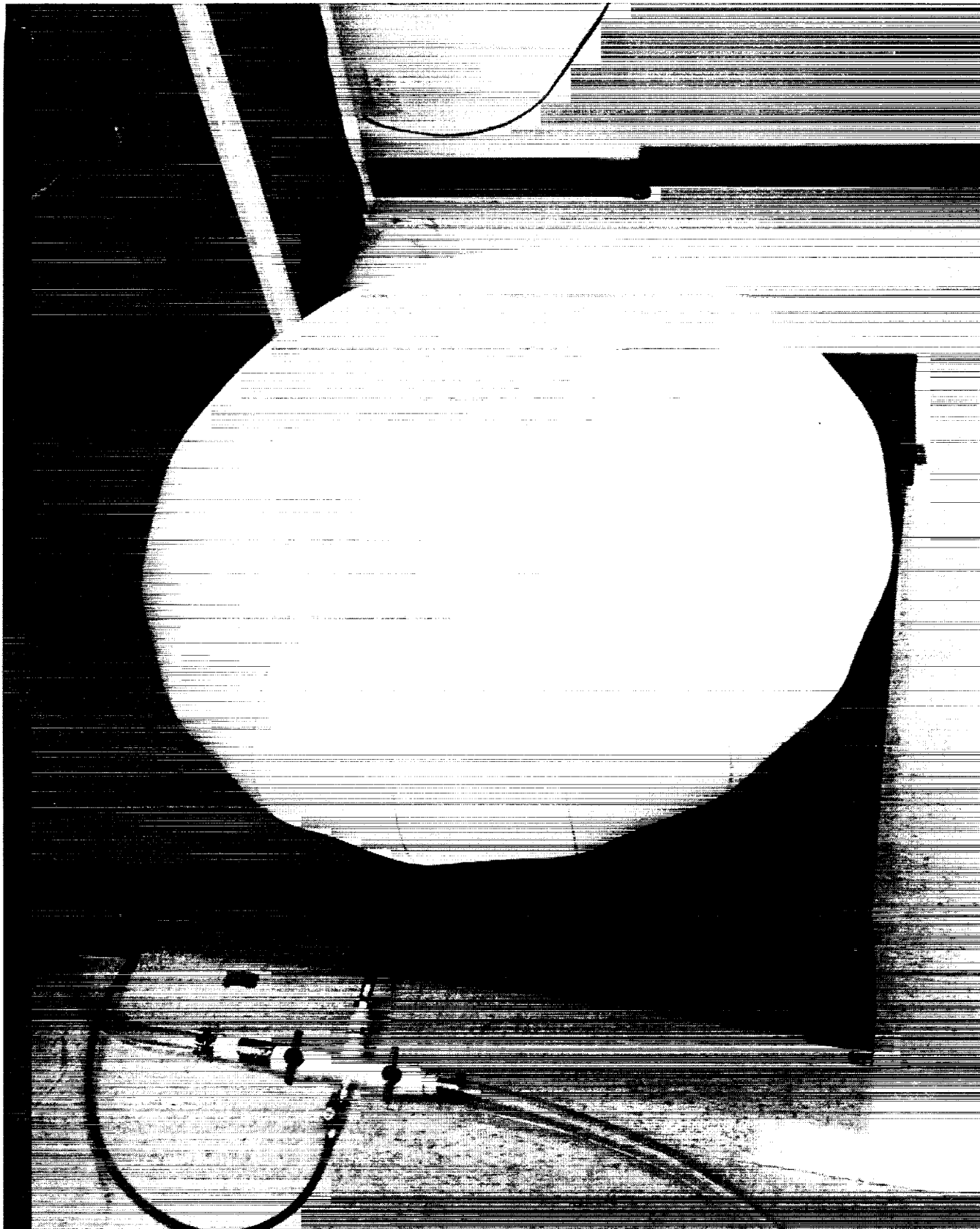
Figure 9. The largest collapsible tank model built in this study, designed to hold 378 L (100 gal), is shown here installed on the larger test fixture. This tank, when empty, weighed less than 10% of a commercially available model of the same capacity, and could be stored in less than 20% of the space.

30

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.

Outer Membrane

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.

Inner Membrane

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

Tensile Modulus Testing

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

32

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).

Sewing Take-up Testing

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.

34

Model Testing

<u>Test Fixtures</u>

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 θ=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.

```
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
```

REPORT DOCUMENTATION PAGE

Public reporting burden for this collection of information is estimated to average 1 hour per response, including the time for reviewing instructions, searching existing data sources, gathering and maintaining the data needed, and completing and reviewing the collection of information. Send comments regarding this burden estimate or any other aspect of this collection of information, including suggestions for reducing this burden, to Washington Headquarters Services, Directorate for Information Operations and Reports, 1215 Jefferson Davis Highway, Suite 1204, Arlington, VA 22202-4302, and to the Office of Management and Budget, Paperwork Reduction Project (0704-0188), Washington, DC 20503.

1. AGENCY USE ONLY (Leave blank)	2. REPORT DATE June 1993	3. REPORT TYPE AND DATES COVERED Contractor Report

4. TITLE AND SUBTITLE
Advanced Collapsible Tank for Liquid Containment

5. FUNDING NUMBERS
NAS-9-18492

6. AUTHOR(S)
David T. Flanagan, Krug International; Robert C. Hopkins, University of Houston Clear Lake

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Krug Life Sciences, Houston, Texas

University of Houston Clear Lake

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING / MONITORING AGENCY NAME(S) AND ADDRESS(ES)
National Aeronautics and Space Administration
Washington, D.C. 20546-001

10. SPONSORING / MONITORING AGENCY REPORT NUMBER
NASA CR-188247

11. SUPPLEMENTARY NOTES

12a. DISTRIBUTION / AVAILABILITY STATEMENT
Unclassified/unlimited
Subject Category 14
Available from the National Technical Information Service,
5285 Port Royal Road, Springfield, VA 22161; (703) 487-4600.

12b. DISTRIBUTION CODE

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.

14. SUBJECT TERMS
collapsible tank; storage; sessile drop; surface-to-volume ratio; membrane; capacity

15. NUMBER OF PAGES
47

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT unclassified	18. SECURITY CLASSIFICATION OF THIS PAGE unclassified	19. SECURITY CLASSIFICATION OF ABSTRACT unclassified	20. LIMITATION OF ABSTRACT UL

Standard Form 298 (Rev. 2-89)
Prescribed by ANSI Std. 239-18
298-102